Finite Element Modeling of Tension Stiffening and Cracking of Reinforced Concrete Components: State of Art

Seema\textsuperscript{1}, Aditya Kumar Tiwary\textsuperscript{2} and R. Zandonini\textsuperscript{3}
\textsuperscript{1, 2} Professor and Assistant Professor, Chandigarh University, Mohali, Punjab, India, www.cuchd.in
\textsuperscript{3} Full Professor, University of Trento, Italy, www.unitn.it

Abstract: The scientific community has been debating the vulnerability of structures to progressive collapse and how to mitigate the impact of local damages leading to un-proportional collapse. Recent tragedies have highlighted the necessity for particular design requirements to provide appropriate safety levels against progressive collapse as a result of damages caused by unusual loads. The performance of composite and reinforced concrete components in the realm of large displacements is presently the focus of study. The behaviour of reinforced concrete (RC) components, as well as the finite element model used to simulate RC parts under tension, were critically examined. This has aided in the understanding of concrete's non-negligible contribution to tension stiffening response up to failure, particularly in the case of composite constructions with discontinuous geometry. The extensive study of literature provided insight into various modelling techniques and advised that experimental and numerical research be used to enhance diverse possibilities of model exploration.

Keywords: Finite Element Modelling, Reinforced Concrete, Non-Linear Analysis, Tension Stiffening, Discrete and Smeared Cracks

1 Introduction
The scientific community is increasingly interested in the vulnerability of structures to progressive collapse and mitigation of the impacts of local damages. The recent progressive collapses, which resulted in a large loss of human life, highlighted the necessity for new design criteria with the goal of designing robust buildings, i.e., structures that can sustain extreme loads without being destroyed in a way that is disproportionate to the resulting cause. A localized damage can lead to progressive collapse extended to all or parts of structure if it is not able to redistribute the load to reach balanced configurations or cannot be absorbed by the inherent continuity and ductility of the structural system. In such circumstances, the
response of the structural system should be determined through analysis of the non-linear time domain integration, given the multiplicity of the possible scenarios. All the possible causes of activation of progressive collapse require identification and new design criteria that can mitigate the damage rather than prevent it. The focus is on the behaviour of reinforced concrete components and structures in tension especially in large displacement field [1–3].

In reality, apart from the traditional ultimate resistance design, reinforced concrete (RC) constructions are built to meet serviceability standards. It is important to forecast cracks and deformations under service loads in order to meet the serviceability criterion. When evaluating and constructing RC components and structures in the past, it was assumed that concrete had no tensile strength. Based on this assumption and the behaviour of concrete in compression, it is possible to determine the stress and strains in the concrete and reinforcement, and therefore the deformation of the member [4–7].

As a result, cracking and, as a result, tension stiffening are essential aspects of concrete behaviour that have a significant impact on the overall response of RC structures. The commencement of cracks is controlled by the tensile characteristics of concrete, and the cracking process under tension begins at a low tensile strain, leading plain concrete to soften gradually. The bond slip phenomenon, which occurs in the transfer of stresses from concrete to steel at fracture locations, adds to this softening. As a result, crack propagation is a complex phenomenon that plays an important role in the study of RC structures [8–11].

2 Discrete and Smeared Crack Modeling Approaches

The crack opening displacements are generally discretized along crack pathways and used as degrees of freedom in a Discrete Crack Approach. These degrees of freedom can be used to express the system's energy. The discrete crack technique, on the other hand, may not be the ideal solution for situations with a large number of cracks since it will result in a large number of degrees of freedom. Furthermore, when the number of cracks grows, the problem's mesh topology may need to be considerably altered to accommodate the new fracture patterns. In addition, the system stiffness equation's singularity problem may emerge. The energy is represented in terms of irreversible crack stresses, which are functions of location and are typically not discretized in a Smeared Crack Approach. Because there is no increase in degrees of freedom or change in mesh topology during the propagation of cracks, the difficulties observed with the discrete crack method may be substantially avoided if the smeared crack approach is used. Although smeared fracture models may encounter the system's singularity problem in the event of a softening branch of concrete, the problem is less severe than with discrete crack models [12–15].

Scientists almost exclusively employ the smeared crack technique to describe concrete cracking behaviour in nonlinear analysis of RC structures nowadays because it is easier to be utilised in a finite element analysis tool than the discrete crack model. In simulations requiring global structural response, computer time limitations favour the spread crack model. The smeared crack model was used to study the effect of the slope of the descending branch of the concrete stress-strain relationship on the behaviour of RC slabs. The influence of mesh size [24,30] and tension stiffening [16–19] on the accuracy of RC structures finite element computations using the smeared crack model was demonstrated in a number of studies. Some researchers add a diminishing post-peak branch in the tensile stress-strain curve for concrete [1].
The rotating crack method was utilised to describe RC under monotonic and reversed cyclic stress. The direction of major stresses was utilised as the axis of orthotropy in this model, which is based on modified compression field theory, to compute the material characteristics (MCFT). As a result, as the fracture spins, these axes shift. For anisotropically RC components, where fractures change direction as stress increases, the rotating crack model typically performs better. The criteria for recognizing the stress strain connections get increasingly difficult when more than one curve is required to characterize a specific area of the response under cyclic loading.

Fiber Reinforced Polymers are a type of polymer that is reinforced with fibres. Reinforced concrete has recently garnered a lot of attention as a result of the development of new structural materials. Researchers are studying its behaviour under various stress circumstances. The flexural behaviour of totally and partially prestressed fibre reinforced concrete beams was investigated using a three-dimensional non-linear finite element analysis. The effects of fibres on the failure surface and stress-strain response of high-strength concrete, as well as the non-linear stress-strain curves of prestressing wires and deformed bar, were studied. Tension stiffening and bond slip between concrete and reinforcement are clearly included in the finite element model.

In an experimental environment, the structural response of tension components composed of Glass Fiber Reinforced Polymers Reinforced Concrete (GFRP-RC) was studied. By testing elements under direct tension, the effect of concrete strength, reinforcement ratio, and bar diameter on tension stiffening is studied. For RC components reinforced by FRP plates/sheets, Ferracuti (2005) proposed a tension stiffening rule. For FRP-concrete and steel-concrete interfaces, discrete concrete cracking and non-linear bond-slip laws are explored.

Despite numerous researches into the bond stress-slip connection between reinforcing steel and concrete, due to the various variables involved, there is still a great deal of ambiguity surrounding these complicated phenomena. As a result, most RC finite element analyses exclude reinforcing steel bond-slip, and many experts believe the tension-stiffening model accounts for this effect.

3 Different tension envelopes from literature review

Many material models have been developed for the finite element analysis of reinforced concrete. Some parts of the investigators' models have been judged to be needed, if not vital, for an acceptable solution to a specific problem. A comparison of different models, however, indicates that many of these findings differ (ASCE 1982). Particularly interesting is the use of tension stiffening, or the use of a descending branch on the tensile stress-strain curve, to improve the realism of post-cracking reinforced concrete models and the ductile behaviour after reinforcement yielding. Many tension-softening representations have been proposed in the literature, including continuous, bilinear, trilinear, discontinuous, dugdale, and exponential curvilinear fading models. These falling branch shapes match the true behaviour of concrete to varying degrees. In general, the bilinear model describes the overall shape of the concrete tensile stress-strain curve, while the dugdale model more closely resembles the behaviour of ductile yielding materials, and the exponential curvilinear decaying models show post-yielding ductility.

The use of ascending and descending branches for concrete behaviour under tension is one approach to include tension stiffening into displacement calculations. Various writers have proposed envelopes with
various parameters, some of which are mentioned further down. Figure 1 depicts the various stress envelopes studied in the literature and described here.

![Diagram of stress envelopes](image)

Elmorsi et al. (1998) [21] and said et al. (2004) [22] used a sophisticated yet basic non-linear finite element model for the study of RC structures under monotonic and cyclic loads. This model uses the fixed crack method, which is characterized by its ability to achieve a compromise between simplicity and precision. The concrete tension envelope, which consists of two parts. The first part is before breaking, when the concrete is thought to be linearly elastic, and it is described by Hooke's law as follows:

\[ f_c = E_c \varepsilon_c \]  

1

Because tension stiffening is generated by the interaction of concrete and steel, features of both materials, such as crack spacing, reinforcement ratio, and interface bond transfer, influence its properties. As a result, tension stiffening, strength degradation of concrete, and stiffness in the direction parallel to the fracture are all taken into account in the second phase, which occurs after cracking. The following diagram depicts the relationship:

\[ f_c = f_{cr} (1 - \alpha) e^{-\lambda (\varepsilon_c - \varepsilon_{cr})^{\alpha}} \]  

2

\[ \alpha = 75 (\rho / d_h) \]  

3

The pace at which the response decays is controlled by this parameter. Figure 2 depicts the stress-strain curve as idealized in finite element analysis, as well as the response decay variation with different values of \( \lambda \).
ANSYS, a finite element simulation package offers the William Warnke five parameter concrete model which includes the discontinuous tension stiffening model as represented in Figure 3. As shown in Figure 3, ABAQUS calculates the retained tensile stress normal to the fracture as a function of normal to the crack deformation, resulting in a linear model in the strain softening domain.

4 Concluding Remarks

Despite the vast number of prior research on nonlinear finite element analysis of RC structures, only a few generalizable results have been reached. One example is the incorporation of the consequences of tension stiffening. Because there have been few rational models of this complex topic presented thus far, it is difficult to determine exactly which components of behaviour are incorporated in each research and
what their proportional contributions are. Other areas of the finite element analysis can be approached to similar conclusions. The variety of proposed approaches can lead to the conclusion that the analyst's ability and experience is the main part of the review, and that the suitable model determination is reliant upon the issue to be addressed, regardless of the way that the shifting degrees of refinement of proposed models are every now and again inspired by computational expense contemplations. Perceiving that a considerable lot of the recently proposed models and methodologies presently can't seem to be thoroughly tested, the objective of this examination is to address a portion of the model selection challenges, explicitly according with the impacts of tension-stiffening and stiffness on steel reinforcement post-yielding.

References

[1] Ajimi S, Simon Keerthy M and Bharati Raj J 2022 Residual Life Assessment of Reinforced Concrete Considering Tension Softening Behaviour ed U K G K P E P R A R J Marano G.C. Ray Chaudhuri S. *Lect. Notes Civ. Eng.* 171 305–12

[2] Lakshmi A, Pandit P, Bhagwat Y and Nayak G 2022 A Review on Efficiency of Polypropylene Fiber-Reinforced Concrete ed M S D S V Nandagiri L. Narasimhan M.C. *Lect. Notes Civ. Eng.* 162 799–812

[3] Karaka H K and Tripathi R K 2022 Performance Evaluation of Masonry Infill Walls in Reinforced Concrete Frames Under Cyclic Loading Using Applied Element Method ed U K G K P E P R A R J Marano G.C. Ray Chaudhuri S. *Lect. Notes Civ. Eng.* 171 941–53

[4] Sarkar N and Dasgupta K 2022 Comparative Study of Concrete Models in OpenSEES for Performing Nonlinear Analysis ed U K G K P E P R A R J Marano G.C. Ray Chaudhuri S. *Lect. Notes Civ. Eng.* 171 1135–43

[5] Kollerathu J A 2022 Curvature Ductility of Reinforced Masonry Walls and Reinforced Concrete Walls ed M S D S V Nandagiri L. Narasimhan M.C. *Lect. Notes Civ. Eng.* 162 9–23

[6] Chaitanya Manikanta C, Elavenil S and Vasugi V 2022 Dynamic Analysis of Tall Building with Cross, Diagonal, V Type and Inverted-V Bracing ed U K G K P E P R A R J Marano G.C. Ray Chaudhuri S. *Lect. Notes Civ. Eng.* 171 727–37

[7] Chirdeep N R, Balaji N C, Jain R and Suresh G S 2022 Studies on the Behavior of Gabion Wall Subjected to Lateral Monotonic Loading ed M S D S V Nandagiri L. Narasimhan M.C. *Lect. Notes Civ. Eng.* 162 415–29

[8] Fataar H, Combrinck R and Boshoff W P 2022 An Experimental Study on the Flexural Fatigue Behaviour of Pre-cracked Steel Fibre Reinforced Concrete *RILEM Bookseries* 36 155–65

[9] Peaston C H 2022 Design, Specification and Failure Investigation of Fibre Reinforced Concrete Ground Bearing Industrial Floors and Hardstandings and Pile Suspended Industrial Ground Floors *RILEM Bookseries* 36 690–701

[10] Llano-Torre A, Serna P and Cavalaro S H P 2022 International Round-Robin Test on Creep Behaviour of FRC - Part 2: An Overview of Results and Preliminary Conclusions *RILEM Bookseries* 36 291–306

[11] Soymi O B and Abbas A A 2022 Exploring the Performance of a Single Panel SFRC Slab Under a Point Load with Fe Analysis *RILEM Bookseries* 36 400–8
[12] Coppens E, Van Itterbeeck P, Dooms B, Richir T and Debournonville G 2022 A Fiber Reinforced Concrete for a Nuclear Waste Container *RILEM Bookseries* 36 628–39

[13] Smarzewski P 2022 Property Assessment of Self-compacting Basalt Fiber Reinforced Concrete *RILEM Bookseries* 36 186–97

[14] Cardoso M G, Lameiras R M and Cavalcante I B 2022 Mix Proportioning of Fiber Reinforced Self-compacting Concrete Adopting the Compressible Packaging Method: Comparison of Two Methods *RILEM Bookseries* 36 24–34

[15] Patel D, Pleesudjai C, Yao Y, Schaefer S and Mobasher B 2022 Validation Testing of Precast Tunnel Lining Segments Using Polymeric Fibers *RILEM Bookseries* 36 820–30

[16] Singh D, Kumar V and Kaur M 2019 Single image dehazing using gradient channel prior *Appl. Intell.* 49 4276–93

[17] Gairola P, Gairola S P, Kumar V, Singh K and Dhawan S K 2016 Barium ferrite and graphite integrated with polyaniline as effective shield against electromagnetic interference *Synth. Met.* 221 326–31

[18] Sarowa S, Singh H, Agrawal S and Sohi B S 2018 Design of a novel hybrid intercarrier interference mitigation technique through wavelet implication in an OFDM system *Digit. Commun. Networks* 4 258–63

[19] Kumar S, Kumar M and Handa A 2018 Combating hot corrosion of boiler tubes – A study *Eng. Fail. Anal.* 94 379–95