IN-LB	Inch-Pound Units
SI	International System of Units

Nonlinear Finite Element Analysis of Reinforced Concrete Beams, Columns, and Beam-Column Joints—Guide

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Using finite element (FE) analysis to model the nonlinear behavior of reinforced concrete can range from relatively simple, phenomenological approaches to highly complex, micromechanics-based models. The choice of approach depends on the desired accuracy, the scale of the analysis, expertise of the analyst, and computational resources. Plastic hinge models, typically used in pushover or nonlinear time-history analyses for global response prediction introduce basic nonlinearity for line-type elements but often fall short in numerous applications, including evaluating the performance or safety of structures; analyzing deep beams and disturbed regions; assessing distress in existing structures; and predicting crack patterns, crack widths, and deflections. In these cases, two-dimensional (2-D) or three-dimensional (3-D) continuum FE methods offer greater advantages. This guide focuses on nonlinear continuum FE methods, which introduce moderate to high levels of nonlinearity. Developed for practicing engineers, the guide aims to balance theory with practical applications, covering modeling approaches for key material aspects for cracked concrete (including mesh effects and regularization) and reinforcing steel (including stress-strain response, buckling, and bond slip), followed by practical guidance on continuum modeling of beams, columns, and beam-column joints.

Keywords: assessment; bond slip; buckling; continuum; cracking; distress; finite element (FE); mesh; nonlinear; regularization.

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CHAPTER 1—INTRODUCTION AND SCOPE

This guide provides an overview of concepts and techniques related to the nonlinear finite element (FE) analysis of reinforced concrete beams, columns, and beam-column joints. It aims to offer a multifaceted and impartial representation of the current modeling methods, acknowledging the presence of alternative approaches. This guide is developed for practicing engineers familiar with linear elastic FE analysis and plastic hinge models who want to advance their knowledge in the nonlinear modeling and assessment of beams, columns, and beam-column joints. Researchers and students interested in this subject will also find it a valuable resource. Readers will gain a well-rounded perspective that balances theoretical aspects and applicability to most commercial FE modeling software. The focus on beams, columns, and beam-column joints, subjected to static load conditions, is driven by their critical role in many types of reinforced concrete structures and the challenges associated with their behavior after cracking.

Modeling the nonlinear behavior of concrete in FE analysis ranges from relatively simple, phenomenological approaches to highly complex, micromechanics-based models (Fig. 1). The choice depends heavily on the desired accuracy, the scale of the analysis, expertise of the analyst, and computational resources. While linear elastic FE analysis (Level 1) is a practical starting point for designing new structures, it does not provide accurate representation of reinforced concrete once cracking or yielding develops, or under high compression. Plastic hinge models (Level 2), typically used in push-over or nonlinear time-history analyses for global response prediction, introduce basic nonlinearity for line-type elements but often fall short in many applications, including evaluating the performance or safety of structures, analyzing deep beams and disturbed regions (where the stress distribution is nonlinear and deviates significantly from the traditional beam theory), assessing distress in existing structures, and predicting crack patterns, crack widths, and deflections. In these cases, two-dimensional (2-D) or three-dimensional (3-D) continuum FE methods offer greater advantages.

This guide focuses on nonlinear continuum FE methods (Levels 3 and 4), which introduce moderate to high levels of nonlinearity. Chapter 3 presents modeling approaches for concrete, including the representation of cracked concrete, response under tension and compression, spurious mesh size effects and regularization, and modeling of cracks. Chapter 4 presents modeling approaches for reinforcing steel, including stress-strain response, buckling, bond-slip deformations, and strain penetration. Chapter 5 provides guidance on continuum modeling of beams, columns, and beam-column joints, including selection of FE types, representation of boundary conditions, application of loads, and definition of analysis parameters. Chapter 6 provides a summary.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A = cross-sectional area, in.^{2} (mm^2)
b = stiffness reduction factor
c_{clear} = clear spacing between bar ribs, in. (mm)
c_t = tension stiffening coefficient
d_a = maximum aggregate size, in. (mm)
d_b = diameter of reinforcing bar, in. (mm)
d_{bi} = diameter of i-th reinforcement component, in. (mm)
E_c = initial tangent stiffness of concrete, psi (MPa)
f_c = stress of concrete at point along stress-strain curve, psi (MPa)
f_c' = concrete cylinder uniaxial compressive strength, specified compressive strength of concrete, psi (MPa)
f_{c1} = principal concrete stress in direction 1, psi (MPa)
$f_{c1,ave}$ = average tensile stress of concrete due to tension stiffening, psi (MPa)
f_{c2} = principal concrete stress in direction 2, psi (MPa)

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