Improvement and Enhancement of Concrete Damage Plasticity Model

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Abstract: *The purpose of this paper is to make an improved concrete damage plasticity model that focus on a post cracking behavior. First, we constitute the material model that simulates a process of closing the large tensile cracks and recovering the compression stiffness. Second, the model is enhanced by adding another feature that simulates a transition from compression to tension again. Finally, experimental simulation analyses are conducted for validation of efficiency.*

Keywords: *Civil Engineering, Concrete, Constitutive Model, Plasticity, Damage, Cyclic Behavior*

1. Introduction

In order to properly assess the safety margins of the reinforced concrete structures under a cyclic loading, it is necessary to properly simulate damage process of the concrete; however, concrete damage models in commercial analysis codes are rarely practicable in terms of a transition behavior from tension to compression, and vice versa.

In Abaqus, elasto-plastic concrete models have been introduced based on plastic damage theory from ver.6.3. Though they have enabled elasto-plastic evaluations under a monotonic loading in practical use, it is hard to say that they can simulate an appropriate behavior under a cyclic loading.

2. Constitutive Law of Concrete

2.1 Isotropic Damage Plastic Theory

In the elasto-plastic analysis of reinforced concrete structures, it is necessary to appropriately configure material properties of concrete, rebar and bond relationship of them.

In particular, material properties of concrete are complex, because compression, tensile and shear behavior is respectively different.

Since Abaqus6.3, isotropic plastic damage model has been introduced. It is characterized by putting damage into a scalar value that does not depend on the direction. According to the model, damage can be captured by the entire state including tensile, shear, and compressive failure.

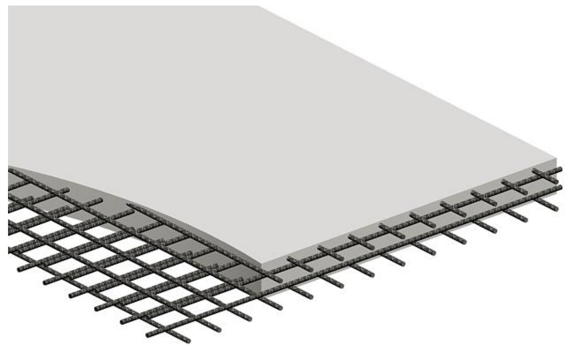


Figure 1. Image of reinforced concrete structures

Uniaxial characteristics in tension and compression in the material models are shown in Figure 2. On tension side, a stress-strain curve follows the linear elastic relationship E_0 until it reaches the value of the fracture stress σ_{t0} corresponding to the generation of micro-cracks in the concrete. Once it exceeds the fracture stress, the formation of micro-cracks is expressed by the tension softening response. On the other side, under uniaxial compression stress strain response, a characteristic is in accordance with the linear elastic relationship E0 until the stress reaches the initial yield stress σ_{c0}. Response in the plastic zone is generally characterized by softening from the ultimate stress σ_{cu}.

According to the test results, it has been found that the slope of the unloading response is reduced, when it is unloaded from any point on strain softening portion of the strain curves. In the isotropic plastic damage theory, its reduction of the elastic stiffness of the material is treated as damage variable. Damages are represented by two damage variables *dt* and *dc* as the reduction factor (zero: no damage to one: fully damage) of the elastic stiffness tension and compression side. These variables can be a function of plastic strain, temperature, and other field variables.

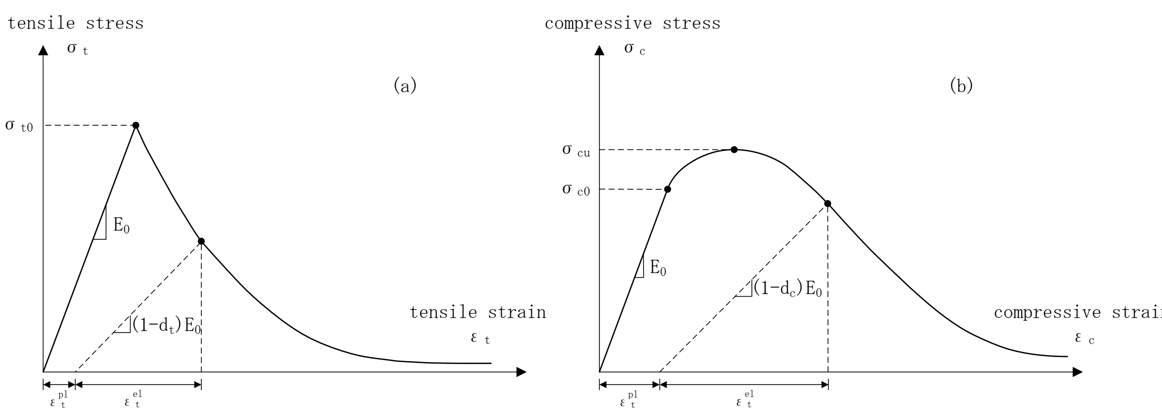


Figure 2. Uniaxial behavior of concrete in compression and tension side

2.2 Behavior under cyclic load

It is known that reinforced concrete recover stiffness even if tensile cracking and stiffness reduction occurs in the tension side. It is result from closing crack again in the process of stress is shifted to the compression side. In order to simulate the crack closing process, the stiffness recovering coefficient of w_t and w_c are set for Abaqus.

Figure 3 is a schematic diagram of a process of a stiffness recovery shown in the Abaqus theory guide [8]. Thus, user can set a stiffness recovering behavior by using a coefficient w_c (0 ~ 1) how the tension damage involve the stiffness at the transition to compression side. And it is the same for a transition back to the tension side.

Figure 3 shows default settings of Abaqus that represents stiffness recovering at the transition from tension to compression side and damage cumulating at the transition from compression to tension side.

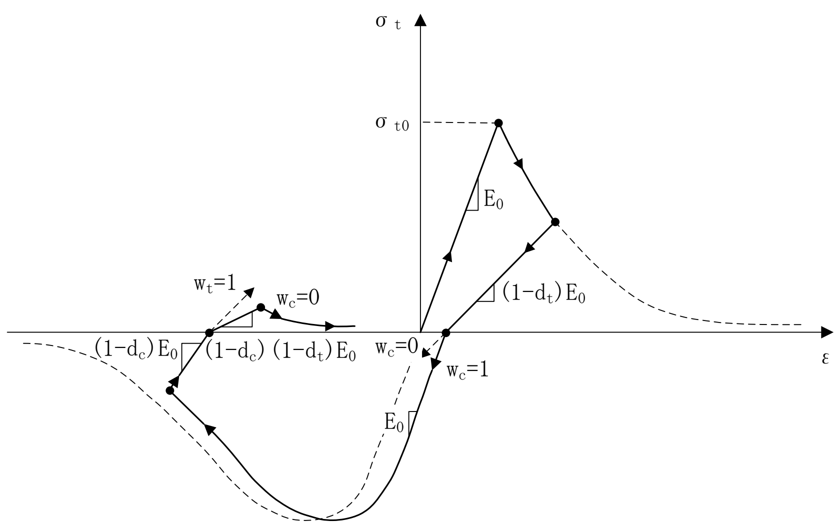


Figure 3. Uniaxial behavior of concrete under cyclic loading

2.3 Problem of current concrete model and proposal of new model

In certain situations, such as shown in Figure 3, a constitutive law of concrete in Abaqus properly captures the macroscopic properties of the concrete. However, in case of a large tensile strain shown in Figure 4, stiffness recovery occurs earlier than expected. It can be attributed to the current material model that judges a transition from tension to compression stiffness recovery by zero stress point.

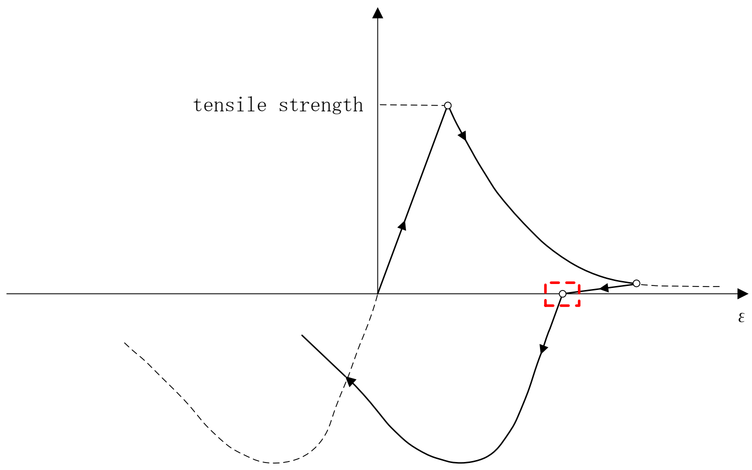
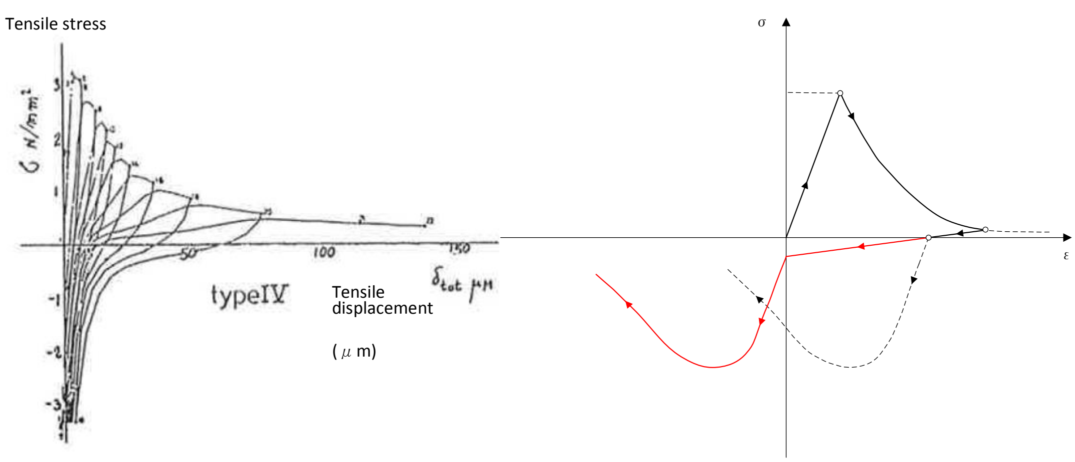


Figure 4. Transition behavior with large tensile strain in current material model

Figure 5 shows an example of behavior of concrete by actual cyclic loading test in [19]. After receiving large tensile stress as shown in the figure, the concrete stiffness reduces as expected in accordance with the degree of damage. Thereafter, through a process of closing the cracks, the concrete gradually recovers the stiffness by interlocking on crack surfaces.

In order to solve the problems shown in Figure 4, we propose a new material model in which compressive stiffness recovery criteria is modified from a zero stress point to a zero strain point. This change enables to simulate the crack closing process that is quite similar to the actual behavior of the concrete such as Figure 5. It is intended that the reduced tensile stiffness is mainly dominant during the tensile strain state and the compressive stiffness become dominant from transition to the compressive strain.



(Actual behavior in an experiment) (Proposed material model)

Figure 5. Actual Behavior of concrete and proposed model

3. Verification Analysis

In this section, verification analyses are performed to check the operation of proposed material model.

3.1 Material Properties

Concrete material characteristics for the study are shown in Table 1. It is the same properties as verification of the concrete material constitutive law in [2].

Table 1. Concrete Material Characteristics

Young's Modulus	**33.8 GPa**
Compressive Strength	**30.9 MPa**
Strain at Compressive Strength	**2.2×10^{-3}**
Tensile strength	**1.57 MPa**
Strain at Tensile Strength	**4.6×10^{-5}**
Poisson's Ratio	**0.2**

Concrete tension stiffening and tension damage characteristics are set according to Eq.(1) and Eq.(2). It was proposed by Izumo et al [5] and has been verified through the dynamic simulation analysis of shear walls [4].

$$\sigma_t = \sigma_{cr}\left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right)^c \tag{1}$$

$$d_t = 1 - \left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right)^d \tag{2}$$

Here,

σ_t : *TensileStress* σ_{cr} : *Tensile Strength* ε_t : *Tensile Strain* ε_{cr} : *Strain at Tensile Strength* $c = 0.4$ $d = 1.0$

Similarly, Concrete compression hardening and compression damage characteristics are set according to Eq.(3) and Eq.(4). Concrete compression hardening and compression damage characteristics follow the previous report [2], which is based on [21] and [7].

$$\sigma_c = \left[\frac{E_0}{E_{cl}} \frac{\varepsilon_c}{\varepsilon_{cl}} - \left(\frac{\varepsilon_c}{\varepsilon_{cl}} \right)^2 \Bigg/ 1 + \left(\frac{E_0}{E_{cl}} - 2 \right) \frac{\varepsilon_c}{\varepsilon_{cl}} \right] f_{cm} \tag{3}$$

$$d_c = 1 - \frac{\sigma_c}{E_0 (\varepsilon_c - \varepsilon_p)} \tag{4}$$

Here,

σ_c : *Compressive Stress* f_{cm} : *Compressive Strength*

ε_c : *Compressive Strain* ε_{cl} : *Strain at Compressive Strength*

E_0 : *Young's Modulous* E_{cl} : *Secant Modulous at* f_{cm} ε_p : *Plastic Strain*

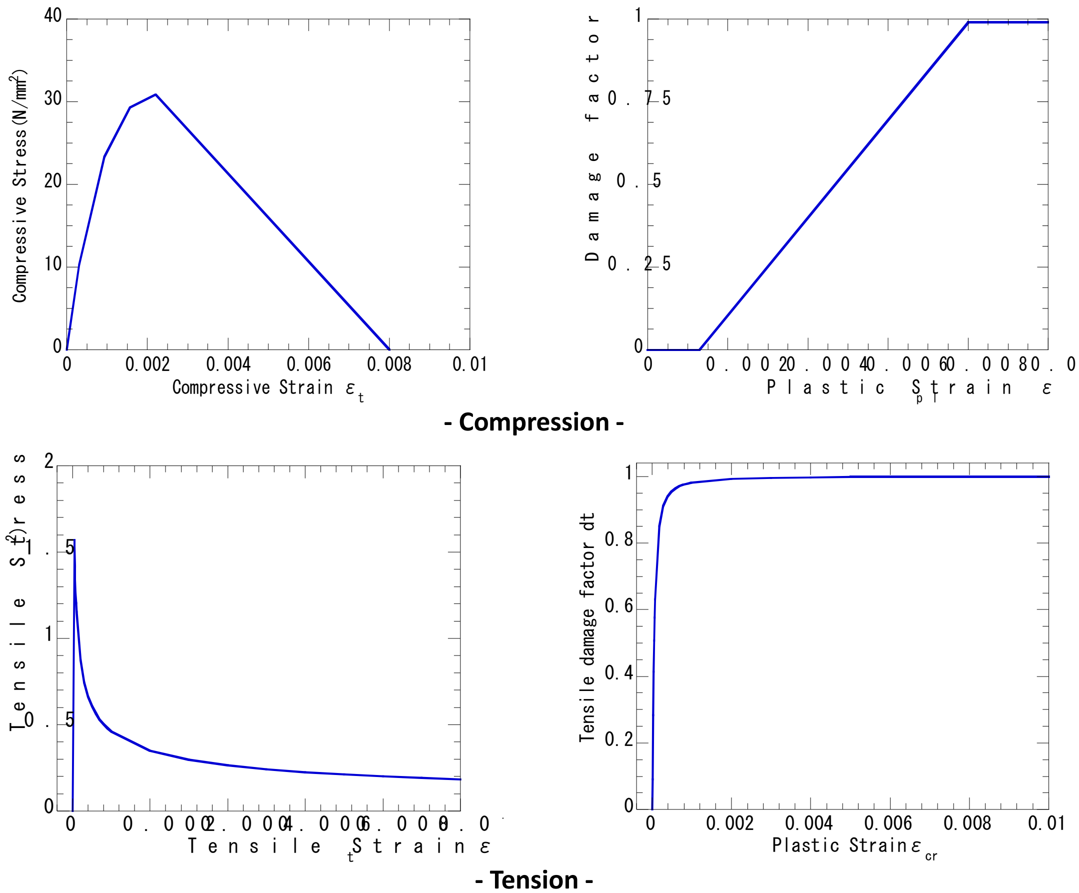


Figure 6. Concrete properties for analysis

3.2 Conditions of Analysis

Analysis for verification is carried out in in the way shown in Figure 7.
An element for the analysis is the reduced integration solid elements (C3D8R).

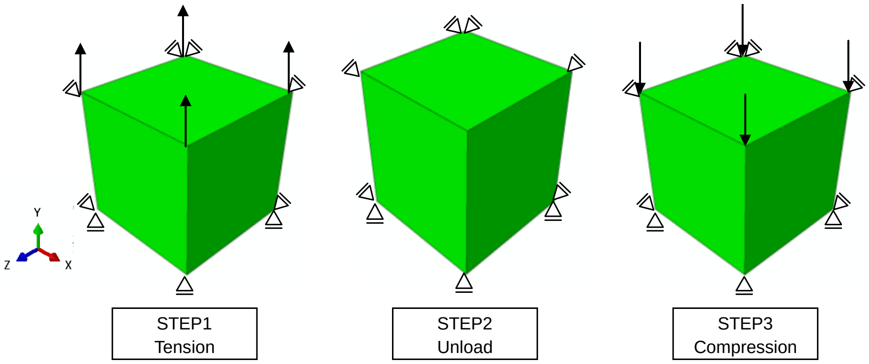


Figure 7. Procedure of analysis (half cycle)

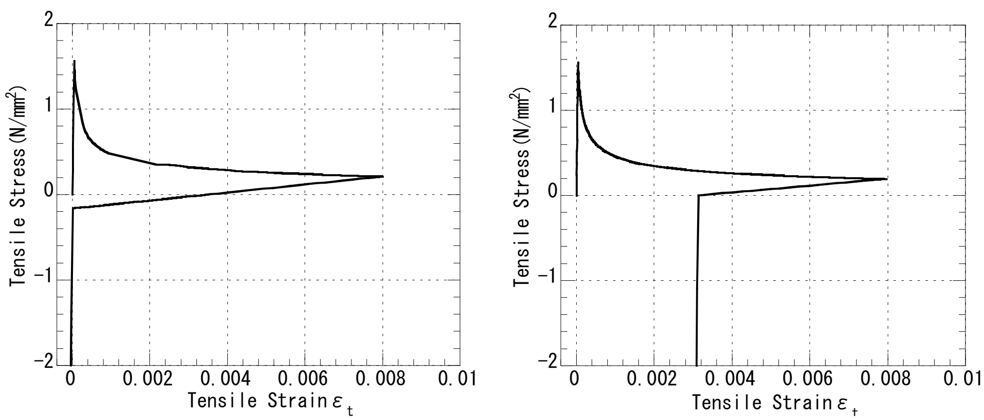
3.3 Results of Analysis

The results of the verification analysis by material conditions of the previous section are reported.

3.3.1 Tension to Compression

For the basic verification, Analysis starts from a half cycle study.

Figure 8 shows the stress-strain relationship in the analysis by proposed and current material model. It appears that the left shows a rigid recovery behavior at zero strain proposed in 2.3. The right shows the analysis results from a current model of the same material and analysis conditions for comparison, but it result in unrealistic transition to the compression side rigidity stress zero point.



(Proposed model) (Current model)

Figure 8. Results of analysis (half cycle)

3.3.2 One cycle

Figure 9 shows the stress-strain relationship in the one cycle analysis by new material model. It appears that proposed model properly work on the compressive damage area after recovering stiffness. Moreover, it also appears that stress-strain relationship transmits tensile damaged stiffness at the zero-stress point such as a transition of current material model shown in Figure 3.

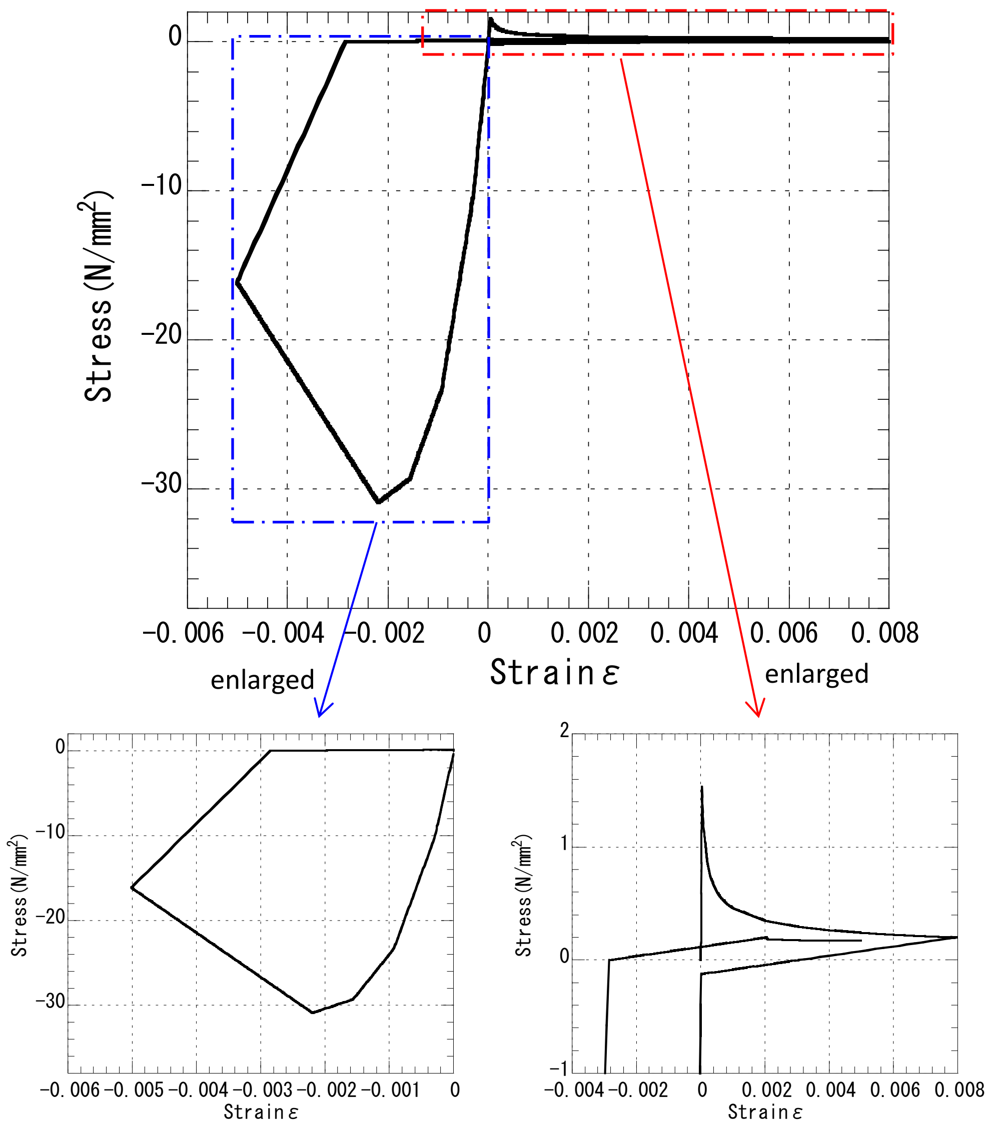


Figure 9. Results of analysis (one cycle)

3.3.3 Two cycles

Figure 10 shows the stress-strain relationship in the two cycle analysis by new material model. It is lucid that proposed model follows current material model under partitioning tensile strain. There are not sufficient data in such regions, however, the current material model seems realistic and the impact on an overall behavior would be limited.

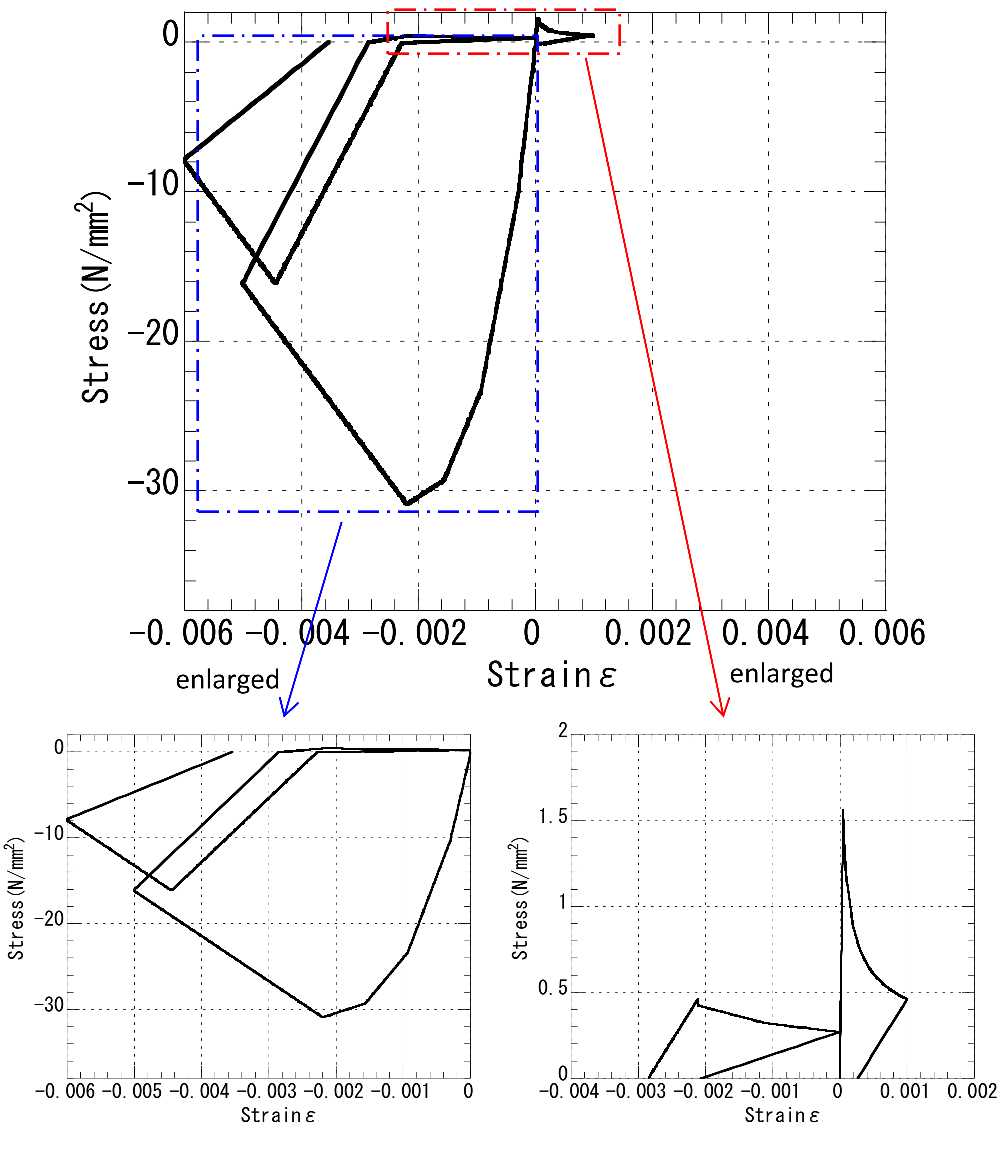


Figure 10. Results of analysis (two cycles)

4. Summary

In order to properly assess the safety margins of the reinforced concrete structures under a cyclic loading, we propose a new material model in which compressive stiffness recovery criteria is modified from a zero stress point to a zero strain point. This change enables to simulate the crack closing process that is close to the actual behavior of the concrete. Though much still remains to be unsettled about a behavior of damaged concrete, I believe we made some contributions to simulate it. Further consideration will be needed to yield any findings toward the practical use.

5. Acknowledgments

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