Nonlinear FE Modeling of Reinforced Concrete

Yunus Dere and Mehmet Alpaslan Koroglu
Necmettin Erbakan Univ., Civil Eng. Dept., Konya, Turkey
Email: ydere@konya.edu.tr, makoroglu@konya.edu.tr

***Abstract*—In this study, nonlinear finite element modeling of plain and reinforced concrete was studied. Several parameters affecting the modeling of reinforced concrete were discussed. Commercial ABAQUS software package along with the concrete damaged plasticity model was suggested to be used for the modeling of reinforced concrete structural members. Compressive and tensile uniaxial stress-strain relationship as well as damage parameter curves for concrete material to be effectively used in ABAQUS were suggested. The performance of the suggested constitutive and damage models was verified with a simple nonlinear model. The analysis results were quite promising.**

***Index Terms*—reinforced concrete, nonlinear modeling, ABAQUS, concrete damaged plasticity model**

I. INTRODUCTION

The behavior of reinforced concrete structural members under various loading and boundary conditions are often studied experimentally. The results of the tests are considered as the real behavior although many uncertainties exist in specimen production, loading, and measurement phases. Experimentally obtained responses are then compared with their analytical counterparts in order to verify if the level of errors originating from experimental uncertainties are within acceptable limits.

With the introduction of high speed computers, 3D Finite Element Modeling (FEM) simulations of reinforced concrete structural systems became popular [1]-[3]. Realistic simulations of laboratory tests of reinforced concrete specimens under monotonic and cyclic loading is quite complicated and difficult. Nonlinear constitutive relations of concrete, aggregate interlock, tension cracks and crushing in compression, adhesion between steel rebars and concrete cause difficulties in the modeling of reinforced concrete [1].

Full scale simulations of structural systems which cannot be produced and tested in a laboratory environment can result in better understanding of the failure and cracking behavior of these systems. Many computer software packages are available for these simulations. The commercially available ABAQUS [4] software has dedicated concrete material models that are quite effective in realistic simulations.

In this study, the parameters and relations required for the concrete damaged plasticity material model available in ABAQUS software will be discussed. Concrete material constitutive relations and damage models that had been previously found successful in simulating laboratory experiments will be suggested. The suggested parameters and relations will be used in a simple demonstration.

II. MATERIAL AND METHOD

A. Concrete Material

Plain Concrete is composed of coarse aggregate, sand, cement and water. It is considered non-homogenous in micro level and homogenous in macro level. Concrete behavior can be assessed by examining the load-deformation relation, cracking and crushing which occur by failing under excessive tensile and compressive stresses, respectively. The behavior depends on many parameters including the composition of concrete, the type of loading which is either compression or tension, the loading fashion which can be uni-axial, bi-axial or multi-axial, confinement effect, loading rate, temperature, etc.

Uniaxial compressive strength can be easily obtained through laboratory experiments of standard sized specimens. Similarly, the uniaxial tension strength can be determined by splitting cylinder tests. The tensile strength of concrete is usually estimated to be 10 to 15 percent of compressive strength. When experimental data is not available, the tensile strength can be calculated from (1) [5].

$$f_{ctsp} = 1.38(f_c)^{0.69} \quad psi \tag{1}$$

Elasticity modulus and Poisson's ratio of concrete are more difficult to obtain by laboratory tests. The elasticity modulus estimation based on compressive strength was given in (2) [6].

$$E_c = 57000\sqrt{f_c} \quad psi \tag{2}$$

Poisson's ratio of concrete is usually taken between 0.15 and 0.20. A more rigorous Poisson's ratio estimate based on compressive strength of concrete was given in (3) [7].

$$\nu_c = 4.5\times10^{-7} w^{1.75} f_c^{0.5} \tag{3}$$

B. Structural Steel

In the scope of this study, mild steel was considered which is used in the production of structural members. Reinforcing bars are embedded in structural members made of concrete. Steel is a homogenous material and, compared to concrete, its material properties can be more easily obtained by a standard tension experiment, since it

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behaves similarly in compression and tension. Experimental stress-strain diagrams of structural steel are used to define properties such as elasticity modulus, hardening modulus, yielding and failure points, etc. Poisson's ratio of structural steel is generally accepted as 0.3.

C. Reinforced Concrete

Plain concrete is reinforced by adding reinforcing steel bars. The behavior of a structural member made of reinforced concrete does not only depend on the individual properties of plain concrete and reinforcing steel but also on the bond between steel and concrete which causes composite behavior. The shear transfer mechanism, as well as bond and slip relation in a reinforced concrete member are usually studied by pull-out tests.

III. Finite Element Modeling

Finite Element (FE) Method is commonly used in evaluating and determining nonlinear load-displacement and cracking behavior of reinforced concrete structural members and systems. The plastic behavior of steel and concrete is quite complicated and hard to analytically model. In the literature, lumped and distributed plasticity models as well as continuum mechanics-based models were developed for inelastic modeling of concrete. Most realistic simulations can be carried out by the FE analysis of 3D models. Many FE packages are available to consider for the analysis of reinforced concrete systems. Each package can have its own strengths and weaknesses, i.e., some can report crack locations and/or widths while others allow easy embedding of reinforcing bars, etc. In this study, the commercially available ABAQUS FEM software package was focused.

Steel rebars can be modeled as smeared within a finite element or can be taken account discretely. Discrete steel rebars can be embedded inside concrete solid elements quite easily through embedding constraint which does not consider slip of reinforcement. The reinforcement interaction with concrete can be taken into account by introducing tension stiffening in the definition of material model. 2-node truss and 8-node solid finite elements are usually preferred in modeling steel reinforcement and concrete, respectively. When embedding constraint is used, the truss elements of reinforcement are joined to concrete solid elements. This option constrains the translational degrees of freedom of the embedded truss nodes to the interpolated values of the corresponding degrees of freedom of the concrete solid element. Therefore, the reinforcement was assumed to be fully bonded to the concrete solid elements.

For concrete material, there are two modeling options in ABAQUS. One is "Smeared crack concrete model" and the other is "Concrete Damaged Plasticity Model (CDPM)". Smeared crack concrete model is preferred for applications where concrete is subjected to monotonic straining. CDPM can be used with monotonic, cyclic, and/or dynamic loading conditions. The CDPM requires concrete compressive and tensile constitutive relationship, cracking and crushing damage parameters and special parameters such as dilation angle, eccentricity, biaxial loading ratio, the coefficient K and viscosity parameter. These parameters can be assigned to their commonly used values in the literature (Table I). A low viscosity parameter helps to improve the convergence rate in the softening regime of concrete stress-strain curve.

TABLE I. CDPM Parameters

Dilation Angle	Eccentricity	f_{b0}/f_{c0}	K	Viscosity Parameter
31	0.1	1.16	0.666	0.001

In the literature there are numerous analytical constitutive models suggested for concrete material. After trying many of these models in ABAQUS, one of them was found to be effective in simulating laboratory experiments using CDPM. In this study, the unconfined stress-strain relationship model for concrete which was first proposed by Popovics [8] and later modified by Thoronfeldt *et al*. [9] was adapted. According to this model, the relation between compressive strain (ε_c) and stress (f_c) is given by (4) [8],

$$\frac{f_c}{f_c^{'}} = \frac{n\left(\dfrac{\varepsilon_c}{\varepsilon_{co}}\right)}{(n-1)+\left(\dfrac{\varepsilon_c}{\varepsilon_{co}}\right)^n} \tag{4}$$

where $f_c^{'}$, ε_{co} are the compressive strength and strain corresponding to the maximum stress, respectively. The 'n' in (4) is defined in (5).

$$n = 0.4\times 10^{-3} f_c^{'}(\text{psi}) + 1.0 \tag{5}$$

Thoronfeldt *et al*. [9] modified Popovics's equation for the descending branch of the stress-strain relation multiplying the power 'n' by a coefficient. In this study, the value of this coefficient was calculated by trials to be 1.25 which produced consistent stress values for the post-peak branch of the stress-strain curve. Tensile stress-strain ($\sigma-\varepsilon$) relationship was assumed to be linear up to the uniaxial tensile strength and then determined using the exponential function in (6).

$$\sigma = f_t\left(\frac{\varepsilon_t}{\varepsilon}\right)^{(0.7+1000\varepsilon)} , \ \varepsilon_t = \frac{f_t}{E_c} \tag{6}$$

Here, E_c is obtained as the slope of the initial tangent of compressive stress-strain curve.

Compression and tension damage parameters describing crushing and cracking behavior were defined as tables within CDPM. The following equations from [10] were successfully used in obtaining the compression and damage parameters. Damage parameters take values ranging from 0 (no damage) to 1 (fully damaged), representing the level of damage.

$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\varepsilon_c^{pl}(1/b_c - 1) + \sigma_c E_c^{-1}}$$

$$d_t = 1 - \frac{\sigma_t E_c^{-1}}{\varepsilon_t^{pl}(1/b_t - 1) + \sigma_t E_c^{-1}} \qquad (7)$$

Description of these parameters can be found in Fig. 1 [10, 4]. The coefficients b_c and b_t take values between 0 and 1. Birtel and Mark [10] suggested b_c=0.7 and b_t=0.1. However, in different pushover analysis simulations, b_c=0.7 and b_t=0.4 were found to produce a convergent solution.

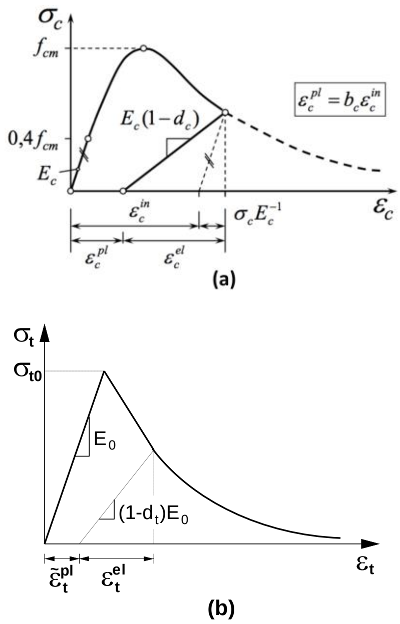
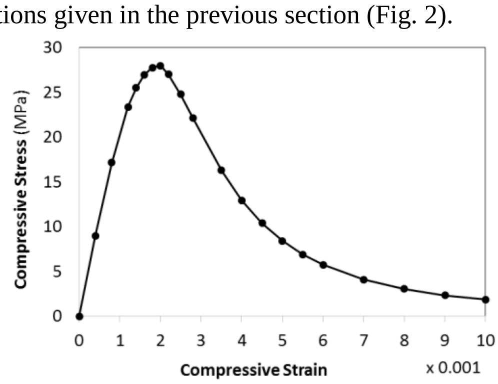


Figure 1. Damage parameters a) Compressive b) Tensile [10, 4].

Damage parameter contour maps in tension and in compression can be utilized for the visualization of tensile cracks as well as crushing regions. It is not possible to draw discrete crack locations since the cracks are smeared through solid finite elements.

IV. Demonstration with CDPM

An example concrete cube element (1x1x1 mm) was considered to discuss the CDPM parameters in detail. The element was fixed at one face and a load was applied at the opposite face. The element was assumed to be made of C20 class concrete with average cylinder compressive strength 28 MPa and tensile strength 2.2 MPa. The compressive and tensile stress-strain relationship of concrete material of the element was obtained using the equations given in the previous section (Fig. 2).



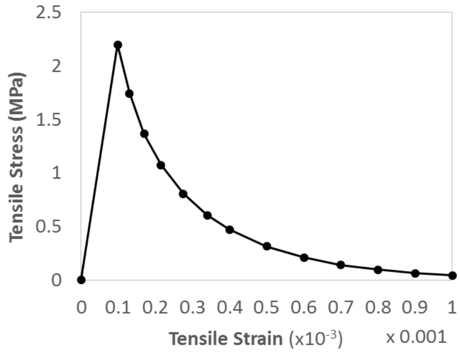


Figure 2. Compressive and tensile stress-strain relations.

The damage parameters of CDPM was calculated as defined in (7) with b_c=0.7 and b_t=0.4 and presented in Fig. 3.

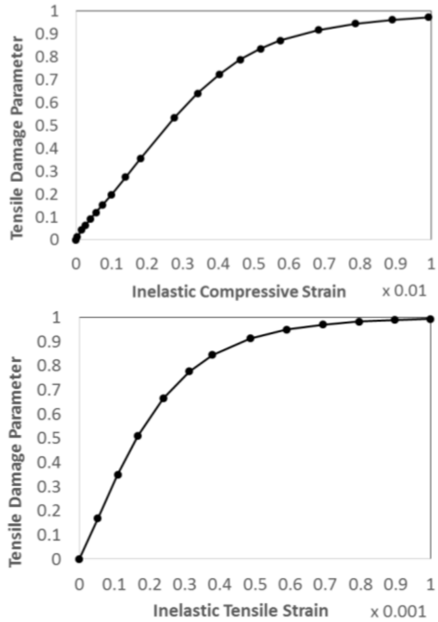


Figure 3. Compressive and tensile damage parameters.

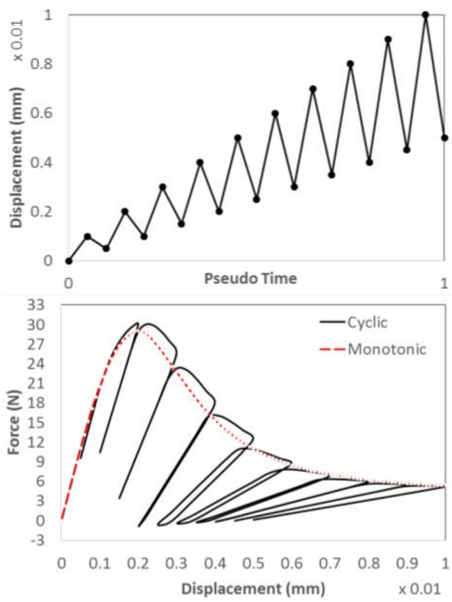


Figure 4. Compressive cyclic loading and force-displacement response

The element was analyzed using monotonic and cyclic displacement loading under compression and tension and the force displacement responses were obtained (Fig. 4-Fig. 5).

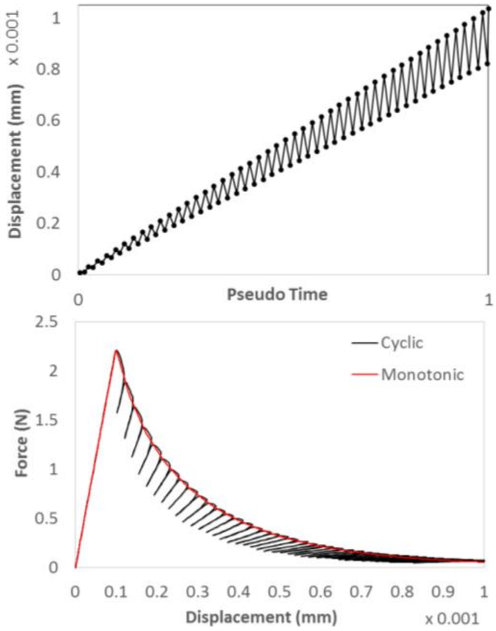


Figure 5. Tensile cyclic loading and force-displacement response

This example presents a general view of what can be obtained from ABAQUS concrete model using CDPM material model.

V. Summary and Conclusions

Realistic simulations of reinforced concrete structural systems became possible through analyses of 3D nonlinear FE models. The definition of concrete behavior and related parameters were discussed in detail for concrete damaged plasticity model available in ABAQUS software package. Some constitutive relations and damage parameter curves which were previously proposed for concrete to be used along with CDPM were presented and tested on a simple cube element in order to show the resulting force-displacement response under monotonic and cyclic type loading considering tension and compression displacement load histories. From the obtained curves, CDPM was found to be promising for the nonlinear analysis of reinforced concrete structural systems.

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Yunus Dere studied and got BA from Selcuk University, Engineering and Architecture, Civil Engineering during 1989 – 1993; master degree from Selcuk University, Engineering and Architecture, Civil Engineering, 1994–1997; He received PhD from Purdue University, Civil Engineering, Civil Engineering in 2002.
Currently he works as an assistant Professor in Necmettin Erbakan University, Turkey