



Influence of material structure on size effect law of concrete structures

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ABSTRACT

The purpose of this paper is to present some results of numerical studies on the basis of fracture mechanics of concrete taking into consideration the heterogeneity of material structure. As a result, it is shown that numerical analysis with a fictitious crack model may predict well the size effect on strength of concrete structures fractured in a quasi-brittle manner such as shear failure.

1 INTRODUCTION

Size of concrete structures has been larger and larger as a result of advances in materials, design methods and construction techniques in recent years. Many design rules used until quite recently, however, are based on empirical formulae which were deduced from test results in testing laboratories. If the strength of concrete structures is independent of the size, prediction of the capacity of large structures can be possible from an existing formula and/or experimental results in a testing laboratory. It is not quite true in many cases and it is very important to consider 'size effect' which is usually defined as the change in the nominal strength due to a change in the size of geometrically similar specimens.

Although many experimental results and theoretical studies were reported on the size effect, there are quite few building codes in which the size effect is taken into consideration. While the size effect is considered in several codes, it is limited to introduce an empirical formula to calculate the shear and punching resistance. Moreover there are often large discrepancies even in those cases between predicted values of the strength and previous experimental results [1]. No codes take into consideration the influence of the deferent mix proportion of concrete on the size effect, though the aggregate size seriously influences the shear strength of RC beams as shown by Shioya et al. [2] (Fig. 1).

As concrete is a composite material with at least two phases that is mortar and aggregate, the material structure is disordered. Besides this intrinsic randomness, a boundary layer near the surface of concrete has a different composition and strength than the interior because of the wall effect and of drying and hydration due to diffusion process effects [for example, 3 & 4]. As a result, strength of concrete structures is random. While the weakest link theory or Weibull model was often used to interpret the randomness [for example, 5], the size effect was also interpreted by the same model on the hypothesis that a larger specimen has a weaker defect. If the strength is determined only by the crack initiation, the model may work but the size effect properties of concrete

cannot be sufficiently described by this model.

Many experimental studies have revealed that most failure phenomena of concrete structures are composed of crack initiation and its propagation. Mihashi [6] proposed a stochastic model for quasi-brittle failure which is different from Weibull model. As one of the results obtained with the stochastic model, Mihashi showed that the difference of the size effects in tensile strength and in compressive one is due to the different mechanism of the propagation process [6].

Since the balance between elastic energy stored in the structure versus fracture energy consumed in crack propagation is obviously affected by the structure size, questions of scaling law have become one of major subjects in the field of fracture mechanics of concrete structures in the nineteen-nineties. An international workshop on "Size Effect in Concrete Structures" was organized by Japan Concrete Institute (JCI) in 1993 and the proceedings was published in 1994 [7]. In the proceedings, various experimental aspects of the size effect, physical mechanisms that cause the size effect, theoretical models and analytical techniques for predicting the size effect, and the design methods for concrete structures that can take the size effect property into consideration are shown. In addition to the papers presented in the workshop, an annotated bibliography on size effect in concrete structures during 1970 and 1993 is also contained.

After this JCI Workshop, there were one IUTAM Symposium in 1994 [8] and one workshop during FRAMCOS-2 in 1995 [9] on size effect in concrete structures. In these symposium and workshop, two size effect laws proposed by Bazant [10] and Carpinteri [11] which give totally opposite results were critically discussed but it is still in question which law is right.

The purpose of this paper is to present some results of numerical studies on the basis of fracture mechanics of concrete taking into consideration the heterogeneity of material structure. As a result, it is shown that both of these two size effect laws have a limitation to be applied for practical purposes. Finally it is concluded that numerical analysis with a fictitious crack model may predict well the size effect on strength of concrete structures fractured in a quasi-brittle manner such as shear failure.

2 EXISTING SIZE EFFECT LAWS

2.1 Weibull's Size Effect Law

Assuming the defect distribution is uniform throughout the structure, it is obvious that the chance is higher to reach the critical conditions when volume of the structure is larger. Weibull demonstrated that the strength of two specimens $f(V_1)$ and $f(V_2)$ with respective volumes V_1 and V_2 are related with the following formula:

$$f(V_1)/f(V_2) = \{V_2/V_1\}^{1/m} \quad (1)$$

where m is called Weibull parameter. This formula may well describe initial cracking stress such as the inclined cracking in short concrete beams but may not do the shear strength, because the Weibull model deals with only pre-existing material defects related to crack initiation.

2.2 Bazant's Size Effect Law

Bazant [10] drove the so-called size effect law given by eq. (2) from a dimensional analysis for the geometrically similar specimens with a notch of the length proportional to the specimen size considering the energy balance at crack propagation in concrete.

$$\sigma_N = B f_t' / \left(1 + \frac{d}{\lambda_0 d_{\max}} \right)^{\frac{1}{2}} \quad (2)$$

where σ_N is nominal strength at failure, f_t' is strength parameter, B and λ_0 are two empirical constants that can be determined by least square by fitting with test results, d is characteristic specimen size, and d_{\max} is the maximum aggregate size. To derive the size effect law, Bazant [10] assumed that the potential energy released at the fracture is proportional to the crack length and the area of fracture process zone, the width of the crack band being assumed constant and proportional to the maximum aggregate size.

The size effect law shows that the nominal strength decreases more and more steeply and finally follows the size effect law driven from LEFM as the size increases. As far as the influence of material structure is concerned, the specimen size is normalized by the maximum aggregate size in this size effect law.

2.3 Carpinteri's Multifractal Scaling Law

Influence of the disorder of a heterogeneous material on the mechanical properties depends on the ratio of the size of the largest material defect to the geometric size of the specimen. From such view point, Carpinteri and his co-workers [11] proposed the multifractal scaling law as follows:

$$\sigma_N = \left(A + \frac{B}{d} \right)^{\frac{1}{2}} \quad (3)$$

where σ_N is nominal tensile strength, d is characteristic structural size, A is a constant with physical dimensions equal to the square of stress, and B is a constant with physical dimensions equal to the square of stress intensity factor. Since the two constants have to be determined by means of a non-linear least square numerical analysis for each test series, this model needs some experimental results with a much wider range of the size than the Bazant's size effect law.

In this scaling law, the influence of the material structure is introduced a priori. Since the microstructure of a disordered material is the same independently of the geometrical size, the influence of disorder on the mechanical properties essentially depends on the ratio between a characteristic internal length (a material constant) and the geometrical size of the specimen. Therefore the influence of microstructural disorder on the mechanical behavior becomes progressively less important at the larger scale range, whereas it represents a fundamental feature at the smaller scale range [11]. Thus the topological multifractality implies the progressive vanishing of fractality as the scale increases.

2.4 Application of Size Effect Laws for Practical Purposes

From the practical view point, both of the size effect law and the multifractal scaling law need an experimental work with large scale specimens to determine the empirical constants, though they may give a backbone curve to one design proposal. Once geometry of the structure is changed, another test series need to be carried out. Moreover it is not clear whether the maximum aggregate size in those tests should be changed proportionally to the size of the specimen or not.

3 INFLUENCE OF DISORDERED MATERIAL STRUCTURE ON FRACTURE MECHANICS PARAMETERS

While concrete is considered as a two-phase composite material, the disordered material structure significantly influences mechanical properties of concrete. It has been generally accepted that a microcracking zone is created in front of a notch before the load reaches to the maximum. It is so-called fracture process zone. Hillerborg and

his co-workers [12] proposed a fictitious crack model which can analyze the development of the fracture process zone. By means of the fictitious crack model, Petersson [13] showed the development of the fracture process zone in front of the notch tip at the maximum load for different beam depth. He concluded that the depth of the fracture process zone increases with increasing beam depth, though ratio of the length of fracture process zone to the beam depth decreases as the beam depth increases. Rokugo and his co-workers [14] investigated the effect of the specimen size and the cross-section shape on the flexural strength of concrete by means of the fictitious crack model.

Mihashi and Nomura [15] reported the microcracking properties of concrete studied by means of a three-dimensional acoustic emission technique to reveal that the length of the fracture process zone ahead of the notch tip seems to be independent of the heterogeneity but the width is obviously influenced by the aggregate size which may result in influencing the critical crack width in the fictitious crack model. The finding was supported by a work of Otsuka [16] who showed by a new x-ray inspection technique that the width of the fracture process zone tends to be wider as the maximum aggregate size increases. Otsuka [16] also reported the influence of specimen size on the length of the fracture process zone to conclude that the length of the fracture process zone at the peak load was not proportional to the specimen size.

The recent findings in experimental studies may suggest that the influence of the disordered material structure on the mechanical behavior of concrete under tensile stress can be analyzed if the constitutive law of the fracture process zone that is tension softening diagram is determined as a function of the material structure. Wittmann and his co-workers including the author [17] analyzed the influence of the maximum aggregate size on the tension softening diagram. Thus now it is possible to introduce the influence of the material structure on the fracture properties of concrete by means of the fictitious crack model.

4 NUMERICAL TEST RESULTS AND DISCUSSION

4.1. CT Specimens with a Notch Proportional to the Specimen Size

For simulating applicability of the size effect law to concrete of different maximum aggregate size, CT specimens with three different sizes (Fig. 2) were analyzed by finite element method using the fictitious crack model. In this case, the notch length was changed proportionally to the specimen size. Three different tension softening diagrams were introduced, which represents the influence of the different maximum aggregate size [17] (Fig. 3).

Normalized results are shown in Fig. 4. Bazant's size effect law was applied to each concrete shown in Fig. 2 to determine values of constants in eq.(1). When the numerical results of the nominal strength and the specimen size are normalized by the parameters corresponding to each concrete, a unique curve is obtained as shown in Fig.4.

As shown in Fig. 4, Bazant's size effect law is supported by the present numerical study even for concrete of different size of the largest aggregate. Mihashi et al. [18] showed that Bazant's size effect law works well also for concrete of different strength as shown in Fig. 5.

Here it may be worthwhile to notice that these results were obtained only when the notch size responsible for the stress singularity is changed proportionally to the specimen size. In usual cases, however, concrete structures are unnotched and the most dominant material defect in concrete is often the interface of the largest aggregates or voids which correspond to the material structure itself but not necessarily proportional to the specimen size. No previous experimental studies have proved that the notch length equivalent to the fracture process zone at the peak load is

proportional to the specimen size. As a result of this discussion, it can be concluded that the applicable case of Bazant's size effect law may be limited to the condition that the material defect causing the stress singularity is much larger than the order of the heterogeneity of the material structure; for example, prediction of pulling out resistance of anchor bolts in a large structure.

4.2. Direct Tensile Tests with a Notch of Constant Length

Assuming ordinary tensile tests of concrete, concrete plates with a notch of constant length were analyzed by the fictitious crack model (Fig. 6). In this case, the tension softening diagram for the maximum aggregate size of 16 mm was used.

The simulated relation between the normalized nominal stress and the normalized specimen size is shown in Fig. 7. In this figure, a curve of solid line obtained by the Bazant's size effect law applied to the direct tensile specimens of a notch length varying proportionally to the specimen size. It is clearly shown that the relation gradually deviates from that of the Bazant's size effect law if the initial notch length is constant. On the contrary, the simulated tendency in the range of large size is closer to the result predicted by Carpinteri's multifractal scaling law, while the shortcomings of the scaling law are clearly improved by the numerical analysis. It is also recognized that the simulated relation is similar within a certain range to experimental results of Shioya and Akiyama [2] who obtained $(-1/4)$ th power law by carrying out size effect tests with large reinforced concrete beams.

5. CONCLUSIONS

Numerical studies using a fictitious crack model were carried out to clarify the influence of the material structure on the size effect of concrete structures. The following conclusive remarks were obtained:

1. If the size of the dominant material defect is proportional to the specimen size, the Bazant's size effect law works well even for concrete of the different material structure.
2. If the size of the dominant material defect is constant independently of the specimen size, the Bazant's size effect law doesn't work but the reduction rate of the strength becomes less than that in the range of a very large size.
3. All of three well known existing size effect laws have a limitation to be applied for practical purposes.
4. Once the tension softening diagram is determined by a laboratory test for concrete used in the structure, a numerical simulation can predict the size effect as one example.

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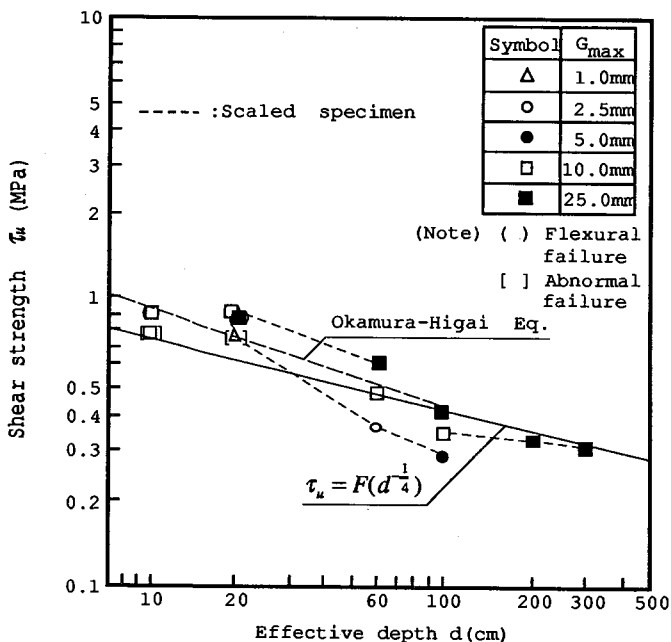


Fig.1 Experimental results of size effect in RC beams [2] (where G_{max} : maximum aggregate size).

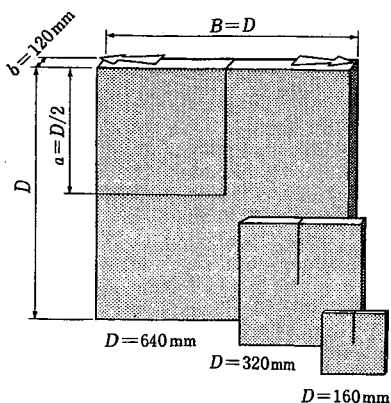


Fig.2 CT specimens of three different sizes.

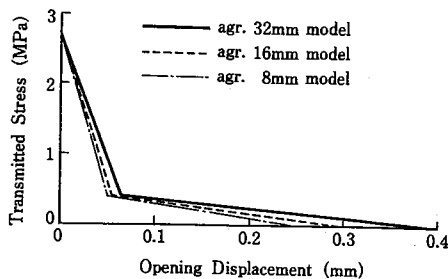


Fig.3 Tension softening diagrams used for the simulation.

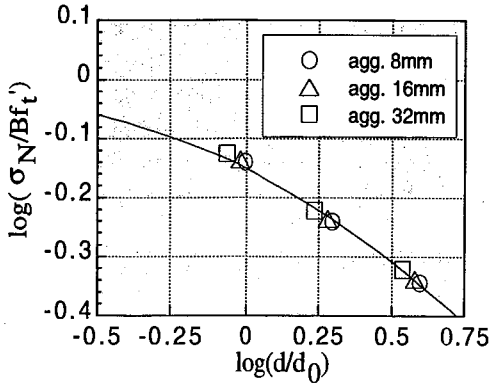


Fig. 4 Results of numerical CT test compared with Bazant's size effect law.

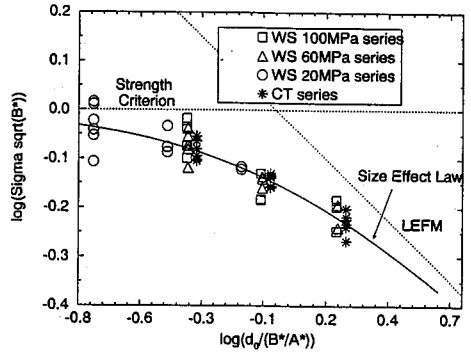


Fig. 5 Experimental results for WS test of different strength concrete [18].

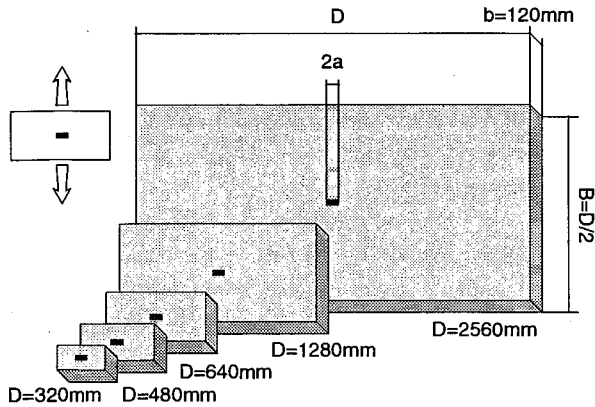


Fig. 6 Direct tensile test specimens (notch length is kept constant).

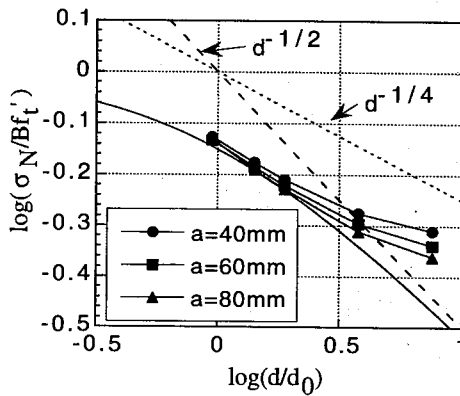


Fig. 7 Results of numerical direct tensile test.