Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

# RISK-INFORMED PERFORMANCE BASED DESIGN: A COMPARATIVE ANALYSIS OF NONLINEAR CONCRETE MATERIAL MODELS

Parth Patel[1], Abhinav Gupta[2], and Mark Cesare[3]

[1]Structural Engineer, PowerN Inc., Raleigh, NC, USA (parth.patel@powern.ai)
[2]Director, Center for Nuclear Energy Facilities and Structures, NCSU, Raleigh, NC, USA
[3]Research Engineer, FDH Infrastructure Services, Raleigh, NC, USA

## ABSTRACT

Capturing the nonlinear behavior of reinforced concrete (RC) structures continues to be a challenging task, particularly in a nonlinear state of concrete where cracking, crushing, tension stiffening, and damage progression play a major role. For safety-critical infrastructure, where performance-based design is required, it becomes even more important to simulate these effects with a high degree of accuracy. Although a number of material models exist across different finite element (FE) platforms to represent concrete behavior, their predictions can vary widely due to differences in how key parameters are defined and how sensitive those parameters are to the type of loading applied. Consequently, there exits a challenge in achieving consistent and reliable predictions using FE models. This study addresses these challenges through a comparative analysis of three widely used nonlinear concrete models—Concrete Damage Plasticity (CDP), Menetrey-Willam (MW), and Coupled Damage-Plasticity Microplane (CDPMP). The models are used in simulating the laboratory based exepriments conducted on a reinforced concrete beam subjected to a four-point bending test. This comparison works as a benchmark for evaluating cracking behavior, post-cracking stiffness, and rebar yielding. The results highlight the importance of parameter tuning and demonstrate that models incorporating both damage and plasticity offer the closest agreement with experimental behavior.

## INTRODUCTION

ASCE/SEI-43 (2021), seismic design criteria for structures, systems, and components in nuclear facilities, emphasizes a performance-based approach that necessitates the evaluation of inelastic behavior in concrete across multiple limit states. This approach focuses on realistically capturing nonlinear responses, which is critical for assessing structural performance under extreme loading conditions. While these guidelines address the need for accurate inelastic modeling, the inherent quasi-brittle nature of concrete displays complex behavior under such conditions, including brittle fracture in tension and strain hardening or softening, leading to crushing under compression, showing degradation in stiffness, and potential recovery of stiffness (Patel et al., 2021, 2025; Patel, 2023). To simulate these responses, finite element (FE) models often rely on nonlinear material models that attempt to account for complex nonlinear behavior of concrete through varied parameter definitions. However, differences in how the parameter is defined across various FE software and material models often lead to inconsistencies in structural performance predictions. Accurately defining and calibrating these parameters is crucial, as they often display varying behaviors depending on the loading scenario, and reconciliation with experimental data can reveal substantial model-specific discrepancies.

In this study, we conduct a comparative analysis of several prominent material models, including the Concrete Damage Plasticity (CDP), Menetrey-Willam (MW), and Coupled Damage-Plasticity Microplane (CDPMP) models, specifically focusing on their application in simulating the behavior of reinforced concrete (RC) beams under a four-point bending test. By examining the load-deflection response generated using FE analyses, we assess how key parameters for each material model affect the formation of the first crack,

crack progression, post-cracking stiffness, and rebar yielding. Our results reveal notable differences in how these models predict the onset of cracking, crack propagation, and rebar yielding, underscoring the critical importance of model selection and parameter calibration. The study demonstrates that the effects of tension stiffening are particularly significant in achieving accurate predictions of nonlinear responses in concrete, supporting the need for careful calibration of model parameters to improve the reliability of predictive FE simulations in concrete structures.

## CONCRETE MATERIAL MODELS

Numerical simulation of reinforced concrete structures under nonlinear loading requires an accurate representation of concrete's complex inelastic behavior. Several material models have been developed for this purpose, each with distinct approaches to modeling cracking, crushing, stiffness degradation, and recovery. This section outlines three widely used models evaluated in this study: the Concrete Damage Plasticity (CDP) model, the Menetrey-Willam (MW) model, and the Coupled Damage Plasticity Microplane Model (CDPMP). These models differ in their treatment of damage and plasticity and are implemented across different FE platforms.

### *Concrete Damage Plasticity (CDP) Model*

The CDP model is one of the most commonly used constitutive models for simulating nonlinear concrete behavior in ABAQUS (2023). It captures both tensile cracking and compressive crushing using a plasticity-based formulation combined with isotropic damage mechanics. The model assumes non-associated flow and defines inelastic behavior through a combination of stress-strain curves in tension and compression, damage parameters ($d_t$, $d_c$), and key plasticity parameters including dilation angle, flow potential eccentricity, and the ratio of biaxial to uniaxial compressive strength.

Tension stiffening, an important post-cracking phenomenon, is incorporated through a softening stress-strain curve in tension, allowing simulation of gradual stiffness loss after cracking. The CDP model allows independent calibration of tensile and compressive responses and is particularly well-suited for cyclic loading due to its damage accumulation capability.

### *Menetrey Willam (MW) Model*

The MW model is a three-parameter failure surface model formulated to represent the triaxial strength of concrete. It uses a smooth convex failure surface in the Haigh-Westergaard space and accounts for the Lode angle dependency, which enables accurate representation of concrete under a wide range of stress states. However, the MW model does not inherently include damage mechanics, which limits its ability to capture degradation effects such as stiffness reduction or residual deformation under cyclic or repeated loading. In this study, the MW model is used in ANSYS (2023), where its implementation includes both a strength surface and plasticity-based flow rule. Due to the lack of a damage formulation, its accuracy is limited in post-cracking regimes, particularly in cases where tension softening and stiffness degradation are dominant.

### *Coupled Damage Plasticity Microplane (CDPMP) Model*

The CDPMP model, implemented in ANSYS as a user-defined material, extends classical microplane theory by combining damage and plasticity mechanisms at the microstructural level. Concrete is modeled as an aggregate of planes with different orientations, where strain and stress relationships are enforced on each microplane. This allows for a more realistic representation of anisotropy, confinement effects, and

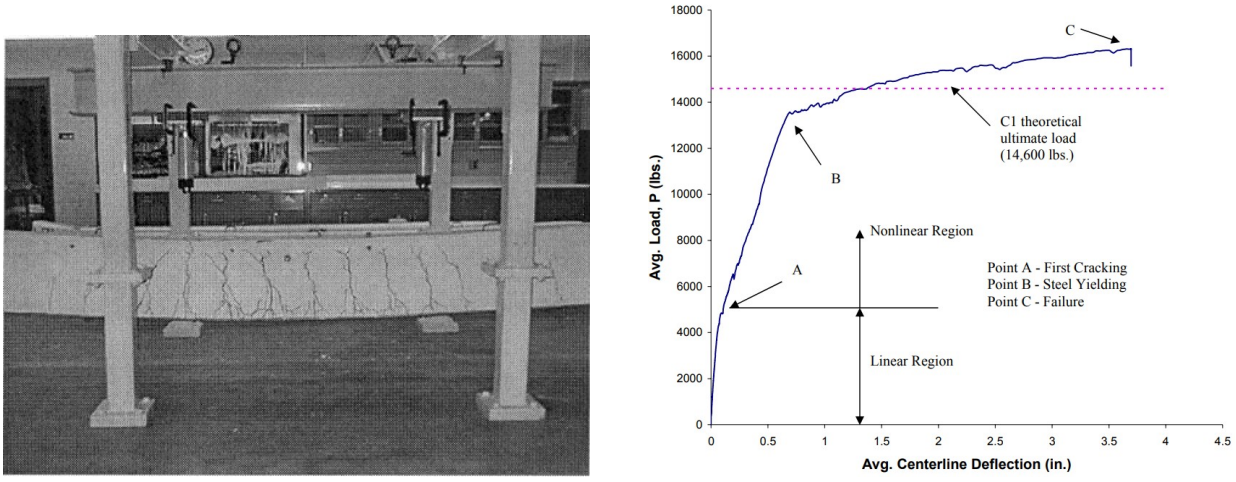
stiffness degradation. The model captures both tensile and compressive damage, including cyclic degradation and stiffness recovery. It is particularly effective in simulating concrete under complex stress states, and the coupling of damage and plasticity enables it to track irreversible deformation along with progressive degradation. The CDPMP model also provides flexibility in incorporating material heterogeneity and is known for its improved accuracy and efficiency when simulating RC structures under both monotonic and cyclic loading conditions.

## 4-POINT REINFORCED CONCRETE BEAM BENDING TEST

To evaluate the accuracy of different nonlinear concrete material models in simulating reinforced concrete (RC) behavior, a four-point bending test is used as the benchmark case. This experimental setup enables detailed observation of flexural response, cracking behavior, rebar yielding, and post-peak stiffness degradation, making it well-suited for validating finite element simulations under controlled loading.

The test specimen, originally documented in the work of Buckhouse (1997), consists of a reinforced concrete beam designed with both longitudinal (flexural) and transverse (shear) reinforcement to reflect realistic structural detailing. The beam is subjected to a monotonically increasing load at two loading points until failure(Figure 1a). This setup ensures a constant moment region between the load points, allowing for focused evaluation of material model performance under flexure-dominated behavior.

The load-deflection response of the beam is recorded throughout the test. As shown in Figure 1b, the curve captures the transition from elastic response to cracking, followed by yielding of the reinforcement and eventual crushing or damage of concrete in the compression zone. The physical cracking and failure pattern observed in the experiment is shown in Figure 1a, providing a visual reference for correlating numerical predictions with actual structural behavior.




(a) Test setup

(b) Load-deflection curve

Figure 1. Reinforced concrete beam in 4-point bending test

## FE SIMULATION OF TEST USING CDP MODEL

To accurately simulate the behavior of the reinforced concrete beam during the four-point bending test, a finite element (FE) model is developed as shown in Figure 2. The concrete beam has dimensions of 180

inches in length, 10 inches in width, and 18 inches in height. The flexural reinforcement consisted of three #5 longitudinal bars, while shear reinforcement is provided by #3 stirrups. In the FE model, the concrete material is represented using 8-node linear brick elements. The element size ranges from 1.5 to 2 inches, ensuring a sufficient level of detail to capture the localized response of the concrete. To simulate the loading conditions of the four-point bending test, loading plates, and support plates are incorporated into the FE model. The midline of the support plate is used to apply the boundary conditions to the beam. Specifically, a pinned connection is employed at one side of the beam, while a roller connection is utilized at the other side. These boundary conditions effectively constrained the beam and allowed for the application of the described loading conditions during the simulation.

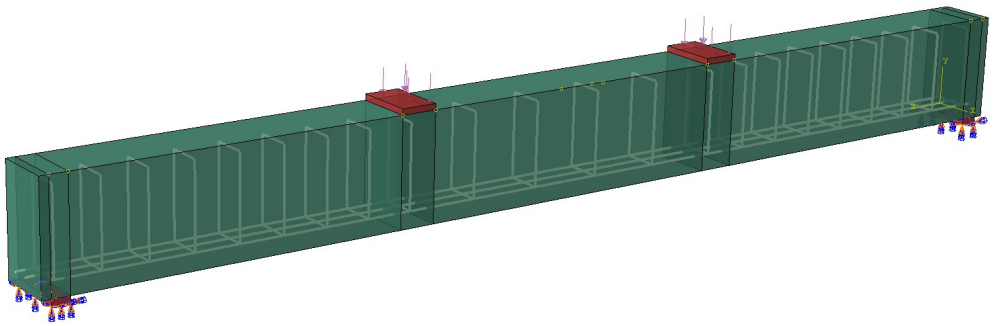


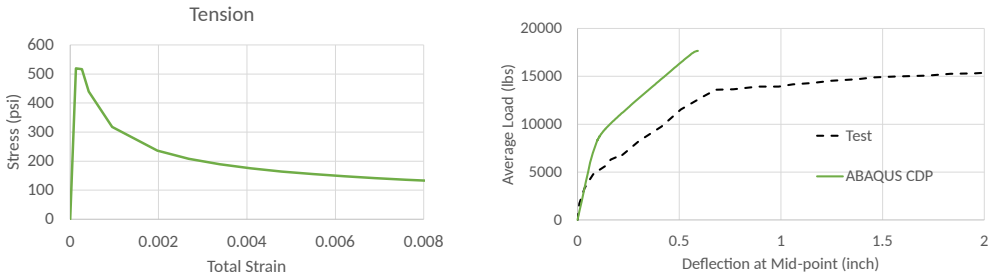
Figure 2. FE model of the beam in 4-point bending test

***Existing Tension Models***

The failed beam from the test shows that the beam cracks due to tension, therefore the behavior and accuracy of beam bending test, and the load-deflection curve will highly depend on the way concrete is defined in the tension. Few existing tension models are used to define the tension behavior of concrete using a concrete damage plasticity model. First, closed-from equations used in the study by Syed and Gupta (2015) are used here to define the tension. If the cracking strain and the maximum tensile strength are known, then the whole stress-strain behavior can be defined in tension using Equation 1. Figure 3a shows the tensile stress-strain behavior generated from closed-form formulations. To define the material behavior of reinforcement, a bilinear curve is used based on yield and ultimate strength of reinforcement.

$$\sigma_t = \begin{cases} f_t & \varepsilon_{cr} \leq \varepsilon_t \leq 2\varepsilon_{cr} \\ f_t \times \left(\dfrac{2\varepsilon_{cr}}{\varepsilon_t}\right)^{0.4} & \varepsilon_t > 2\varepsilon_{cr} \end{cases} \tag{1}$$

Using this tension model, a static nonlinear analysis is executed to simulate a 4-point bending test on the reinforced concrete beam. The applied load and the centerline deflection at the bottom of the beam are extracted at each time step during the analysis. Figure 3b shows the load-deflection behavior from tests and from the simulation. The load-deflection curve exhibits notable differences compared to the actual test results. One significant variation observed is the change in slope, indicating the initiation of cracking, which occurred after 8000 lbs in the FE simulation curve, as opposed to 5000 lbs in the test curve. However, it is noted that the maximum stress in tension reached around 5000 lbs in both the simulation and the test. This observation suggests that up to the point of reaching the maximum tension stress, the FE model accurately captured the behavior of the reinforced concrete beam.

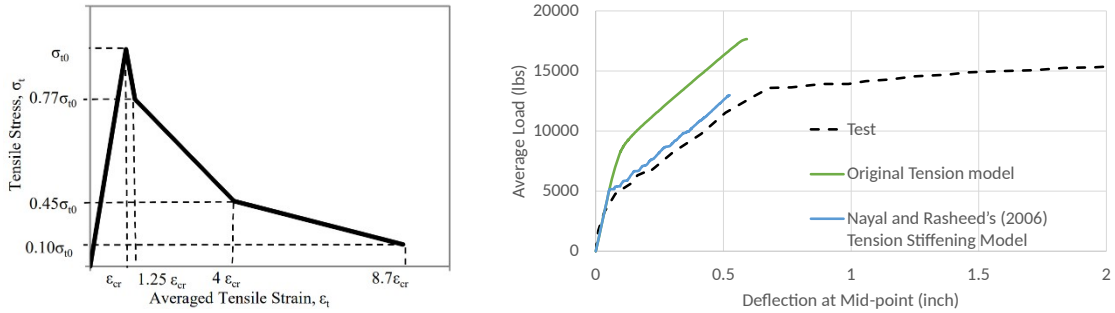



(a) Tensile stress-strain behavior (b) Comparison of load-deflection behavior

Figure 3. FE based Load-deflection behavior comparison

To address the discrepancy in the load-deflection curve after the initiation of cracking, a different tension model is used, which has a steeper drop after reaching the peak tension stress, to refine the simulation and achieve a better correlation with the experimental results. Figure 4a shows Nayal and Rasheed (2006) tension stiffening model.

The results indicate that the simulation curves are able to replicate test behavior well compared to the previous model, as shown in Figure 4b. Despite this adjustment, the test and simulation curves still showed discrepancies. The deviation between the two curves suggests that there are additional factors contributing to the discrepancy between the simulated and experimental behavior of the reinforced concrete beam. Further investigation is required to identify and address these factors, potentially involving modifications to the tension model to influence the overall response of the concrete under bending.




(a) Nayal and Rasheed's (2006) tension stiffening model (b) Comparing new load-deflection behavior

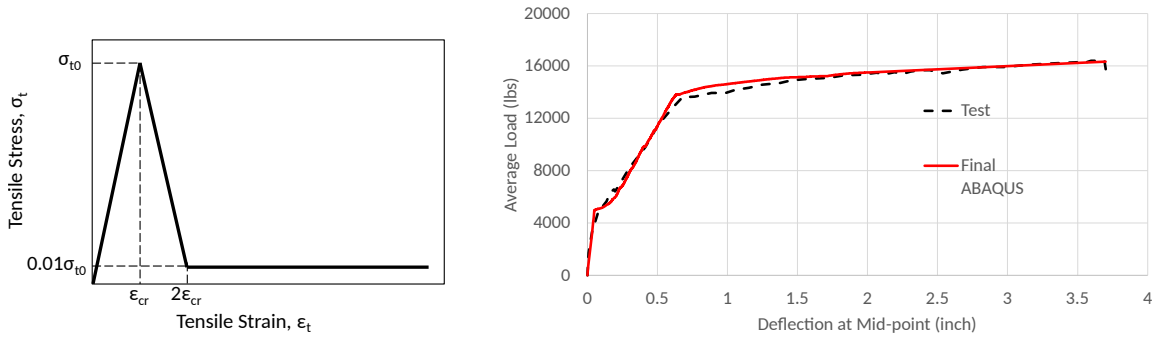
Figure 4. Effect of tension stiffening on load-deflection behavior

### *Proposed Tension Model*

To achieve a more accurate representation of the load-deflection behavior a new tension model is proposed here. The tensile stress-strain curve drops more steeply compared to the previously discussed two models, as shown in Figure 5a. The tensile stress in the proposed model drops to 1% of peak stress at the strain of two times the cracking strain. A steeper drop will help the first crack to initiate sooner compared to previous models. Using this proposed tension model in CDP, the concrete beam 4-point bending analysis is carried out. When the constantly increasing load with each time interval is applied in the model, the analysis experiences a failure in achieving convergence after multiple cracks are formed. To overcome this issue, variable loading rates are used for all three zones of analysis. For the linear elastic zone, a loading rate of 4500 lbs/s is used.

Before the start of the first crack, this loading rate is reduced to 2800 lbs/s till the point of steel yielding. After the steel yields, the deflection increases significantly, even after applying a relatively smaller increase in load. Therefore, for the final phase of the analysis, the loading rates in the range of 25 to 100 lbs/s are used.

Figure 5b shows the load-deflection behavior captured during the analysis. It can be clearly observed from the figure that the use of the proposed tension model is able to create the concrete beam behavior very close to the test behavior. All three phases of the concrete beam bending, 1) elastic region, 2) behavior after crack initiation, and 3) behavior after steel yielding, are accurately captured with the FE analysis.

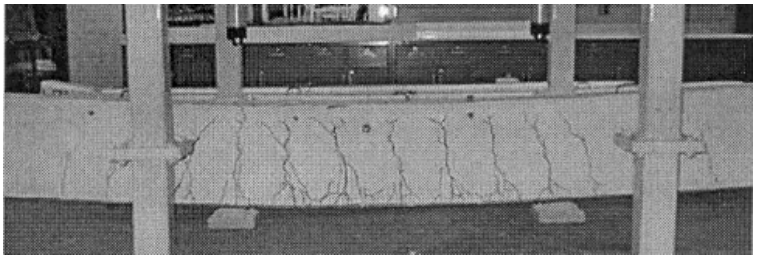



(a) New tension stiffening model

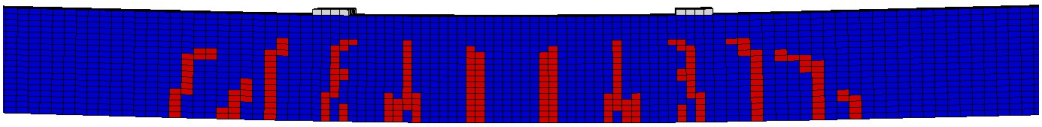
(b) Comparing new load-deflection behavior

Figure 5. Effect of new tension stiffening model on load-deflection behavior

In the context of the finite element (FE) analysis using the Concrete Damage Plasticity (CDP) model, cracks are identified based on the tensile damage at each element. During the simulation, elements undergo stiffness degradation according to the defined stress-strain and damage behavior. This degradation is visualized through the tensile damage parameter, in Figure 6b, blue indicates undamaged elements and red indicates fully damaged elements. These fully damaged elements in tension are interpreted as tensile cracks in the concrete. In addition to comparing the load-deflection curves, the cracks formed in concrete while the test simulation is also compared as shown in Figure 6. The cracks shown from the FE analysis in red color show a good representation of the cracks formed during the experiment. This even includes relatively vertical cracks towards the middle of the beam compared to diagonal cracks formed as we go far from the center.



(a) Cracked beam from bending test



(b) Cracks from the FE simulation

Figure 6. Comparison of the damage from test and FE model

## USING OTHER CONCRETE MODELS TO SIMULATE TEST

### *Menetrey-Willam Model*

A similar reinforced concrete beam is modeled in FE software ANSYS to evaluate the capability of other concrete models in capturing an accurate bending behavior as showed in the previous section using the CDP model. To achieve this task, first a MW concrete model is used to define concrete behavior.

Based on the known stress-strain data and other material properties discussed in the previous section, the parameters are generated for the MW concrete model. To define the tension behavior using the MW concrete model, two models are used to compare the simulation results: 1) closed from equations used in the study by Syed and Gupta (2015), and 2) the proposed tension model. With the variable loading rates, the non-linear static analysis is conducted for the concrete beam bending. Figure 7 shows the comparison of load-deflection behavior observed from using the MW concrete model with two different tension models and compares it with the load-deflection curve from the test. As seen in load-deflection behavior using the CDP model, the proposed tension model provides a closer representation of test behavior compared to the tension model from closed-form equations. However, in general, the comparison of the test and simulation curves is better when the CDP model is used compared to the MW model in ANSYS.

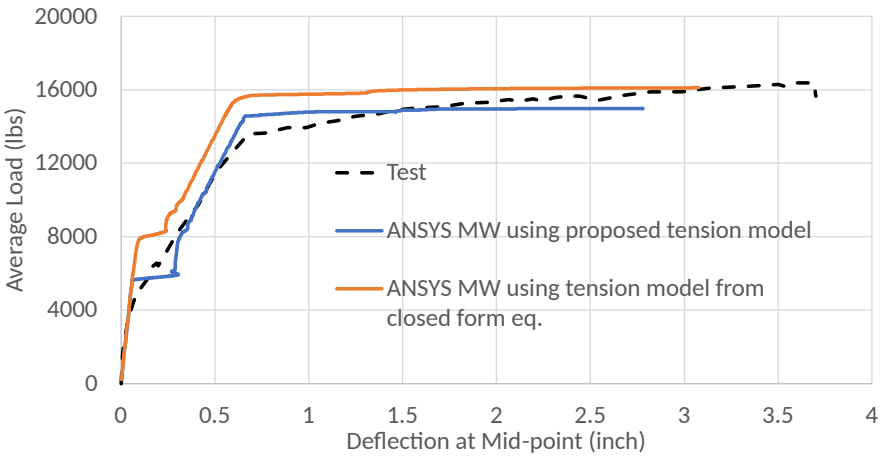


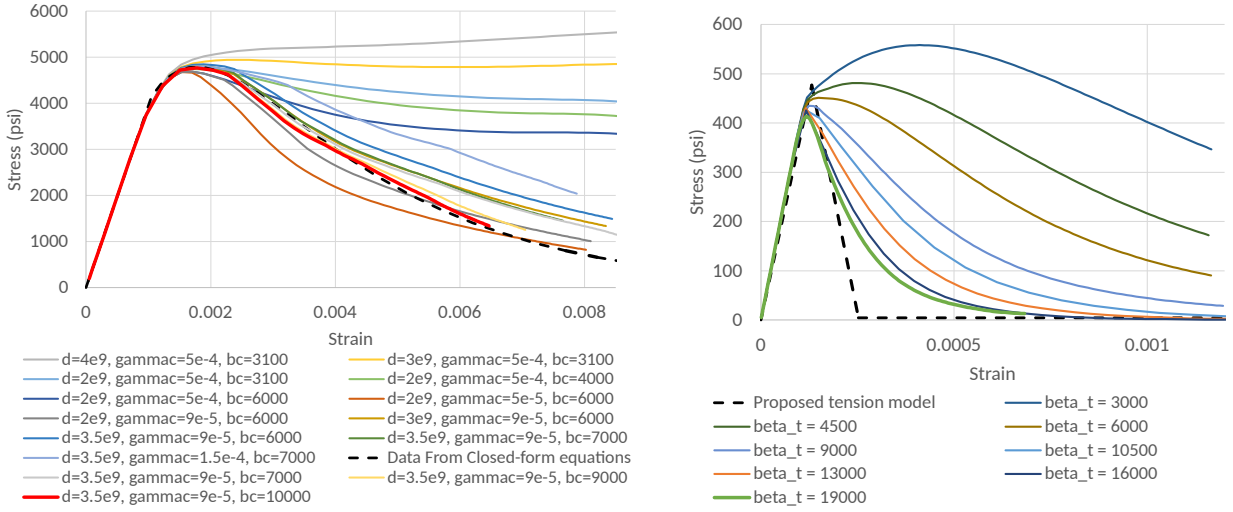

Figure 7. Comparing load-deflection behavior using MW model

### *Coupled Damage-Plasticity Micro-plane Model*

To achieve a better representation of test curves using ANASYS models, the CDPMP model is explored for defining concrete behavior. As discussed previously, the CDPMP model couples damage and plasticity to define concrete behavior, unlike the MW model, where damage is not present. Therefore, potentially, it can be able to provide closer simulation results to the experiments compared to the MW model. To test this hypothesis, the first task is to define the parameters for the CDPMP model to represent the concrete properties of the beam.

Zreid and Kaliske (2018) shows that the CDPMP model has various sensitive parameters that need to be calibrated based on the stress-strain curves of concrete in tension and compression. With sensitivity studies on parameters, it is found that four parameters affect the inelastic stress-strain behavior and, therefore, the load-deflection behavior, Compressive hardening constant ($D$), compressive damage threshold ($\gamma_c$), tension and compression damage evolution ($\beta_t$ & $\beta_c$). To achieve calibrated parameters for conducting this analysis,

a parametric study is carried out for various values of sensitive parameters to make the stress-strain curve generated from a unit cube test converge to the target stress-strain curves. The proposed tension model is used as the target response for tensile behavior. The Figure 8 shows the compressive and tensile stress-strain curves generated for various values of sensitive parameters for the parametric study.




(a) Compressive behavior

(b) Tensile behavior

Figure 8. Parametric study for evaluating CDPMP parameters

Using the calibrated parameters for the CDPMP model, the non-linear static analysis with a variable loading rate is conducted. Figure 9 shows the comparison of the load-deflection curve generated from the FE simulation and the experiment. It can be clearly observed that the CDPMP model is able to achieve a close representation of experimental load-deflection behavior with the use of the proposed tension model. One noticeable difference is the plateau seen in the simulation curve around 7500 lbs. This seems to happen because, in the CDPMP model, the first tensile crack forms around 7500 lbs, whereas in the test, it starts closer to 5000 lbs. This delay is likely due to how the microplane model works, where the damage spreads over multiple orientations before a significant crack shows up. As soon as the first crack initiates, the deflection jumps up with a small increase in load, which causes that flat section in the curve. After that, the model does a good job replicating the test behavior, especially in how the cracks progress and how the rebar starts yielding. In addition to the close representation of test curves, the CDPMP model provides much faster analysis time compared to the MW model and CDP model.

It is observed that the curve generated using the CDP model achieves the closest representation of the test curve. In addition, the curve from CDPMP does provide a very close curve to the test plot. However, the use of the CDP model in ABAQUS and the MW model in ANSYS takes 6-8 hours of analysis time to conduct this analysis compared to only 2 hours in the case of the CDPMP model. Hence, the CDPMP model is the most efficient concrete model among the tested models in this study providing close behavior to that of the experiment.

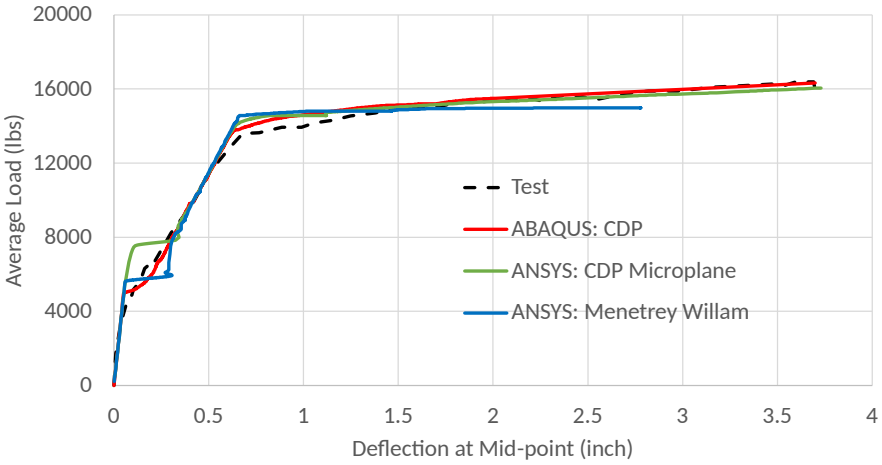



Figure 9. Comparing load-deflection behavior using Coupled Damage-Plasticity Micro-plane model

## CONCLUSION

This study presents a comparative evaluation of nonlinear concrete material models for simulating reinforced concrete beam behavior under four-point bending. Building on the need for accurate inelastic modeling in performance-based seismic design, the analysis focused on how different models capture critical behaviors such as cracking, post-cracking stiffness, and rebar yielding. A proposed tension stiffening model is introduced to improve alignment between simulation and experimental results. The study highlights the strengths and limitations of each material model and provides guidance on selecting appropriate models for reliable and efficient finite element analysis. Some key conclusions from this study are:

- FE simulation of 4-point beam bending test showed the use of existing tension models does not provide close load-deflection behavior to the experimental curve. However, the proposed tension model can help to achieve accurate load-deflection behavior.
- It is observed that the use of the MW model for simulating the beam bending test does not end up in a good representation of load-deflection behavior. This is potentially due to the absence of damage in the MW model definition.
- CDP model shows the best comparison of load-deflection curve to the test curves, however the CDPMP also gives good comparison while allowing simulation to be conducted in only a fraction of computational time compared to all other models.

## REFERENCES

ABAQUS (2023). *ABAQUS/CAE User's Manual*. Dassault Systèmes Simulia Corp.

ANSYS, I. (2023). *ANSYS mechanical APDL material reference*.

ASCE/SEI-43 (2021). *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*. American Society of Civil Engineers, doi:10.1061/9780784415405.

Buckhouse, E. R. (1997). "External flexural reinforcement of existing reinforced concrete beams using bolted steel channels."

Nayal, R. and Rasheed, H. A. (2006). "Tension stiffening model for concrete beams reinforced with steel and FRP bars." *Journal of materials in civil engineering*, 18(6), pp. 831–841.

Patel, P., Bodda, S. S. and Gupta, A. (2021). "Modeling the behavior of reinforced concrete slabs subjected to impact." *Nuclear Engineering and Design*, 385, p. 111512.

Patel, P., Gupta, A., Bodda, S. S. and Sandhu, H. K. (2025). "Physics-trained artificial intelligence framework to detect chloride induced degradation in concrete." *Journal of Infrastructure Intelligence and Resilience*, p. 100139.

Patel, P. A. (2023). *Simulating Damage and Degradation in Concrete Structures*. North Carolina State University.

Syed, S. and Gupta, A. (2015). "Seismic fragility of RC shear walls in nuclear power plant part 1: characterization of uncertainty in concrete constitutive model." *Nuclear Engineering and Design*, 295, pp. 576–586.

Zreid, I. and Kaliske, M. (2018). "A gradient enhanced plasticity–damage microplane model for concrete." *Computational Mechanics*, 62(5), pp. 1239–1257.