Modeling of concrete for nonlinear analysis Using Finite Element Code ABAQUS

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ABSTRACT

Concrete is the main constituent material in many structures. The behavior of concrete is nonlinear and complex. Increasing use of computer based methods for designing and simulation have also increased the urge for the exact solution of the problems. This leads to difficulties in simulation and modeling of concrete structures. A good approach is to use the general purpose finite element software ABAQUS. In this paper a 3D model of a concrete cube is prepared using smeared crack model and concrete damage plasticity approach. The validation of the model to the desired behavior under monotonic loading is then discussed.

Keywords

Finite element, ABAQUS, smeared cracking, concrete damage plasticity, tension stiffening.

1. INTRODUCTION

Since 1970, analyses of reinforced concrete structures using finite element method, have witnessed a remarkable advancement. Many researchers have made valuable contributions in understanding the behavior of concrete and have developed sophisticated methods of analysis. These achievements are well documented and available in various reports and technical papers but still there are many areas in which much remains to be understood and researched.

The past decade with the advancement in computing techniques and the computational capabilities of the high end computers has led to a better study of the behavior of concrete. However the complex behavior of concrete sets some limitations in implementing FEM. The complexity is mainly due to non-linear stress-strain relation of the concrete under multi-axial stress conditions, strain softening and anisotropic stiffness reduction, progressive cracking caused by tensile stresses and strains, bond between concrete and reinforcement, aggregation interlocks and dowel action of reinforcement, time dependant behavior as creep and shrinkage [1].

Several researchers have documented about nonlinear analysis of reinforced concrete and prestressed concrete structures. For nonlinear analysis many commercial software are available, such as ANSYS, ABAQUS, NASTARAN, and ADINA. All these softwares are not tailor made applications which can work automatically on just feeding few data and the requirements.

An acceptable analysis of any structure as a whole or a part there in, using Finite element software, and the correctness of it totally depends on the input values, especially the material properties used. However when one is working with concrete a sound technical background is required to use them in a proper manner and get the desired results.

Concrete used in common engineering structures, basically is a composite material, produced using cement, aggregate and water. Sometimes, as per need some chemicals and mineral admixtures are also added. Experimental tests show that concrete behaves in a highly nonlinear manner in uniaxial compression. Figure.1 shows a typical stress-strain relationship subjected to uniaxial compression. This stress-strain curve is linearly elastic up to 30% of the maximum compressive strength. Above this point tie curve increases gradually up to about 70-90% of the maximum compressive strength. Eventually it reaches the pick value which is the maximum compressive strengthσ_{cu}. Immediately after the pick value, this stress-strain curve descends. This part of the curve is termed as softening. After the curve descends, crushing failure occurs at an ultimate strainε_{cu}. A numerical expression has been developed by Hognestad [2],[3] which treats the ascending part as parabola and descending part as a straight line. This numerical expression is given as:

For $0 < \varepsilon < \varepsilon_0'$, $\quad \frac{\sigma}{\sigma_{cu}} = 2\frac{\varepsilon}{\varepsilon_0'}\left(1 - \frac{\varepsilon}{2\varepsilon_0'}\right)$ (1)

For $\varepsilon_0' < \varepsilon < \varepsilon_{cu}$, $\quad \frac{\sigma}{\sigma_{cu}} = 1 - 0.15\left(\frac{\varepsilon - \varepsilon_0'}{\varepsilon_{cu} - \varepsilon_0'}\right)$ (2)

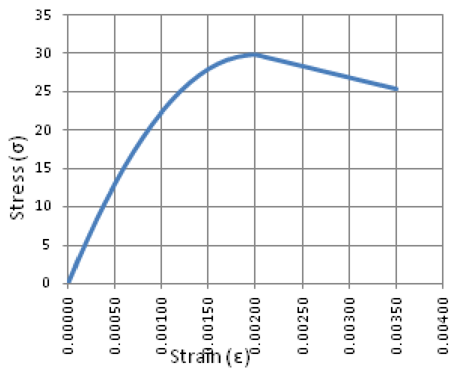

Figure 1. Stress-strain curve for concrete.

2. FEA MODELING

The nonlinear analysis of concrete which is mostly by using smeared crack approach or by damaged plasticity approach is described below.

2.1 The smeared crack concrete model

In the smeared crack concrete model the initiation of cracking process at any location happens when the concrete stresses reach one of the failure surfaces either in the biaxial tension region or in a combined tension-compression region [4].

This model is intended for applications in which the concrete is subjected to essentially monotonic straining and a material point exhibits either tensile cracking or compressive crushing. Plastic straining in compression is controlled by a "compression" yield surface. Cracking is assumed to be the most important aspect of the behavior, and the representation of cracking and post-cracking anisotropic behavior dominates the modeling. The concrete model is a smeared crack model in the sense that it does not track individual "macro" cracks. Constitutive calculations are performed independently at each integration point of the finite element model. The presence of cracks enters into these calculations by the way in which the cracks affect the stress and material stiffness associated with the integration point. The smeared crack concrete model provides a general capability for modeling concrete in all types of structures, including beams, trusses, shells, and solids. It can be used for plain concrete, even though it is intended primarily for the analysis of reinforced concrete structures. It is designed for applications in which the concrete is subjected to essentially monotonic straining at low confining pressures. It consists of an isotropically hardening yield surface that is active when the stress is dominantly compressive and an independent "crack detection surface" that determines if a point fails by cracking. It uses oriented damaged elasticity concepts (smeared cracking) to describe the reversible part of the material's response after cracking failure [2].

The strain is decomposed in to elastic train and plastic strain.

$$\varepsilon = \varepsilon_e + \varepsilon_p \qquad (3)$$

Where, the elastic strain is $\varepsilon_e = \sigma / E_c$.

And σ is obtained by using equation 1 and 2, for the strain range 0< ε <0.002 and 0.002< ε < 0.0035 respectively. The plastic strain and corresponding stress for concrete grade M30 are calculated using equation (3).

The cracking and compressive responses that are included in the concrete model are demonstrated by the uniaxial response of a specimen as shown in the Figure 2.

When concrete is loaded in compression it shows elastic response in the beginning. As the stress is increased inelastic straining occurs which is non recoverable, and the material response softens. After the material softens, an ultimate stress is reached beyond which it can no longer carry any stress. If the load is removed at some point after inelastic straining has occurred, the unloading response is softer than the initial elastic response: the elasticity has been damaged. This effect is ignored in the model because we assume monotonic straining.

When a uniaxial concrete specimen is loaded in tension, it responds elastically until, at a stress that is typically 7%-10% of ultimate compressive stress, cracks form. These cracks are formed so quickly that it is very difficult to observe the actual behavior. As the loss of elastic stiffness gives rise to an open crack and the crack is a damage to the structure, the model assumes that cracking causes damage. It is also assumed that there is no permanent strain associated with cracking. This will allow the cracks to close completely if the stress across them becomes compressive [5].

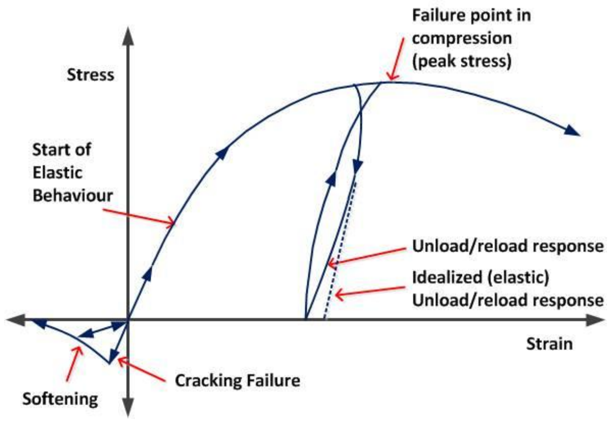

Figure 2. Uniaxial behavior of plain concrete [5].

A "compression" failure surface forms the basis of the model for the non-linear response when the principal stresses are dominantly compressive. In tension (including tension-compression zone), cracking is assumed to occur when the stress reaches a failure surface which is called the "crack detection' surface. Once the crack occurs ABAQUS uses a smeared crack approach in which constitutive calculations are performed independently at each integration point of the finite element model, and the presence of cracks enters into these calculations by the way that the cracks effect the stress and material stiffness associated with integration points [6].

2.2 Concrete Damaged plasticity

Under low confining pressures, concrete acts in a brittle manner and the main failure mechanisms are cracking in tension and crushing in compression. If the confining pressure is adequately large to prevent the crack, the brittle behavior of concrete disappears.

The damage in quasi-brittle materials can be defined by evaluating the dissipated fracture energy required to generate micro cracks,[7]. The main ingredients of the inviscid concrete damaged plasticity model are as under:

Strain rate decomposition is assumed for the rate-independent model as

$$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl} \qquad (4)$$

where $\dot{\varepsilon}$ is the total strain rate , $\dot{\varepsilon}^{el}$ is the elastic part of the strain rate, and $\dot{\varepsilon}^{pl}$ is the plastic part of the strain rate[5].
The stress-strain relations are governed by scalar damaged elasticity:

$$\sigma = (1-d)D_O^{el} : (\varepsilon - \varepsilon^{pl}) = D^{el} : (\varepsilon - \varepsilon^{pl}), \qquad (5)$$

Where D_O^{el} is the initial (undamaged) elastic stiffness of the material; $D^{el} = (1-d)D_O^{el}$ is the degraded elastic stiffness; and d is the scalar stiffness degradation variable, which can take values in the range from zero (undamaged material) to one (fully damaged material). Damage associated with the failure mechanisms of the concrete (cracking and crushing) therefore results in a reduction in the elastic stiffness. Within the context of the scalar-damage theory, the stiffness degradation is isotropic and characterized by a single degradation variable, d. Following the usual notions of continuum damage mechanics, the effective stress is defined as

$$\bar{\sigma} \stackrel{\text{def}}{=} D_O^{el} : (\varepsilon - \varepsilon^{pl}). \qquad (6)$$

The Cauchy stress is related to the effective stress through the scalar degradation relation:

$$\sigma = (1 - d)\bar{\sigma}. \quad (7)$$

3. THE MODEL

A concrete cube of size 150 mm is modeled in ABAQUS using C3D8 element. A steel plate of thickness 25 mm is placed on top and at the bottom of the cube to ensure the uniform distribution of the compressive load applied. See Figure 3 and 4. The plate is also modeled with C3D8 elements. The plates are secured in place by applying Constraint type tie, available in the ABAQUS. The material properties are used for M30 grade concrete as per IS 456- 2000 [8] for concrete. i.e. The average compressive stress, $\sigma_{cu} = 30\,MPa$, ultimate strain, $\varepsilon_{cu} = 0.0035$, and the strain at pick stress, $\varepsilon_0^{'} = 0.002$.

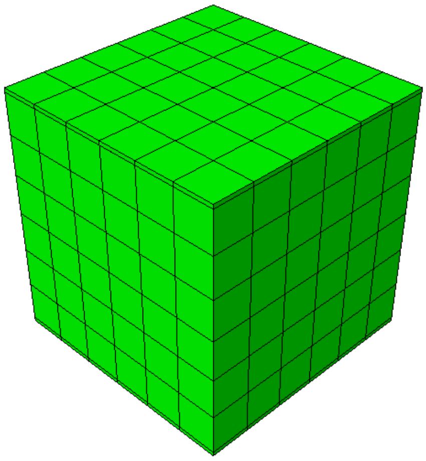

Figure 3. Meshed model of cube.

4. ANALYSIS

4.1 The Input Option:

In ABAQUS, the material properties required for non-linear analysis are as follows:

There are two options by which the material properties can be incorporated for the analysis in ABAQUS: a) through CAE and b) through input file.

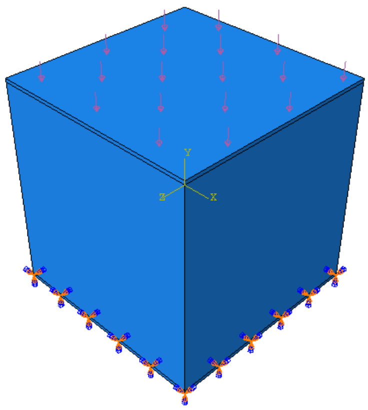

Figure 4. Loading and boundary conditions.

The ELASTIC option is used to give elastic properties. The CONCRETE option is used to describe compressive stress strain relationship outside the elastic range. Here the plastic strain values, (not total strain values), are used in defining the hardening behavior. Furthermore, the first data pair must correspond with the onset of plasticity (the plastic strain value must be zero in the first pair). The TENSION STIFFENING option is used to define the concrete’s post failure behavior after cracking. The TENSION STIFFENING allows defining the strain-softening behavior for cracked concrete. Tension stiffening is required in smeared cracking model. Tension stiffening can be specified by means of a post failure stress-strain relation or by applying a fractured energy cracking criterion. A typical tension stiffening model is as shown in Figure 5.

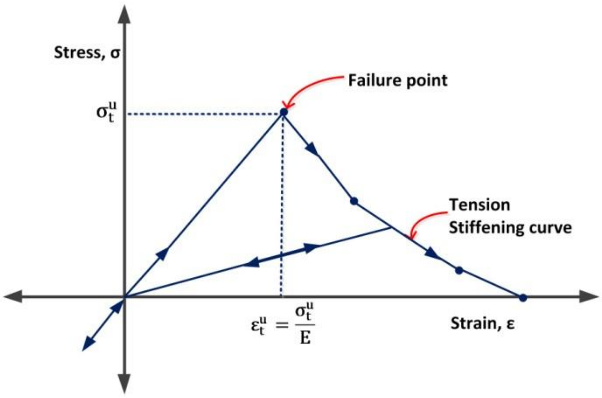

Figure 5. The tension stiffening model [5].

The selection of tension stiffening parameters is important in Abaqus/Standard since, more tension stiffening makes it easier to obtain numerical solutions. Too little tension stiffening will cause the local cracking failure in the concrete to introduce temporarily unstable behavior in the overall response of the model.

In ABAQUS, Plastic strain values, not total strain values, are used in defining the hardening behavior. Furthermore, the first data pair must correspond with the onset of plasticity (the plastic strain value must be zero in the first pair).

The values for concrete properties are calculated by using equations 1, 2 and 3.

The FAILURE RATIOS are

1. Ratio of the ultimate biaxial compressive stress to the uniaxial compressive ultimate stress, default being 1.16. Absolute value of the ratio of uniaxial tensile stress at failure to the uniaxial compressive stress at failure. (3.0/30.0 =0.1), default being 0.09.
2. Ratio of the magnitude of a principal component of plastic strain at ultimate stress in biaxial compression to the plastic strain at ultimate stress in uniaxial compression, default being 1.28.
3. Ratio of the tensile principal stress value at cracking in plane stress, when the other nonzero principal stress component is at the ultimate compressive stress value, to the tensile cracking stress under uniaxial tension, default is 1/3.

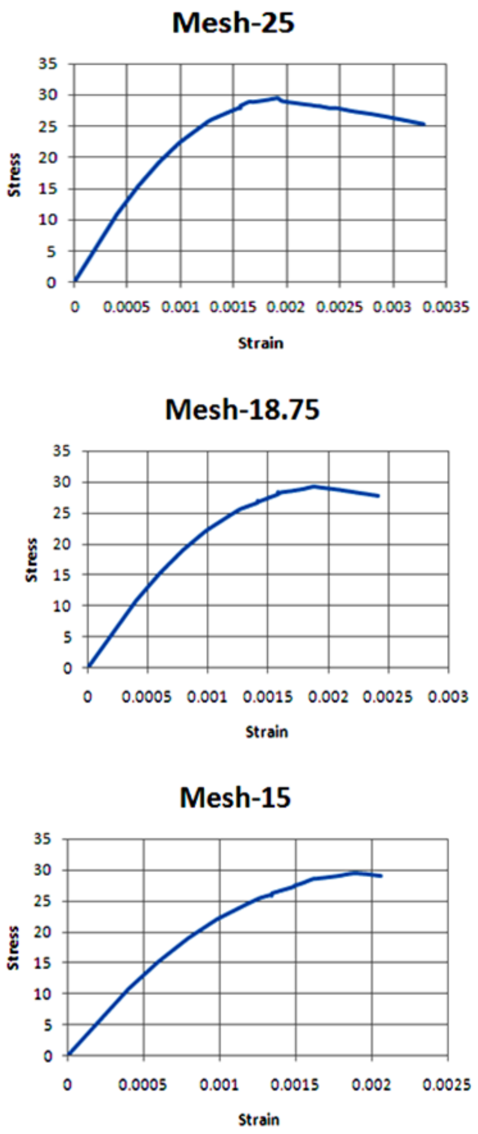

Figure 6. Stress-strain curves at different mesh sizes using Smeared crack model

The TENSION STIFFNING in numerical simulation can be represented either by modifying the stiffness of reinforcing bars or by modifying the stiffness of concrete so that the concrete can carry the tensile force after cracks. The value of 0.002 is adopted for this analysis.

The SHEAR RETENTION option is used to give a multiplying factor, ϱ, that defines the modulus for shearing of cracks as a fraction of the elastic shear modulus of the uncracked concrete. The first value is 1 and the second is a very large number for full retention.

5. RESULTS

Figure 6 shows, the stress-strain curves at different mesh sizes using smeared crack model and Figure 7 shows the stress train curves at different mesh sizes using concrete damage plasticity model.

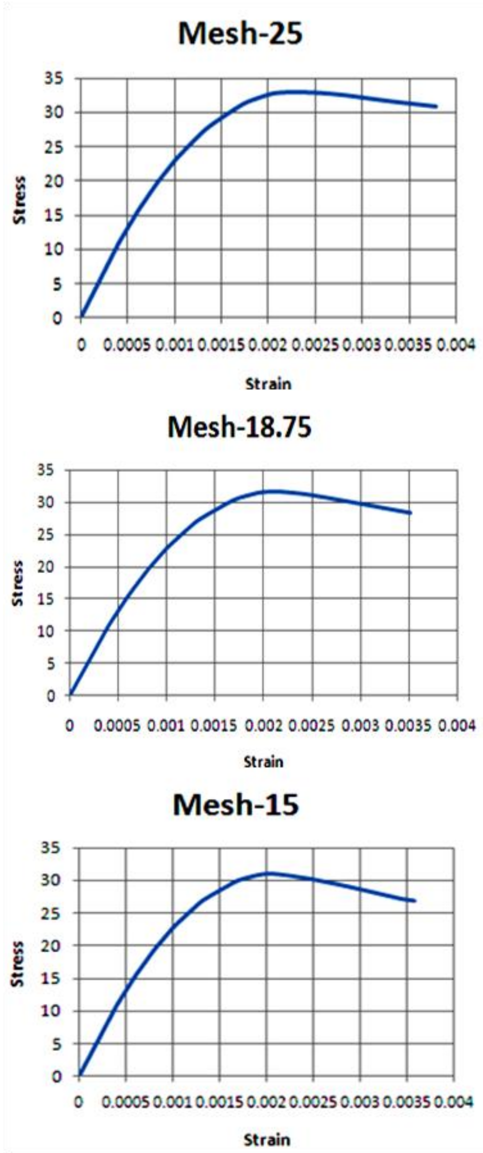

Figure 8. Stress-strain curves at different mesh sizes using Concrete damaged plasticity model

6. CONCLUSION

1. In both the cases the concrete shows a perfectly nonlinear behavior.

2. Using smeared crack modeling at mesh size 25 the obtained stress-strain curve gives max stress about 29.39MPa at 0.00190 strain and then after the curve shows the descending nature.

3. In case of Concrete damaged plasticity model at mesh size 25, the stress obtained is 32.33 MPa at 0.00195 strain and then after it starts descending.

4. Since in the case of damaged plasticity the material depicts over estimation of the stress the mesh sensitivity was performed. Again using smeared crack modeling there is no significant change in the values of stresses is noticed. But in the case of damage plasticity model mesh size plays the vital role. As the mesh size reduces the value of stress is

also approaches closer to the actual desirable value i.e. 30 MPa.

5. Because of analytical constraints the mesh size could not be reduced beyond 15 mm.

6. The material modeling of concrete is said to be validated as theoretical values for stresses obtained by the equations 1 and 2 are closely matching with the values found by non linear finite element modeling using ABAQUS.

7. The smeared crack model of concrete is found suitable as it gives desired results at coarser mesh size in comparison with concrete damage plasticity model as it doesn't over estimate..

7. ACKNOWLEDGMENT

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