Fracture Mechanics of Concrete and Concrete Structures -
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The characteristics of the biaxial flexure test for concrete

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ABSTRACT: The characteristics of the biaxial flexure test are discussed. Using this method, the biaxial tensile strength of concrete can be measured economically. Various parameters which may influence the result of the test are discussed. The stress distribution and the effect of eccentricity were discussed by means of the finite element method. The effect of the support condition, the geometry and the size were studied experimentally.

1 INTRODUCTION

Concrete crack is one of the most important factors because it influences the serviceability significantly. Especially, for some structures with concrete plate such as rigid pavements, long span slab and deck panel, the tensile failure or crack development is directly related to the safety of the structures [3]. Tensile strength is considered as a significant parameter used to evaluate tensile failure of concrete structures together with the fracture energy [2,5],

The strength depends on the stress state. However, for practical reasons, the uniaxial strength is chosen as a reference value in many applications. The uniaxial tensile strength of concrete can be measured by several methods like the direct tension test, the splitting (or Brazilian) test and the modulus of rupture test.

While various indirect methods are available for the uniaxial tensile strength, the biaxial tensile is still measured by the direct method [4]. To perform biaxial tensile test, generally four actuators are needed and also a big frame. It is an expensive test as well. Because of these reasons, Biaxial Flexure Test(BFT) was recently developed to measure the biaxial tensile strength of concrete [1]. Howerer, the strength measured by BFT was influenced by several factors.

The paper is organized as follows. We introduce a biaxial flexure test method to measure the biaxial tensile strength of concrete and other quasibrittle materials in Section 2. Various parameters which may influence the result of the test method are discussed by means of the finite element method. Then effects of the geometry and size of biaxial flexure specimens are mentioned in Section 3. Our experimental data of the biaxial tensile strength obtained from the biaxial flexure test are followed in Section 4. Finally, we draw conclusion in Section 5.

2 THE BIAXIAL FLEXURE TEST(BFT) METHOD

The modulus of rupture method can be generalized to three dimensions for the BFT. Instead of a prismatic specimen, we use a circular plate. The plate is supported on the top of an annular support. The external loading is applied to the specimen through a circular edge. Schematic specimen drawing of the biaxial flexure test (BFT) is shown in Figure 1.

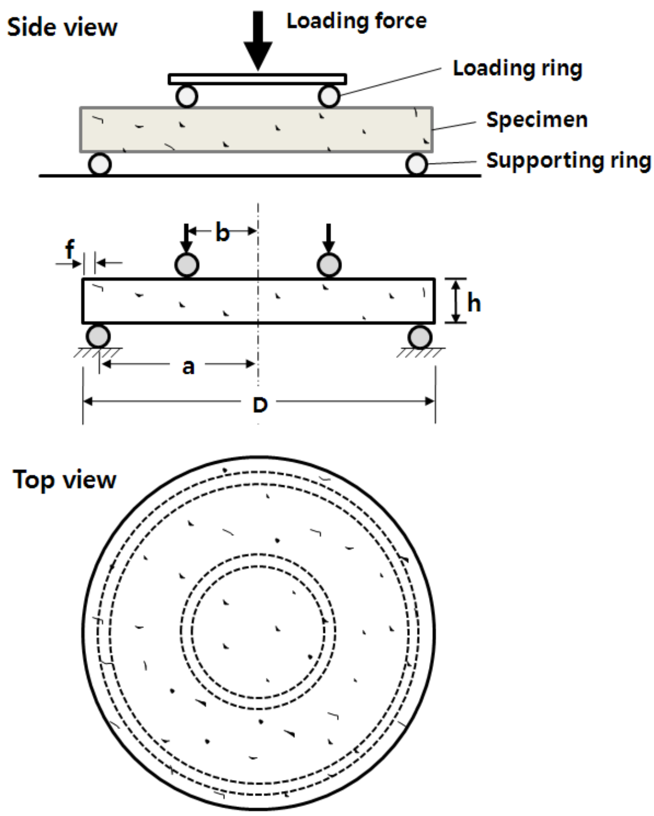

Figure 1. Schematic drawing of the biaxial flexure test (BFT) method.

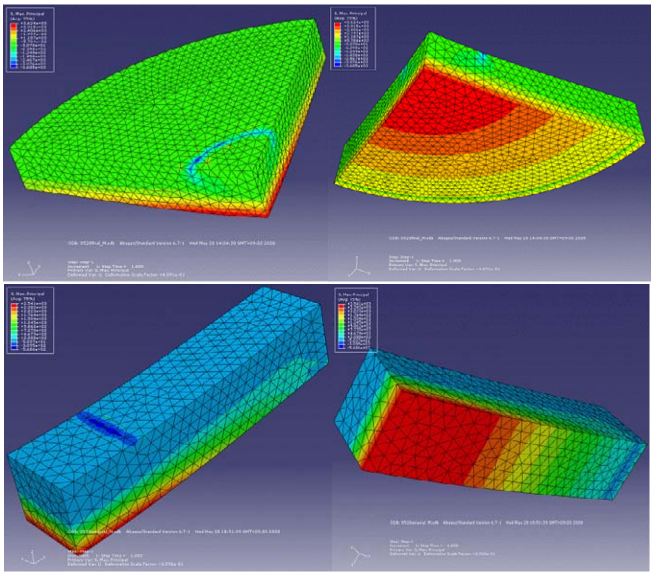

Figure 2. Distribution of the principle stress on the bottom surface of (a) BFT specimen and (b) the uniaxial specimen.

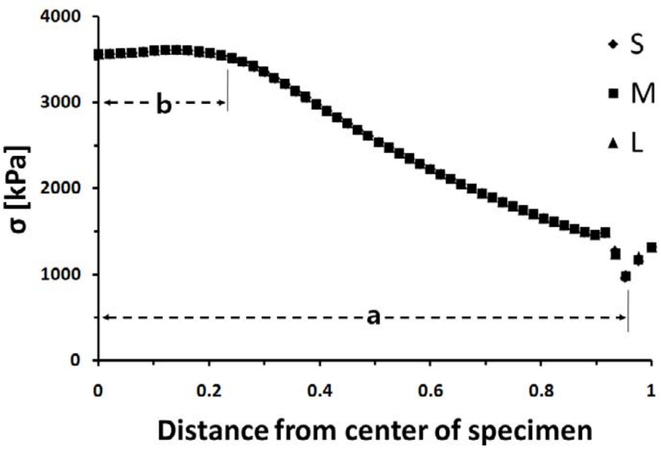

Figure 3. The stress distribution on the bottom of a BFT specimen; the distance is scaled with respect to **a.**

Distribution of the principle stress of the BFT specimen and uniaxial specimen calculated by the finite element method is shown in Figure 2. As shown in Figure 3, due to axisymmetry of the specimen and theory of elasticity, it is obvious that on the bottom surface of the concrete plate within the circle on which the load in applied, the stress is constant in any direction in the region (2b).

The Equation for stress of a BFT specimen caused by the applied load P is expressed as

$$\sigma = \frac{3P}{4\pi h^2}\{[(1-\nu)[1-(b/a)^2]-2(1+\nu)\log(b/a)]\} \qquad (1)$$

in which ν is Poisson's ratio, a, b is radii to the support and the load, respectively. The stress σ is a nonlinear function of the aspect ratio b/a.

3 NUMERICAL INVESTIGATION OF THE CHARACTERISTICS OF BIAXIAL FLEXURE TEST(BFT) SPECIMENS

3.1 *Optimum geometry of the BFT specimen*

Using a three-dimensional finite element method, the effect of parameters such as radious of the support and the loading, thickness(h) and free length(f) were studied to propose the optimum geometry of the BFT specimens. According to numerical investigation of the characteristics of BFT specimens, Table 1. lists the optimum geometry of the biaxial flexure test(BFT) specimens for h/a=0.24 and f/a=0.05 from the finite element analysis.

Table 1. The optimum geometry of the biaxial flexure test (BFT) specimens from the finite element analysis.

Size	H [mm]	2a [mm]	2b [mm]	F [mm]	h/a	f/a	b/a
S	30	250	63	6.5	0.24	0.052	0.252
M	60	500	125	12.5	0.24	0.05	0.25
L	90	750	188	19	0.24	0.051	0.251

Figure 4 shows the theoretical solution and the numerical solution for various b/a ratio of BFT specimen according to Equation 1. When b/a is at 0.25 the theoretical solution of the BFT specimens identify with the numerical solution of analytical method.

The theoretical solution obtained from Equation 1 and the numerical one of the proposed optimum geometry of the BFT specimens are given in Table 2 as well.

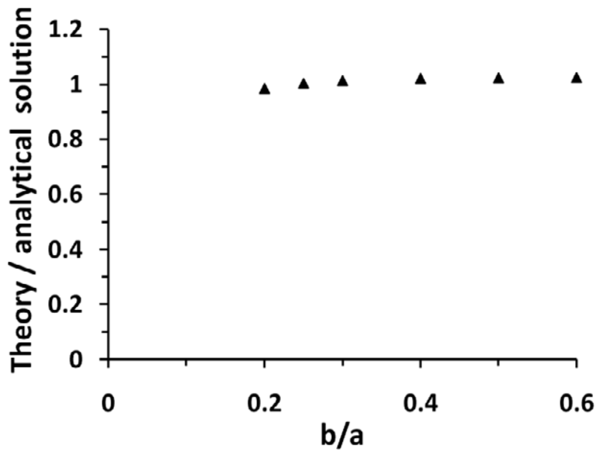

Figure 4. The theoretical solution and the numerical solution for various b/a ratio.

Table 2. Comparison between the theoretical solution and the numerical solution of the BFT specimens.

		Theoretical solution / numerical solution
Specimen Size	S	1.008
	M	1.003
	L	1.005

3.2 *The effect of eccentric loading*

If the center of loading ring does not coincide with the center of BFT specimen, as the biaxial flexural test was conducted, the different stresses occurred at the end points 2b of the specimens. The deviation of the stress due to the eccentricity of the loading point is presented in Figure 5. The principle stress distribution of bottom surface subjected to eccentric loading (e/a=0) and non eccentric loading (e/a=0.05) is shown in Figure 6.

Results of the finite element analysis showed that e/a must be within 3.5% so that the deviation of the stresses at the end points 2b of the specimens are not over 10% of stresses at the center point of the specimens.

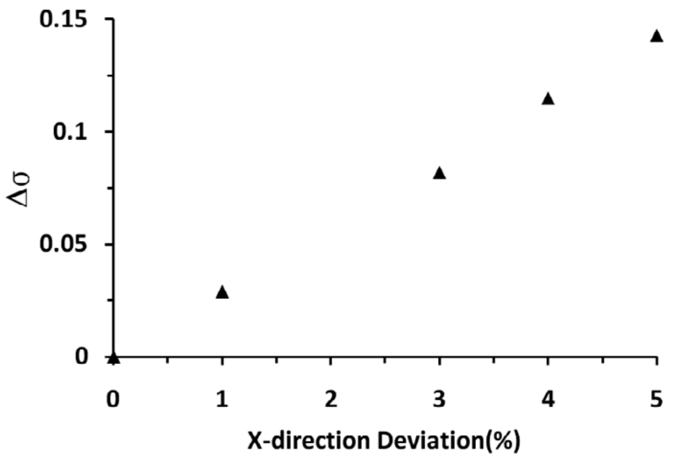

Figure 5. The deviation of the stress due to the eccentricity of the loading point.

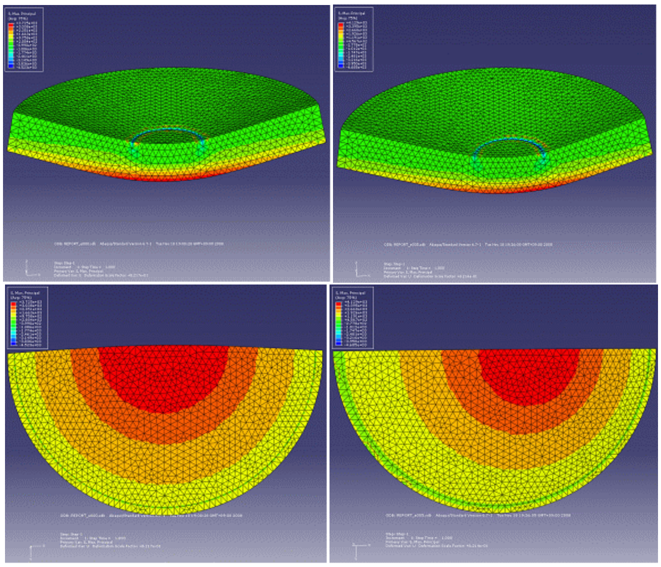
Figure 6. Principle stress distribution of bottom surface subjected to eccentric loading (a) e/a=0 and (b) e/a=0.05.

4 EXPERIMENT OF OPTIMAL BIAXIAL FLEXURE SPECIMENS

In order to investigate various parameters which may influence the result of the test, optimal BFT specimens were proposed through the finite element analysis. Using the BFT, the specimens were tested. The test results of the modulus of rupture strength suggested by ACI 318-05 and these of the biaxial tensile strength obtained from the proposed optimal BFT specimens are given in Table 3. Then the tensile strength was calculated from the maximum load, using Equation 1. The average biaxial tensile strength was greater than the average uniaxial strength.

Table 3. Test results obtained from the proposed optimal BFT specimens.

Size (h×d) [㎜]	modulus of rupture [MPa]	average biaxial flexural trength [MPa]	Standard deviation	COV
30×263		8.72	1.884	0.22
60×525	4.56	6.59	0.585	0.09
90×788		3.39	0.723	0.21

5 CONCLUSIONS

In this paper, the biaxial flexure test (BFT) for concrete is introduced. Using this method, we determined the tensile strength of concrete subjected to biaxial loading condition simply and economically. Numerical investigation of the characteristics of biaxial flexure test (BFT) specimens was presented and discussed. The stress distribution and the effect of eccentricity were studied by means of the finite element method. According to the result, the optimal BFT specimens were proposed to measure the optimal biaxial tensile strength of concrete. Using the BFT, the specimens were tested. The biaxial tensile strength of concrete was higher than the uniaxial one as reported by others.

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