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Selection of Constitutive Models for Concrete in simulating Reinforced Concrete Members

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Abstract

Reliable, accurate and robust constitutive model for concrete is very much essential in simulating Reinforced Concrete Members such as Beam, Column and Shear wall properly. For an accurate and reliable prediction of Reinforced Concrete Members response an effective and robust hysteretic constitutive model for concrete is needed. A good concrete model addresses important issues such as the hysteretic behavior in both cyclic compression and tension, the progressive degradation of stiffness of the unloading and reloading curves for increasing values of strain, and the effects of confinement, tension stiffening and gradual crack closure. Refined and generalized model takes into account concrete damage and hysteresis, while retaining computational efficiency. In this paper a review of concrete constitutive models available in the literature has been made with their individual advantages and disadvantages in modeling Reinforced Concrete Members and at the end, which concrete constitutive model is appropriate for which type of member has also been discussed.

Keywords: *Constitutive Models, Concrete, Reinforced Concrete Members, Hysteretic behavior.*

1. Introduction

Characteristics of the constitutive relationships implemented in the model for concrete influence the analytical model response of Reinforced Concrete Members. Reliable, accurate and robust constitutive model for concrete is very much essential in simulating Reinforced Concrete Members such as Beam, Column and Shear wall properly. For an accurate and reliable prediction of RC member response, an effective and robust hysteretic constitutive model for concrete is needed. The tensile behavior of the model takes into account tension stiffening and the degradation of the unloading and reloading stiffness for increasing values of maximum tensile strain after initial cracking. Some concrete constitutive models have the inability of to simulate gradual gap closure due to progressive contact stresses within the cracks in concrete. This may impair significantly, the accuracy in predicting the pinching properties (i.e., characteristic variation in section stiffness from unloading to reloading in the opposite direction) of RC elements subjected to cyclic loading. Another limitation of some constitutive models is that it lacks the flexibility of a generalized model. Some model do not allow control on most of the parameters associated with the monotonic and hysteretic branches of the stress-strain relationship, thus restraining the calibration of the model or re-assessment of the parameters as new data become available**.** In this paper a review of concrete constitutive models available in the literature has been made with their individual advantages and disadvantages in modeling Reinforced Concrete Members.

2. Different Concrete Constitutive Models

Two different constitutive models with different capabilities are discussed in this study, the first being relatively simple and commonly used, and the latter more refined and generalized. Although two constitutive models are discussed below other concrete models are also discussed under these two main categories.

Hysteretic Constitutive Model by Yassin [7]

Studies on the stress-strain relations of concrete under cyclic loading have been much fewer than those under monotonic loading. Sinha et al. [2]) and Karsan and Jirsa [5] have studied the behavior of plain concrete subjected to repetitions of compressive stress. It is found that the envelope for cyclic loading coincides with stress-strain curve for monotonic loading. The model by Yassin takes into account concrete damage and hysteresis, while retaining computational efficiency.

The monotonic envelope curve of the hysteretic model for concrete in compression follows the monotonic stress-strain relationship model of Kent and Park [3] as extended by Scott, Park and Priestley [1]. Even though more accurate and complete monotonic stress-strain models have been published since, the so-called modified Kent and Park model offers a good balance between simplicity and accuracy, and is widely used.

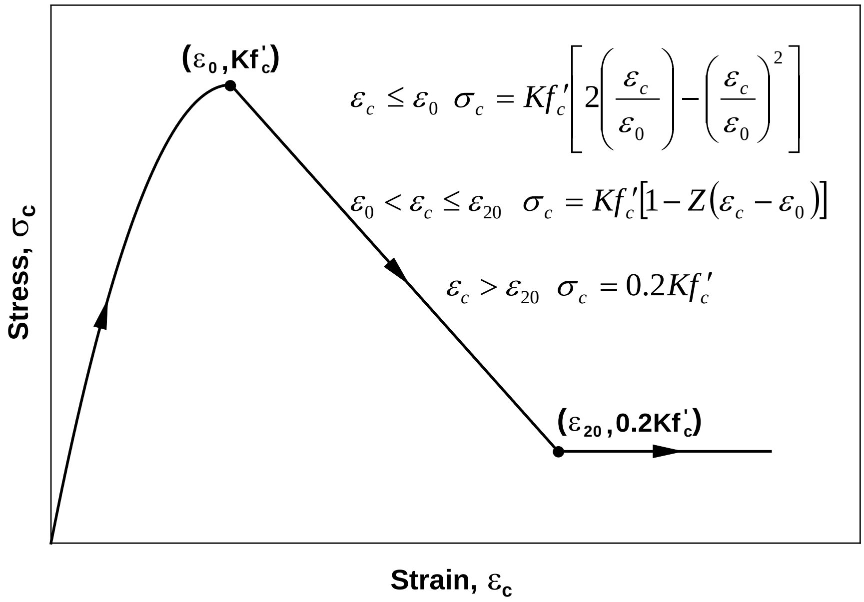

Fig. 1 The Modified Kent & Park Model [3] for Concrete in Compression

In the modified Kent and Park model (Figure 1), the monotonic concrete stress-strain $(\sigma_c - \varepsilon_c)$ relation in compression is described by three regions.

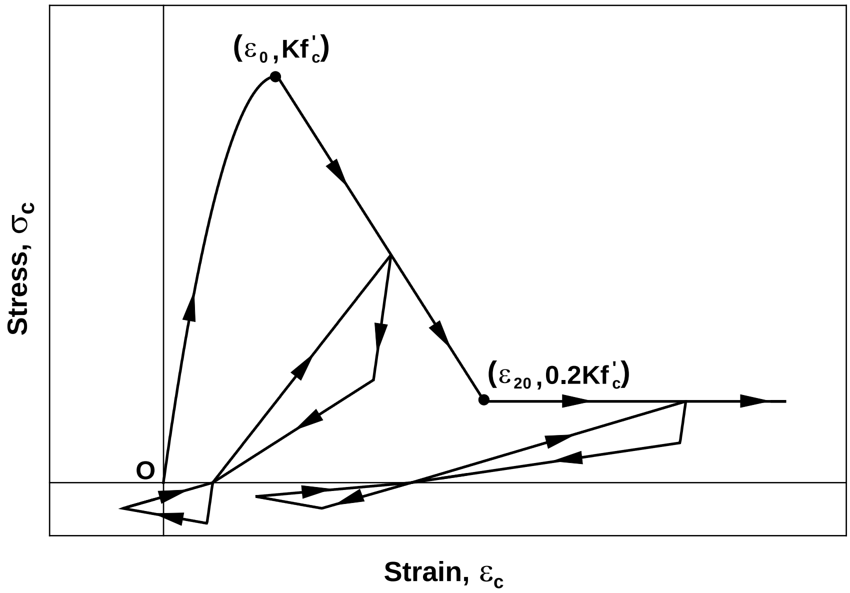

Fig. 2 Hysteretic Unloading and Reloading Rules (Yassin,[7])

The hysteretic unloading and reloading rules proposed by Yassin [7] are a set of linear stress-strain relationships, as shown in Figure 2. The figure illustrates that hysteretic behavior occurs in both compression and tension. Although the compressive and tensile hysteresis loops are continuous, they are discussed separately for the sake of clarity. Figure 2 shows two consecutive tensile hysteresis loops, which are part of a sample cyclic history that also includes compressive stresses. The model assumes that tensile stress can occur anywhere along the strain axis, either as a result of initial tensile loading or as a result of unloading from a compressive state. In the latter case, a tensile stress occurs under a compressive strain. The tensile stress-strain relation is defined by three points with coordinates $(\varepsilon_t, 0)$, $(\varepsilon_n, 0)$ and $(\varepsilon_u, 0)$, as represented by points J, K and M, respectively in Figure 3.

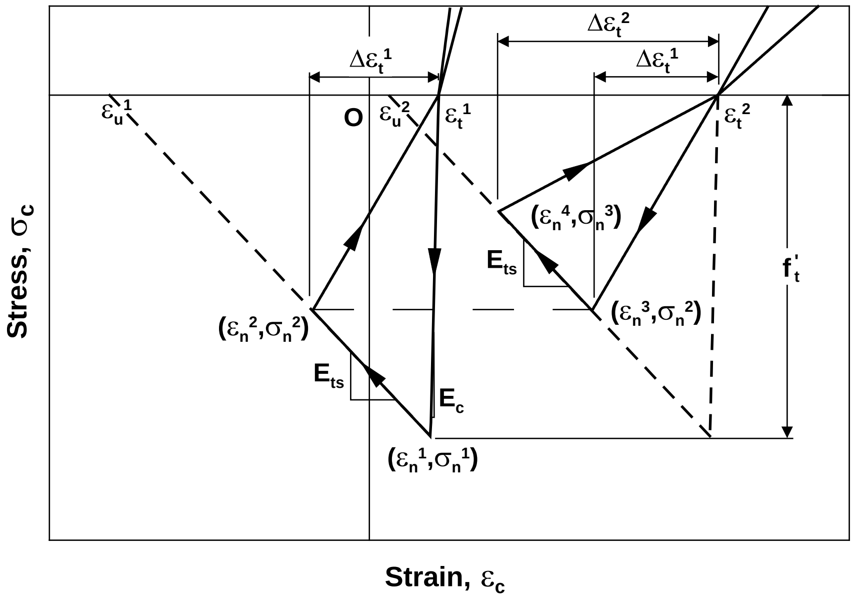

Fig. 3 Hysteresis Loops in Tension

Due to its computational efficiency and reasonable level of accuracy, the constitutive model is commonly used by researchers, and is implemented in the state-of-the-art computational platform OpenSees ("OpenSees[8]") developed by the Pacific Earthquake Engineering Research Center at the University of California, Berkeley. The model successfully generates continuous stress-strain behavior in hysteretic compression and tension, and considers damage in the form of cyclic stiffness degradation.

The primary shortcoming of this concrete constitutive model is the inability of the model to simulate gradual gap closure due to progressive contact stresses within the cracks in concrete. This may impair significantly, the accuracy in predicting the pinching properties (i.e., characteristic variation in section stiffness from unloading to reloading in the opposite direction) of RC elements subjected to cyclic loading. Another limitation of the constitutive model is that it lacks the flexibility of a generalized model. The model does not allow control on most of the parameters associated with the monotonic and hysteretic branches of the stress-strain relationship, thus restraining the calibration of the model or re-assessment of the parameters as new data become available. Furthermore, the monotonic stress-strain envelope associated with the constitutive model may be considered out-of-date, more accurate monotonic stress-strain models for both unconfined and confined concrete have been proposed since.

Hysteretic Constitutive Model by Chang and Mander [4]

The constitutive model by Chang and Mander [4] is an advanced, rule-based, generalized, and non-dimensional model that simulates the hysteretic behavior of confined and unconfined, ordinary and high-strength concrete in both cyclic compression and tension. Upon development of the model, the authors focused particular emphasis on the transition of the stress-strain relationship upon crack opening and closure, which had not been adequately addressed in previous models. Most existing models (including the model by Yassin [7] previously described) assume sudden crack closure with rapid change in section modulus (i.e., sudden pinching behavior). Similar to the model by Yassin [7], in the model by Chang and Mander, the monotonic curve forms the envelope for the hysteretic stress-strain relationship. This was shown to be a reasonable assumption based on experimental results presented by Sinha et al. [2] and Karsan and Jirsa [5], and modeled by Mander et al. [6] for unconfined concrete in cyclic compression. In the model by Chang and Mander, concrete in tension is modeled with a cyclic behavior similar to that in compression. The model envelopes for compression and tension have control on the slope of the stress-strain behavior at the origin, and the shape of both the ascending and descending (i.e., pre-peak and post-peak) branches of the stress-strain behavior.

Compression Envelope Curve

The compression envelope curve of the model by Chang and Mander is defined by the initial slope E_c, the peak coordinate (ε_c', f_c'), a parameter r from Tsai's [9] equation defining the shape of the envelope curve, and a parameter $x_{cr}^- > 1$ to define the spalling strain (Figure 4).

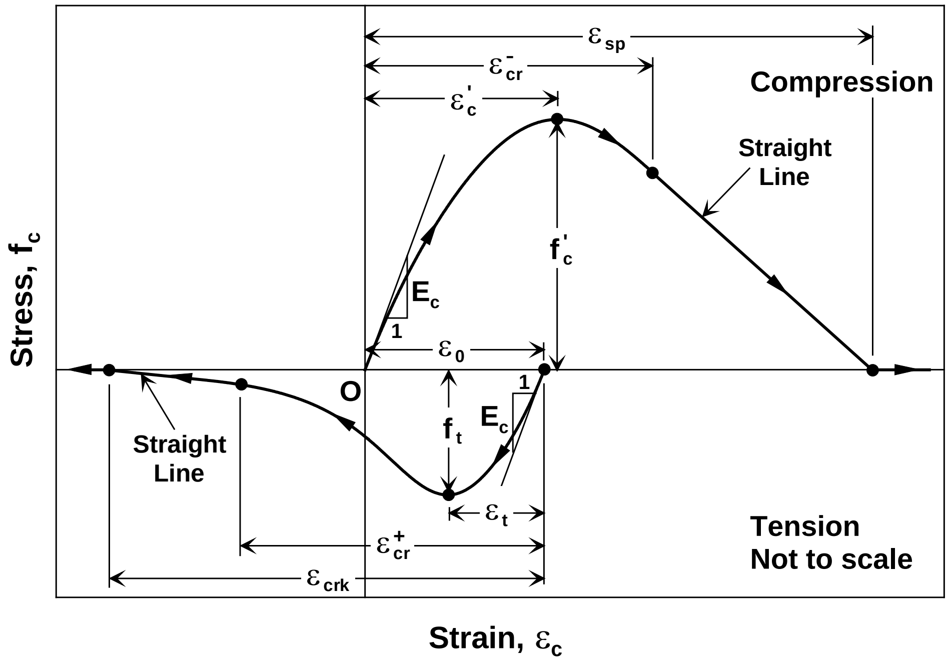

Fig. 4 Compression and Tension Envelope Curves of the Model by Chang and Mander [4]

Tension Envelope Curve

The shape of the tension envelope curve in the model by Chang and Mander is the same as that of the compression envelope curve (Figure 4). In terms of modeling generalized hysteretic behavior, the constitutive model uses smooth "connecting" curves for unloading and reloading between the compression and tension envelope curves, and smooth "transition" curves for partial unloading and reloading between the connecting curves (Fig. 5).

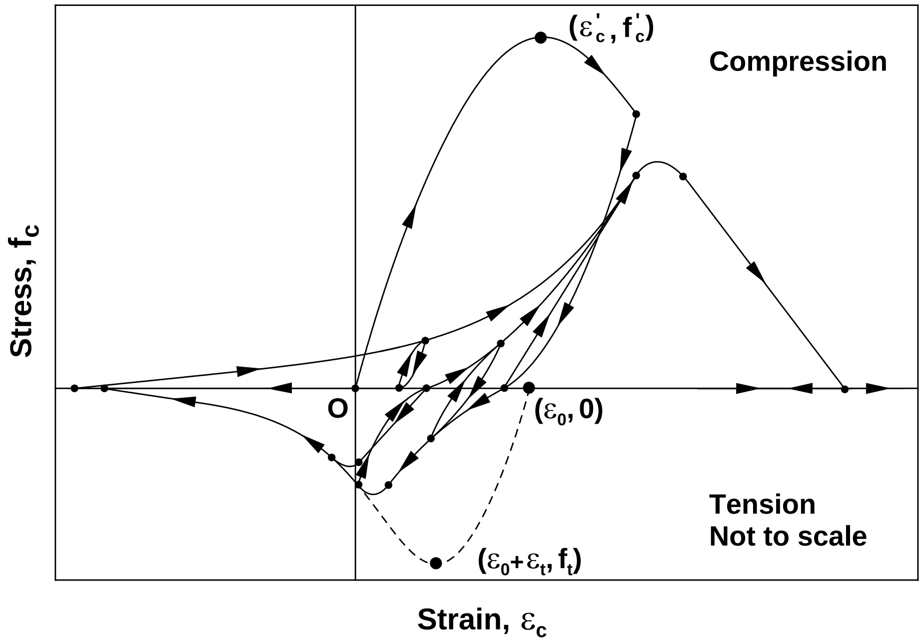

Fig. 5 Continuous Hysteresis in Compression and Tension

Overall, the model by Chang and Mander [4] is the current state-of-the-art uniaxial constitutive relationship for modeling the cyclic stress-strain behavior of concrete. It simulates gradual crack opening and closure under cyclic loading and incorporates a refined and well-established definition of the hysteretic properties. The model is in the form of a generalized stress-strain relationship, which can further be advanced, via re-assessment of model parameters, or upon availability of further experimental results (e.g., for cyclic tension). It allows control on the parameters associated with the monotonic envelopes as well as the hysteretic parameters for a refined calibration of the stress-strain relationship based on particular experimental results, or for conducting sensitivity studies on model parameters.

3. Conclusion

For an accurate and reliable prediction of Reinforced Concrete Members response an effective and robust hysteretic constitutive model for concrete is needed. Two different constitutive models for concrete (Yassin, [7]; Chang and Mander, [4]) have been discussed in this paper. Both models address important issues such as the hysteretic behavior in continuous cyclic compression and tension, the progressive degradation of stiffness of the unloading and reloading curves for increasing values of strain, and the effects of confinement and tension stiffening. However, the model by Chang and Mander [4], being the current state-of-the-art uniaxial constitutive relationship for modeling the cyclic stress-strain behavior of concrete, is clearly superior to the hysteretic model by Yassin [7]. The model by Chang and Mander is a generalized constitutive model that allows control on the parameters associated with the monotonic envelopes, as well as the hysteretic parameters, for a refined calibration of the stress-strain relationship based on particular experimental results. Furthermore, the model by Chang and Mander successfully simulates the gradual closure of cracks under cyclic loading, due to progressive contact stresses within the cracks. On the other hand, the model by Yassin assumes sudden crack closure, which may impair significantly, the accuracy in predicting the pinching properties of RC member. Due to these limitations, the model by Yassin is very seldom used in modeling RC members.

4. References

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