

SENSITIVITY TO MATERIAL MODELING CHOICES IN SEISMIC DEMAND ESTIMATION FOR REINFORCED CONCRETE FRAMES

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ABSTRACT:

This paper examines the sensitivity of computed seismic system demands to modeling choices made at the material level. Accurate constitutive models of the constituent materials in a reinforced concrete (RC) section, namely, unconfined concrete, confined concrete and reinforcing steel are necessary for direct use in fiber-section discretization of RC components. The characteristics of the cyclic constitutive model can also directly influence the efficiency and accuracy of the element model used in the analysis. An additional aspect of modeling sensitivity resulting from ground motion characteristics, in the context of material model sensitivity, is also explored in the study. A series of numerical simulations of a typical ductile RC frame building is conducted with a view to gaining additional insight into response sensitivity resulting from modeling choices at the material level. Results of the simulations indicate that proper choice of parameters representing the behavior of confined concrete and the post-elastic behavior of reinforcing steel can influence the computed inelastic response of RC structural systems.

KEYWORDS: confined concrete; constitutive models; reinforcing steel; seismic response

1. INTRODUCTION

The need for improved analytical tools to predict the inelastic response of reinforced concrete (RC) structures for performance-based seismic evaluation have led to advances in modeling the inelastic behavior of RC components. Fiber-based discretization of a section is one such advancement that permits consideration of dynamic axial force-moment interaction. Since the response of the element based on fiber discretization of the cross-section is controlled primarily by section behavior, two issues need to be dealt with to ensure a reliable response: modeling of the constitutive behavior of the constituent materials and integration of the section deformations to yield component deformations. The latter aspect of fiber-section modeling is beyond the scope of this paper. The focus of this study is on the relevance and significance of constitutive modeling in the overall scheme of nonlinear response prediction of RC structures using section-based element discretization. Some work has been undertaken to examine the sensitivity of hysteretic models on seismic demands (Lee et al. 1999, Riddell et al. 2002). However, very few researchers have carefully examined the consequences of using different constitutive models in nonlinear simulations wherein the element model is based on a sectional discretization. A systematic analytical study was therefore carried out to examine the significance of constitutive models in the context of inelastic response prediction of RC structures.

2. CONSTITUTIVE MODELS

An elemental cross-section in an RC member is composed of three types of materials: unconfined concrete, confined concrete and reinforcing steel. All reinforced concrete components are detailed with transverse steel which provide both shear resistance and confining action. The confining effects of transverse steel are

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considered implicitly by modifying the stress-strain response of the core concrete. Numerous researchers have developed stress-strain models of confined concrete based on observed experimental behavior. The concrete cover will typically spall at relatively small strain levels therefore the modeling of unconfined concrete is generally not critical for damage limit states in the inelastic range. The response of RC components and consequently the system is a function of the behavior of the confined core and the longitudinal steel. In the case of non-ductile sections, the response of the core will be only marginally different from the response of the cover concrete. Hence this study will focus primarily on structures with ductile detailing.

2.1. Confined concrete modeling

Confinement models have been developed by numerous researchers to describe the stress-strain behavior of concrete as a function of certain key parameters that are related to the amount and type of transverse reinforcement. Given the large number of confined concrete models in the literature, only two representative models were selected for this study. The first is the widely used and often referenced model for predicting the strength of confined concrete proposed by Mander et al. (1988):

$$\frac{f_{cc}'}{f_{co}'} = 2.254 \sqrt{1 + 7.94 \frac{f_L}{f_{co}'}} - 2 \frac{f_L}{f_{co}'} - 1.254$$
(2.1)

where f'_{cc} is the maximum strength of the confined concrete, f'_{co} is the corresponding unconfined strength, f_L is the effective lateral confining pressure. The constants that appear in the Eqn. (2.1) were obtained from empirical calibration of experimental data. The second confinement model considered in the study is taken from Hoshikuma et al. (1997):

$$\frac{f_{cc}'}{f_{co}'} = \begin{cases} 1.0 + 3.83 \frac{\rho_s f_{yh}}{f_{co}'} - circular \ section \\ 1.0 + 0.73 \frac{\rho_s f_{yh}}{f_{co}'} - square \ section \end{cases}$$
(2.2)

In the above expression, ρ_s and f_{yh} are the volumetric ratio and yield strength of the hoop reinforcement, respectively. The only remaining parameter of significance to complete the confinement model is a description of the failure (crushing) strain in compression. Of some relevance also is the post-peak response of the material. Though several equations have been proposed for the descending portion of the stress-strain curve, a linear approximation is generally adequate. Though Mander's stress-strain equation is valid in the softening region, a linear relationship is used in this study due to the limitation of the concrete constitutive model used in the nonlinear simulations.

For the purpose of this study, a similar form of the stress-strain curve is used for both unconfined and confined concrete (Figure 1a) characterized by an initial ascending branch up to the maximum compressive strength, f'_c (which is either f'_{co} or f'_{cc} depending on whether unconfined or confined concrete properties are used) followed by a linear descending branch up to the residual strength. It is also the base concrete model implemented in OpenSEES (2008), the nonlinear simulation platform used in the analytical studies reported herein. Also, the computed stress-strain curves, using the confined models described above, for a typical column and a typical beam for the case study presented later in this paper are plotted in Figures 1b and 1c.





Figure 1 Modeling of unconfined and confined concrete

(a) General stress-stain model; and computed confined properties for (b) typical column; (c) typical beam

2.2. Modeling of reinforcing steel bars

A review of the literature on nonlinear modeling of reinforced concrete structures using refined fiber-section discretization reveal that little attention has been paid to detailed or refined models for reinforcing steel. Typically, an elastic-perfectly-plastic or bilinear model is used to represent the stress-strain response of the main longitudinal steel bars. In this investigation, three material models are considered: a simple bilinear (referred to as Steel01 in this paper) model (Figure 2a), a smooth formulation (referred to as Steel02) with control parameters to specify hardening (not shown in Figure), and a more refined model (Figure 2b) referred to as "Reinforcing Steel" (RS) - all three models are available in OpenSEES (2008). The BL model is characterized by an initial elastic modulus, E_s , a yield stress, f_y , and a post-yield modulus defined by the strain hardening

parameter, b, as shown in Figure 2b. For cyclic loading, the elastic modulus is used for unloading and reloading. Model Steel02 is similar to the bilinear model but allows a smooth transition from elastic to inelastic state using the well-known Menegotto-Pinto (1973) model. Additionally, the control parameters for hardening can be assigned negative values to induce softening. On the other hand, the Reinforcing Steel model represents an advanced model with features to characterize complex degrading effects. The backbone curve of the RS model is developed from the base model proposed by Chang and Mander (1994) and includes a yield plateau and strain hardening. The model also includes parameters to consider strength degradation and buckling. The parameter controlling strength degradation behavior can be calibrated to the well-known Coffin-Manson coefficients (Kunnath, Heo, and Mohle 2009). A qualitative description of the model showing both degradation and buckling is depicted in Figure 2b.



Figure 2 Cyclic stress-strain response for reinforcing steel (a) Steel01 model; (b) Reinforcing steel model



3. SIMULATION OF SYSTEM RESPONSE

The sensitivity of constitutive models is investigated at the system level by considering the seismic evaluation of a twelve-story moment-resisting RC frame. The frame was designed to meet the requirements of IBC-2000 in a region of high seismicity. Essential details on the frame configuration including reinforcement details are listed in Table 1. While there may be other factors that also contribute to the sensitivity of the response, the results presented here are primarily those resulting from sensitivity to material modeling.

3.1. Simulation Models

The numerical simulations of the dynamic response of the frame to seismic loads were carried out using the open-source computational platform, OpenSEES (2008). A reinforced concrete member is modeled as an inelastic beam-column element with distributed plasticity. The concrete section was discretized into 3 fibers in each cover region and uniform fibers of 10 mm in the confined core region. The cover concrete was modeled using unconfined properties while the core concrete was modeled with properties obtained from the different confinement models presented previously. The behavior of the reinforcing steel in the section was modeled with the three different material models discussed in Section 2.2.

		<u>الم</u>				Column	•		Beam	
				Story	Section	Reinforcement		Section	Reinforcement	
				1	20, 20	Long.	24#11	28,21	Long.	18#10
		×		1	38×38	Trans.	#3@4	38×34	Trans.	#3@9
		~~		2-4	38×38	Long.	24#11	38×34	Long.	20#10
	L,	,,J L				Trans.	#3@4		Trans.	#3@9
				57	24~24	Long.	20#10	2422	Long.	18#10
		×۲		5-7	54 × 54	Trans.	#3@4	54×52	Trans.	#3@8.5
				9 10	32×32	Long.	16#10	32×32	Long.	18#9
	777777	7/////	777777	8-10		Trans.	#3@4		Trans.	#3@8
5 bays with bay width of 24 ft Story Height of 12 ft			11-12	28×24	Long.	16#8	28×24	Long.	20#8	
					Trans.	#3@4		Trans.	#3@7	

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Table 3 I Configuration and	i reinforcement i	derails of renre	esentative mil	Instory trame
		uctuins of repre	countair ve mu	motory mame

3.2 Results of numerical study

A number of simulations were carried out using numerous earthquake records and only a relevant set of results highlighting the general findings of the investigation is described herein. Table 3.1 presents the essential details of all the selected records used in the study. In order to induce significant inelastic action in the frame, each record was scaled to produce roof drifts on the order of about 2%. The final scale factors are also provided in the table. In each simulation, a different combination of concrete and steel material model was considered – therefore, for each record, a set of nine simulations were carried out. Additional simulations were required when comparing the combined influence of material and element models.

3.3.1 Sensitivity to Material Models

The choice of a constitutive model to describe the cyclic stress-strain characteristics of the core concrete and reinforcing steel is investigated in this phase of the study. As discussed previously, the inelastic action in an element is controlled primarily by material behavior when employing a fiber model discretization of the cross-section. The numerical simulations using different confinement models for concrete and different constitutive models for reinforcing steel is shown in Figure 3.



EQ. ID	EQ. Name	Year	Station	PGA (g)	File name	Scale factor
EQ1	Cape Mendocino	1992	Petrolia	0.66	PET090.AT2	2.0
EQ2	Northridge	1994	Sylmar - Converter Sta. East	0.49	SCE288.AT2	2.0
EQ3	Imperial Valley	1979	El Centro Array #7	0.46	H-E07230.AT2	2.0
EQ4	Northridge	1994	Rinaldi Receiving Sta	0.84	RRS228.AT2	1.0
EQ5	Superstition Hills	1987	Parachute Test Site	0.45	B-PTS225.AT2	1.3
EQ6	Northridge	1994	Newhall W Pico Canyon Rd.	0.45	WPI046.AT2	1.5
EQ7	Chi-Chi, Taiwan	1999	TCU052	0.42	TCU052-N.AT2	1.2
EQ8	Kobe, Japan	1995	Takatori	0.62	TAK090.AT2	2.0

Table 3.2 Ground Motion Details

The variability in the response is also a function of the ground motion, however, substantial differences were noted in several simulations and the results presented in Figure 3 are a representative sample. The drifts shown in Figure 3a corresponds to cases in which the concrete core in both beams and columns was modeled either as unconfined or confined while those in Figure 3b considers the effect of different steel models. For the case investigating the effect of confined concrete models (Figure 3a), Steel02 was selected as the reinforcing steel model with a post-yield stiffness of 1%. For the case (Figure 3b) comparing different steel models, concrete was modeled using Mander's confinement model. Hence the variation shown in the figures is primarily due to the effect of changes in either concrete or steel.



Figure 3 Variation in computed drift demands for different material models: (a) Sensitivity to confined concrete models (EQ5); (b) Sensitivity to reinforcing steel models (EQ8)

In the above simulations, the effective post-yield stiffness of the steel material was fixed at 1% of the initial modulus. To examine the consequence of changing the post-yield stiffness, the simulation presented in Figure 3b was re-run using a post-yield stiffness of 2% (for the case of Steel02). A significant change in computed demands is observed as shown in Figure 4a. Next, the control parameter for material hardening was modified to introduce slight degradation in the cyclic response. The difference in response for a sample simulation (due to EQ7) is shown in Figure 4b. Concrete02 with Mander's confinement model was used for simulating the behavior of concrete in both cases.





Figure 4 Variation in computed drift demands for same steel models with different control parameters: (a) Sensitivity to post-yield stiffness; (b) Effect of material degradation (a<0.0)

Similarly, the choice of model parameters for specifying the behavior of confined concrete can be complicated by other factors, such as the characteristics of the ground motion or the details of the cyclic constitutive model. Figure 5a and Figure 5b show the computed drift demands using the same set of model parameters for two different ground motions. Results in Figure 5a suggest that both the Mander model and Hoshikuma model produce similar results thereby leading to the conclusion that the modeling of concrete confinement is not important or that the response is not sensitive to the choice of confinement models. However, changing the earthquake record (Figure 5b) produces a dramatically different response with the predicted peak demand changing by as much as 50%. Likewise, if the description of the cyclic behavior is changed, the predicted demands also change. As demonstrated in Figure 5c, the concrete model that incorporates tensile strength (Concrete02) produces demands that are approximately 60% higher on the 5th and 6th floor while the model that ignores tension results (Concrete01) results in even higher differences on the 8th and 9th floor.



Figure 5 Variation in computed drift demands for same steel models and different concrete models: (a) - (b) Sensitivity to ground motions (EQ5 vs. EQ4); (c) Sensitivity to concrete models

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3.3.1 Sensitivity to Element Models

In this phase of the study, demand sensitivity to material models is investigated in the context of element models. Response sensitivity and loss of objectivity using force-based element models have been addressed by Coleman and Spacone (2001) and Scott and Fenves (2006). Since deformations localize at a single integration point rather than across an entire element in force-based elements, the response changes as a function of the number of element integration points rather than as a function of the element length. In this study, however, the central issue being investigated is the impact of material characteristics and the parameters controlling the material response in an overall inelastic analysis. However, these issues are also interlinked.

The simulations presented thus far were based on a flexibility based element with distributed plasticity. Another common approach to modeling RC members is to assume a fixed plastic hinge zone at locations of expected inelasticity. The particular element considered in this study is the beam-with-hinges element implemented in OpenSEES which employs four integration points: two end-points at the ends of the element and two interior points. A complete description of the element formulation is reported by Scott and Fenves (2006). First, the computed responses are compared in Figure 6a for the case of the distributed plasticity element (labeled as Nonlinear in the figure) with 4 integration points and the beam-with-hinges element (labeled as Hinge) with a fixed plastic zone equal to the depth of the section. Next, model sensitivity at the element level is examined by varying the number of integration points (from 4 to 7) for the case of the fully distributed plasticity model and by changing the length of the plastic hinge (either the depth of the section or 10% of the element length). The resulting responses for the latter two cases are shown in Figures 6b and 6c, respectively. The variations considered in these simulations are not extreme values, rather they are typical parameters used by researchers and engineers in nonlinear simulations.



Figure 6 Variation in computed drift demands for same earthquake (EQ08), steel (Steel02) and concrete (Concrete 02 with Mander's confinement model) models: (a) Sensitivity to element models (b) Sensitivity to number of integration points (c) Sensitivity to the length of plastic hinge zone

CONCLUDING REMARKS

The findings in this paper highlight one aspect of inelastic seismic demand that has not received much attention. The advent of pushover and nonlinear dynamic analysis in performance-based seismic engineering require knowledge of nonlinear procedures and an understanding of model sensitivity. The results of the investigation in this study indicate that the choice of material models and the control parameters that define cyclic stress-strain behavior can produce significant differences in the computed drift demands in buildings. Such



discrepancies – resulting both from record-to-record variability and differences in modeling – are difficult to interpret. What is evident is that material models play an important role in demand estimation and particular attention should be given to properly calibrating these models prior to their use is seismic evaluation studies.

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