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A PROPOSAL OF FAILURE CRITERIA FOR 3D CONCRETE STRUCTURES

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1. INTRODUCTION

Interest in nonlinear analysis of concrete structures has increased steadily during recent years as a result of the increasing need to evaluate the design of new and existing reinforced and pre-stressed concrete structures, and been driven by the ever-increasing computational power and ever-decreasing price of scientific workstation.

Under even small values of applied stress, concrete exhibits a complex structural response with the following material specific characteristics: nonlinear stress-strain behavior from the outset, tensile cracking, temperature-dependent creep deformations, and dilatation under high compressive stress (Berg 1961; Geniev et al.1974; Karpenko 1976; Cedolinet al.1977; Kotsovos and Newman 1977; Bathe and Ramaswamy 1979; Bazant and Kim 1979; Elwi and Murray 1979; Niwa 1980; Chen 1982; Aoyagi and Yamada 1983; Chen and Buyukozturk 1985; Vecchio and Collins 1986). All these nonlinear response characteristics depend strongly on the multi-axial state of stress.

In the last two decades, numerous constitutive models have been proposed and used for the analysis of concrete structures. Many of these models have a greater conceptual importance than practical significance since they can describe only certain aspects of concrete behavior. Furthermore, many of these constitutive models are not economically viable in a large-scale analysis of concrete structure.

Important features of a concrete constitutive model, in addition to the essential requirement of accurate representation of the actual mechanical behavior, are the clarity of formulation and the efficient implementation in a robust and stable nonlinear state-determination algorithm.

The strength of concrete under multi-axial stresses is a function of the state of stress and can not be predicted by limitations of simple tensile, compressive, and shearing stresses independently of each other. Therefore, strength of concrete elements can be properly determined only by considering the interaction of the various components of the state of stress. In formulating failure criteria for concrete under combined states of stress, one must first agree on a proper definition of *failure*. Such criteria as yielding, initiation of cracking, load carrying capacity, and extent of deformation have been used to define failure.

A review of the literature indicates that only a few models for full three-dimensional (3D) finite-element (FE) analysis of reinforced concrete (RC) structures have been reported. A comparative listing given in Selby and Vecchio (1993) also indicates the diversity in constitutive models used for the pre-cracking response of concrete. Almost all the reported models have followed the smeared crack approach using either fixed (orthogonal and non-orthogonal) or rotating crack version. But recently with the computer hardware development and with new findings in material research, the finite element method can be used for analysis the experiments and the prediction of structural safety and serviceability performance of reinforced concrete in general.

In this paper, 3D constitutive models of reinforced concrete are introduced. It was modified from a 2D constitutive models adopted by Okamura and Maekawa (1985). The purpose of this study to present a simple model deal with concrete in tension-tension and tension-compression regions in 3D.

2. FAILURE CRITERIA

The first branching point into non-linearity in reinforced concrete is the generation of cracks. However, the precise prediction is quite difficult because the generation of cracks is greatly affected by so many factors as the size effect of the structural member, the method of curing and the shrinkage during drying. In this 2D model, the cracking criterion is determined mainly from the tensile stress, and the effects of those factors are be taken into account by modifying the uni-axial tensile strength. As for the fracture envelope under biaxial stress, the 2D model had been improved depending on the Niwa model (1980) derived for the compression-tension domains together with Aoyagi-Yamada model (1983) for the domains of tension-tension (Fig.1).

For the 2D stress state we have four regions (one tension-tension, one compression-compression, and two tension-compression, but in the case of 3D stress state we have eight spaces (one tension-tension, one compression-compression, and six tension-compression).Therefor, in 3D case it is impossible to combine all the stresses in three formulas. At least the author needs six formulas for tension-compression and another one for tension-tension. In this paper the author modified the 2D constitutive laws to 3D constitutive, the modification here is by inserting the third stress σ_3 and changing some parameters.

2.1. Tension-tension

To develop any formula in 3D it has to be sufficient in 2D. Considering this fact the author expanded a 2D formula to the 3D one and then put it in the 2D case to compare between the two formula. The 2D formula in tension-tension by Okamura and Maekawa (1985) is;

$$(\sigma_1/f_t)+0.3(\sigma_2/\sigma_1)^2=1 \tag{1}$$

To develop the 3D formula, the form of the 2D formula must be changed to be able to insert σ_3,and also the value of the parameters has to be changed. Then the 2D form can be put in the following form;

$$\frac{\sigma_1}{f_1}+\frac{\sigma_2}{f_1}+\frac{\sigma_3}{f_1}+A\left[\left(\frac{\sigma_2}{\sigma_1}\right)^B+\left(\frac{\sigma_3}{\sigma_2}\right)^B+\left(\frac{\sigma_1}{\sigma_3}\right)^B\right]=1 \tag{2}$$

Now, the author needs to know the values of the parameters A and B. Since, there is no mathematical method, the author can get them by try and error.

After trying and comparing with the original formula the author can find A and B as follows;

A= -0.4 ,   B= -0.05

So, the formula can be put in the form;

$$\frac{\sigma_1}{f_t}+\frac{\sigma_2}{f_t}+\frac{\sigma_3}{f_t}-0.4\left[\left(\frac{\sigma_2}{\sigma_1}\right)^{-0.05}+\left(\frac{\sigma_3}{\sigma_2}\right)^{-0.05}+\left(\frac{\sigma_1}{\sigma_3}\right)^{-0.05}\right]=1 \tag{3}$$

2.2. Tension-compression

The 2D formula by Okamura and Maekawa (1985)

$$(\sigma_1/f_t)^3+(\sigma_2'/f_c')=1 \tag{4}$$

So we can recognize that, the 3D formula will a combination of the three stresses changing from tension to compression

$$\begin{aligned}
&(\sigma_1/f_t)^3+(\sigma_2'/f_c')+(\sigma_3'/f_c')=1\\
&(\sigma_1/f_t)^3+(\sigma_2'/f_c')+(\sigma_3/f_t)^3=1\\
&(\sigma_1/f_t)^3+(\sigma_2/f_t)^3+(\sigma_3'/f_c')=1\\
&(\sigma_1'/f_c')+(\sigma_2'/f_c')+(\sigma_3/f_t)^3=1\\
&(\sigma_1'/f_c')+(\sigma_2/f_t)^3+(\sigma_3/f_t)^3=1\\
&(\sigma_1'/f_c')+(\sigma_2/f_t)^3+(\sigma_3'/f_c')=1
\end{aligned} \tag{5}$$

Where, f_c' compressive strength, f_t tensile strength, $\sigma_1, \sigma_2, \sigma_3$ stresses in 3 directions.

Using these six formulas, we can express the failure criteria for the tension-compression regions.

2.3. Compression-compression

There is no need to develop any model for failure criteria in compression-compression region because it already exists. The model developed by Maekawa et al (1993), whose reliability was confirmed by experiment results, is applied in this study.

3. VERIFICATION

Now the author verify the constitutive laws so, the author put the 3D modified constitutive laws in 2D form and compare them with another model (5-Parameter Model, by Willam and Warnke) (Fig.2).

We can see that, for the tension-tension and compression-compression regions, it is almost the same, but there is a difference in the tension-compression region.

At first we have to know as experiment fact that, in the tension side the largest tensile stress is found in the tension-tension region rather than tension-compression region, and that rather constant tensile stress is found in tension-tension region. Figure 2, however, indicates that the 5-Parameter Model gives larger tensile stress in tension-compression region than in the tension-tension region and varying tensile stress in tension-tension region. On the other hand, the modified model gives a failure envelope agreeing with the experiment fact.

4. CONCLUSION

In this paper failure criteria of concrete in tension in 3D stress condition was presented. The failure criteria were developed by modifying an existing 2D failure criteria. They are very convenient to use because they are just depending on compressive strength $f_c^{'}$ and they do not need to conduct a tri-axial test as other models need.

5. REFRENCES

- Maekawa, K., Okamura, H.: Nonlinear Analysis and Constitutive Models of Reinforced Concrete, 1991
- Chen, W. F.: Plasticity in Reinforced Concrete, McGraw-Hill, 1982.

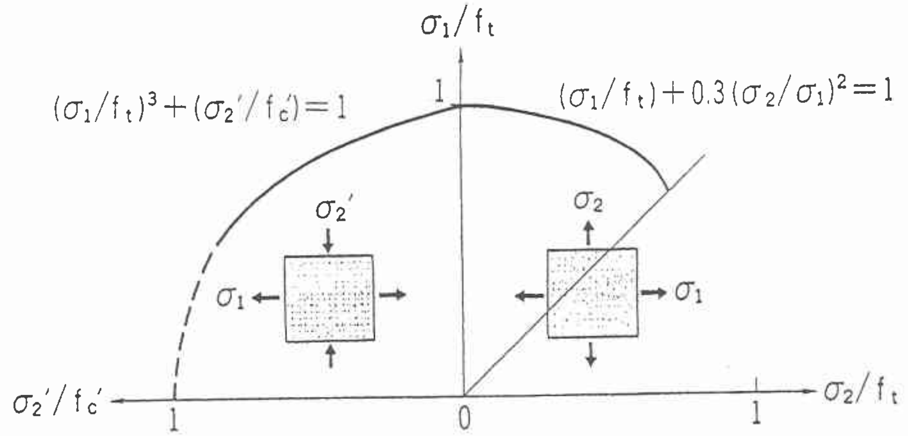

Fig.1

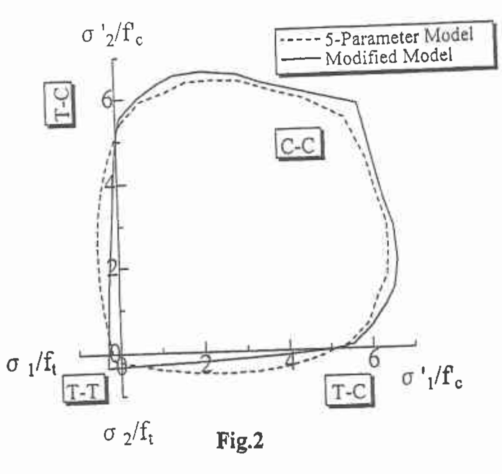

Fig.2