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Calibrated analytical element for lateral-strength degradation of reinforced concrete columns

M.R. LeBorgne [a], W.M. Ghannoum [b,*]

[a] Chevron, 333 Clay Street, Houston, TX 77002, United States
[b] Dept. of Civil, Architectural, and Environmental Engineering, University of Texas at Austin, 301 E. Dean Keeton St. STOP C1700, Austin, TX 78712, United States

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ABSTRACT

An analytical element is proposed to simulate the cyclic nonlinear lateral-strength behavior of reinforced concrete columns. The element possesses a unique and novel combination of functionalities that allow increased accuracy of simulation as well as ease of use. Key functionalities are: (1) the ability to simulate cyclic as well as in-cycle strength degradation including hysteretic pinching and damage accumulation, (2) the ability to monitor column boundary condition and adjust behavior accordingly, (3) full calibration to a dataset of column tests allowing users to only define column material and geometric properties for the element to automatically determine all cyclic behavior parameters. Parameters of the material model governing the element were related through regression analyses to predictor variables to arrive at governing relations for the parameters. In the process of calibrating model parameters, correlations were uncovered that provide insight into mechanisms that affect column cyclic lateral-strength. The proposed element and material model were calibrated to simulate the seismic behavior of lightly confined reinforced concrete columns that experience flexural yielding prior to sustaining lateral-strength degradation through a shear failure mechanism. Calibration to other column types is the subject of future work.

1. Introduction

Engineers evaluating the performance of reinforced concrete (RC) structures under seismic excitation are increasingly resorting to nonlinear dynamic analyses. This is particularly the case when structures are pushed to large inelastic deformations and near collapse damage states. In such cases, simplified linear or static analysis methods struggle to capture the consequences of strength loss in critical elements, be it on structural stability or load redistribution to adjacent elements.

When developing analytical models for nonlinear dynamic analyses of reinforced concrete structures, engineers are currently faced with a difficult task. While guidance on modeling the elastic behavior of members can be found in many documents and standards (e.g., ACI 318-11 [1]; ASCE 41-06 [2,3]), it is very limited regarding the modeling of nonlinear and degrading behaviors. More often than not, no recommendations can be found regarding modeling the behavior of structural elements at large deformations, leaving engineers to either, directly infer modeling parameters from experimental evidence, which is impractical in most cases, or neglect strength degradation in analyses.

The proposed analytical element was developed with two overarching objectives in mind: (1) improve accuracy of nonlinear simulations of RC structures through a tool that is capable of simulating the cyclic degrading behavior of RC columns up to complete loss of lateral strength, and (2) facilitate the use of nonlinear dynamic analyses for concrete columns by offering a tool that only requires users to input column material and geometric properties to automatically calculate all necessary modeling parameters.

Several analytical models are available in the literature to aid engineers in simulating the nonlinear lateral-strength behavior of reinforced concrete columns. Most available models however only define the critical point at which lateral strength begins to degrade. Such models define the critical point through either a limiting lateral strength or limiting deformations (e.g., [4–14]). Some models also define the negative lateral-stiffness slope that ensues once lateral-strength begins to degrade in a column (e.g., [14–17]). Only one model, other than the one proposed, defines parameters necessary to simulate the lateral cycling behavior of concrete columns [16]. In the latter model however, all model parameters are fixed at the model building phase. Thus, that model does not adjust behavior during analyses to account for varying boundary

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* Corresponding author.
E-mail addresses: mattleborgne@gmail.com (M.R. LeBorgne), ghannoum@mail.utexas.edu (W.M. Ghannoum).

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Nomenclature

a	shear span
A_{cc}	area of column core to outer edge of confining reinforcement
A_g	column gross section area
A_v	transverse reinforcement area at spacing s in the direction of loading
b	column section width
d	effective depth measured from extreme compression face to centroid of outermost layer of tension steel
d_b	diameter of longitudinal bars
dmgRCyc	cyclic reloading stiffness damage parameter
dmgSCyc	cyclic strength damage parameter
E_c	elastic modulus of concrete = $57{,}000\sqrt{f'_c}$ (psi units) = $4750\sqrt{f'_c}$ (MPa units)
f'_c	concrete compressive strength
f_{yL}	yield stress of longitudinal steel
f_{yt}	yield stress of transverse steel
G	section shear modulus
h	section height in direction of loading
K_{deg}	shear-spring backbone degrading slope
$K_{elastic}$	shear-spring elastic slope
l_d	longitudinal bar development length as per ACI 318-11 equation 12-1
L	column clear length
M	applied moment at column end
N_u	applied axial load for use in ASCE 41-06 shear-strength equation (positive in compression, =0 for tension forces)
p	p-value of the F-statistic
P	applied axial load (positive in compression)
r	Pearson product-moment correlation coefficient
R^2	coefficient of determination for regression models
s	spacing of transverse reinforcement
v	applied shear stress at peak shear = $V_{sf}/(b * d)$
V	applied shear to column
V_r	shear-spring residual strength
V_{sf}	force in shear spring at initiation of lateral-strength degradation (Fig. 10)
XpinchR	reloading X-axis pinching factor = fraction of the deformation at the unloading point. The addition of *NP* signifies the negative-to-positive loading direction and *PN* the positive-to-negative loading direction
YpinchR	reloading Y-axis pinching factor = fraction of the load at the unloading point. The addition of *NP* signifies the negative-to-positive loading direction and *PN* the positive-to-negative loading direction
YpinchU	unloading Y-axis pinching factor = fraction of the load at the unloading point. The addition of *NP* signifies the negative-to-positive loading direction and *PN* the positive-to-negative loading direction
Δ_r	load-axis intercept of the shear-spring backbone negative slope (Fig. 10)
Δ_{sf}	deformation in shear spring at initiation of lateral-strength degradation (Fig. 10)
λ	lightweight concrete factor in the ASCE 41-06 shear-strength equation; taken as unity in the proposed implementation
μ	concrete Poisson ratio
ρ_L	longitudinal reinforcement ratio = A_s/A_g (A_s = area of longitudinal steel, A_g = column gross section area = $b * h$)
ρ_t	transverse reinforcement ratio = area of transverse reinforcements in direction of loading/$(b * s)$
θ_f	limit rotation across the plastic hinge region (including bar-slip rotations) at initiation of lateral-strength degradation

conditions, which have been shown to vary significantly on columns in building structures subjected to seismic motions [18].

The proposed element was developed with versatile and novel functionality to allow the simulation of in-cycle as well as cyclic degradation [19], while being able to adapt to varying column boundary conditions during analyses; notably axial load, the ratio of shear to moment, and plastic rotations [20]. The proposed lateral-strength degradation element consists of a zero-length shear spring that is placed in series with flexural frame elements to simulate the seismic behavior of a column member (Fig. 1). A shear-spring implementation was chosen for its computational efficiency and compatibility with the commonly used line-element analytical approach. A nonlinear degrading material model governs the behavior of the spring, while a degradation trigger monitors key boundary conditions for critical combinations of forces and deformations to initiate lateral-strength degradation in the element. As such, the proposed element addresses the following main shortcomings of available shear-spring models: (1) it has the ability to continually monitor forces and deformations in the flexural elements for conditions that trigger lateral-strength degradation, (2) it is able to trigger lateral-strength degradation through either a limiting lateral force or element deformation (whichever is reached first), and (3) it has a built-in function that compensates for flexural deformation offsets that arise from the degrading behavior of the shear spring. The proposed element also introduces damage algorithms to control the cyclic degrading behavior through pinching, reloading stiffness degradation, and strength degradation (Fig. 2).

The proposed element is implemented and ready to use in the open sources analytical software OpenSEES [21]. The element is available in OpenSEES in two variations. The first variation consists of a non-calibrated element that allows users to specify all element parameters manually and is described in detail in [20,22]. The second variation, which is discussed here, consists of a calibrated element that can evaluate all parameters automatically. For the calibrated element, all parameters were calibrated to a database of reinforced concrete column tests. Statistical analyses were conducted using test results to relate the parameters governing the behavior of the element to column geometry, reinforcing details, material properties, as well as column deformations and forces. Using the developed statistical relations, the element is capable of calculating all parameters necessary to simulate the complete nonlinear cyclic degrading behavior of reinforced concrete columns; while only requiring users to input column material and geometric properties.

The proposed element was calibrated to simulate the seismic behavior of lightly confined reinforced concrete columns, as their presence can lead to a significant increase in the risk of structural collapse during earthquakes [23]. More specifically, the element was calibrated to a class of lightly confined reinforced concrete columns that experience flexural yielding prior to sustaining lateral-strength degradation through a shear failure mechanism (herein referred to as flexure-shear critical (FSC) columns). FSC columns can be critical to the stability of a structure. They can sustain severe lateral-strength degradation that results in large force redistributions to adjacent elements, in changes to the dynamics of a