

Title: Validation of Finite Element Model Ability to Evaluate Residual Live Load Capacity of Bridge Columns

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Validation of Finite Element Model Ability to Evaluate Residual Live Load Capacity of Bridge Columns

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ABSTRACT

Modern highway bridges in California designed according to the California Department of Transportation's Seismic Design Criteria are expected to perform adequately during both frequent and extreme seismic events. Adequate performance implies ductile system and component response, limited and repairable damage, and the ability to maintain at minimum a gravity and live load load-carrying capacity. Bridges on lifeline routes are expected to carry emergency traffic load immediately after a major earthquake event. Furthermore, the importance of lifeline routes implies that some portion of regular bridge traffic capacity should be enabled in a reasonably short period after a major earthquake event.

The analytical models in widespread use today are calibrated to reproduce the behavior of bridge columns during a major earthquake event. However, they are not calibrated to model the strength and deformation of the same bridge after some damage, moderate or severe, has occurred. Validation and calibration of analytical models for bridge columns is the first crucial step towards enabling a confident estimate of the ability of a bridge to carry traffic load after an earthquake.

Estimates of the residual axial load-carrying capacity of an array of typical Caltrans bridge columns subjected to progressively increasing levels of lateral displacement ductility are presented in this paper. The variation of configurations of the bridge columns is obtained from the prototypical five-span, reinforced concrete highway bridge, selected as a testbed for researchers at the Pacific Earthquake Engineering Research Center. The analytical models of the bridge and the columns are developed in OpenSees using force-formulated, fiber cross-section beam-column elements. The results show that the remaining axial load-carrying capacity of columns, subjected to lateral displacement ductility demands consistent with regions of high and moderate seismicity, is satisfactory.

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INTRODUCTION

Recent seismic codes have made progress toward preventing brittle failure modes in columns. Unless complete failure occurs, columns subjected to earthquake excitation have some level of residual strength remaining. Quantifying this level of residual strength has seen little treatment in current research. Numerous researchers (e.g., Elwood, 2002) have looked at the issue of axial failure, defined as the lateral demand at which a column fails to carry its prescribed dead load. Testing setups include constant axial loads applied during lateral excitation (e.g. Kato and Ohnishi, 2002, Yoshimura and Nakamura, 2002), as well as several axial load control strategies based on levels of lateral deformation (e.g., Tasai, 1999). However, the explicit force-deformation characterization in the axial direction post-excitation has largely been ignored. Tasai (1999) conducted an experimental and analytical program to investigate this; however, the axial capacity envelope was based largely on sectional analysis. The analytical results were compared to only two experimental results and showed little or no axial degradation under low axial loads during the lateral testing.

This study attempts to further the understanding of residual axial strength through an analytical and experimental approach. To facilitate this, five scaled models of typical circular bridge columns will be tested in two phases. The first phase involves lateral cyclic loading using a prescribed displacement history to a pre-determined level of lateral displacement ductility. The second phase involves compressing the specimen by axial loading using a compress-tension machine. Such loading allows the determination of the remaining axial load capacity after a controlled amount of lateral load-induced damage. These tests will be used to develop axial load capacity vs. ductility demand degradation curves and calibrate the finite element model. The calibrated finite element model will be used to vary column design parameters and generate axial load degradation curves for a dense parameter space. Two additional hybrid simulation tests, conducted at the *nees@berkeley* NEES Equipment Site, will be used to validate the proposed procedure. In the hybrid tests, the column specimens will be subjected to earthquake ground motions that equivalent counterpart components would experience in a real bridge, followed by axial load tests.

The results of the experimental tests will be used to calibrate finite element, fiber cross-section, beam-column elements used in the OpenSees (<http://opensees.berkeley.edu>) platform, developed by the Pacific Earthquake Engineering Research Center (PEER). Final objective of this study will be developing of axial loss versus ductility demand curves for design provisions. A calibrated bridge column finite element model will then be used to develop seismic demand and capacity models for bridges using the Pacific Earthquake Engineering Research (PEER) Center performance-based earthquake engineering (PBEE) framework. Examples of such demand and capacity models for highway overpass bridges can be found in Mackie and Stojadinovic, 2005. The ultimate goal of this research is to capture the degradation of strength in analytical models that can be applied to more complex bridge and building structures in demand and capacity simulations within the PEER Center PBEE framework (Cornell and Krawinkler, 2000).

MODERATE-SCALE BRIDGE COLUMN SPECIMENS

Specimen selection

The ¼- scale bridge column specimens are designed using a prototype Caltrans bridge (Ketchum et. al. 2004) shown in Figure 1. Two principal parameters that affect the remaining axial

load capacity of bridge columns (Mackie, 2004) are column aspect ratio (L/D) and column shear strength (or transverse reinforcement ratio ρ_t). Different possible values of these two parameters, bounded by the provisions of the Caltrans SDC, are investigated. Additionally, two column specimens, referred to here as the *base* and *shear-short* specimens, were chosen. The *base* specimen, typical for a tall column overpass bridge ($L/D = 4$, $\rho_t=0.75\%$) is modeled based on bridge Type 11 in Ketchum et. al., 2004. Permanent deformation after an earthquake event and the subsequent increased importance of the $P - \Delta$ effect may play an important role on the remaining axial load-carrying capacity of columns of this type. The *shear-short* specimen is typical of short column overpass bridges ($L/D = 2.5$, $\rho_t = 0.65\%$) and is modeled based on bridge Type 1 (Ketchum et. al., 2004). The short specimen will be tested to evaluate the ability of the model to represent the behavior of a specimen that is not shear-critical, but is at the boundary where shear cracking and sliding along such cracks may begin to affect the axial load-carrying capacity.

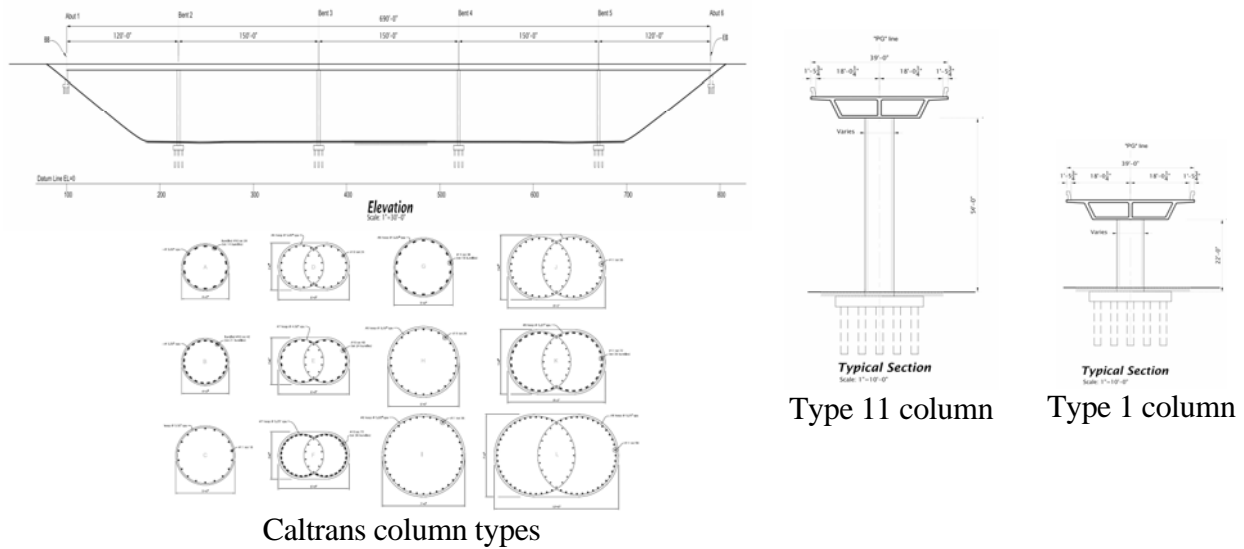


Figure 1 - Prototype Caltrans bridge. (Ketchum et. al., 2004)

Note that, because the column specimen will be tested in single curvature, the L/D aspect ratios should be doubled to model the more typical double-curvature bending of bridge columns. Thus, the base specimens will have an equivalent aspect ratio of 8, while the short specimens will have an equivalent aspect ratio of 5 in a double-curvature arrangement. The exact scale of the specimens with respect to the example prototype bridge is difficult to determine without conducting analyses to establish the location of the inflection point of the columns.

Experimental Procedure

The four *base* specimens and one *shear-short* specimen will be tested in two phases, the lateral and the axial. Each bridge column will be damaged by first applying lateral load in a quasi-static manner under displacement control. The difference among the bridge columns is the level of applied lateral load. Four levels of lateral load are planned in this project:

1. No lateral load: undamaged column.
2. Lateral displacement up to displacement ductility of 1.5: induce yielding of the column.
3. Lateral displacement up to displacement ductility of 3.0: induce significant yielding and strain hardening in steel and spalling of concrete, and bring the column to its peak lateral load resistance level.
4. Lateral displacement up to displacement ductility of 5.0: induce bar buckling in compression and possible bar fracture such that the lateral load resistance of the column drops by more than 20% from peak resistance. The column is expected to develop permanent lateral deformation during this test.

Each of the lateral load tests will produce data on the lateral load-deformation response of the columns. The lateral displacement will be applied in both lateral column axes, causing biaxial bending, following the clover-leaf pattern shown in Figure 2. The increments in displacement magnitude will follow the standard ACI ITG 1.99 sequence up to a determined target ductility listed in TABLE I. Note that Specimen 1 will not have lateral loading.

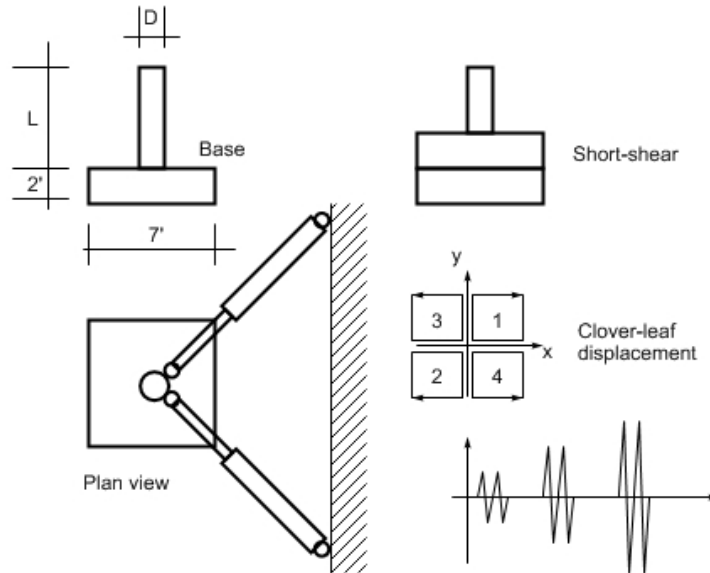


Figure 2 – Column specimens, test setup and bi-directional displacement sequence

TABLE I - MODERATE-SCALE BRIDGE COLUMN TEST MATRIX

Specimen Type/Test	$\mu = 0$	$\mu = 1.5$	$\mu = 3$	$\mu = 5$	10% in 50yr. earthquake	2% in 50yr. earthquake
Base	Sp. 1	Sp. 2	Sp. 3	Sp. 4	Sp. 6	Sp. 7
Shear-Short				Sp. 5		

After completing each of the lateral load tests, specimen will be re-centered and the remaining axial load-carrying capacity of the column specimens will be evaluated by conducting an axial load test: the columns will be crushed to obtain their axial load strength as well as the axial load-deformation response. The axial load tests will be conducted without applying lateral load. Additionally, horizontal displacements of the specimen will be constrained.

Specimens 6 and 7 will be tested using the hybrid simulation technique utilized within NEES (Stojadinovic et. al, 2006). The prototype bridge, shown in Figure 1, will be modeled using the hybrid modeling technique: one column of the bridge will be modeled physically on the laboratory floor, while the rest of the bridge will be modeled using calibrated finite element models in OpenSees. The OpenFresco framework will be used to implement the hybrid simulation, and the facilities of the *nees@berkeley* Equipment Site will be used to conduct the tests. Specimen 6 will be tested under a ground motion with a 10% in 50 year probability of occurrence at a site located at the University of California Berkeley campus, while Specimen 7 will be tested using an earthquake with a 2% in 50 year probability of exceedance for the same site.

In the axial test phase, all specimens will be tested in the 4,000,000-pound compression machine at the *nees@berkeley* Equipment Site. These compression tests will reveal the residual axial load-carrying capacity of the columns. Furthermore, Specimens 6 and 7 will provide the baseline for validating OpenSees beam-column models under a realistic dynamic earthquake loading.

PRELIMINARY ANALYSIS OF BASE COLUMN SPECIMEN

Analytical modeling of the *base* column specimen is performed using OpenSees to develop a preliminary relationship between the displacement ductility and the residual axial load-carrying capacity. A finite element model of the column was developed using force-formulated, fiber cross section, beam-column elements.

Specimen geometry

Specimen geometry and dimensions are detailed in Figure 3. The specimen has a 16-inch diameter circular column 64 inches in height. The specified unconfined compressive strength of the concrete is 3.25 ksi.

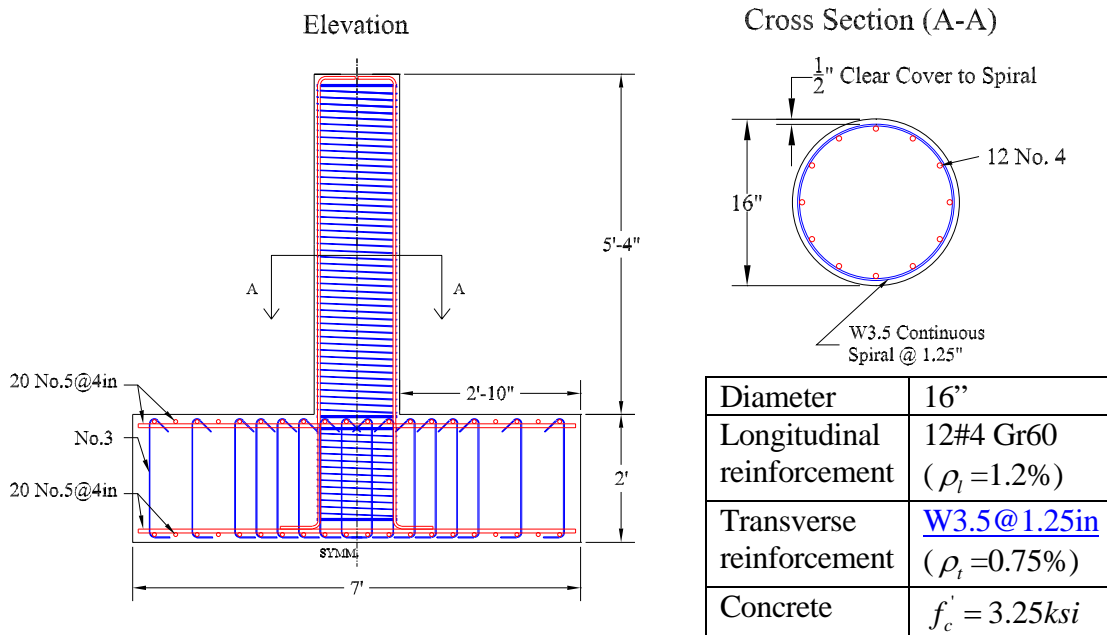


Figure 3 – Geometry and dimensions of *base* column specimen

Grade 60 steel was used for the longitudinal reinforcement. Twelve longitudinal #4 reinforcing bars are placed around the perimeter of the column. Transverse steel reinforcement is continuous W3.5 spiral at 1.25-inch on center spacing. The cover is 1/2" all around.

Constitutive models

The constitutive models employed for the fibers include a strain hardening steel model and a Kent-Scott-Park concrete model. The steel model has a yield strength of 65 ksi, a strain-hardening ratio of 1.5%, a maximum strain of 0.12, and isotropic hardening. There are no discontinuities in the tangent stiffness during loading of this model. The concrete model has no tensile strength for both the confined core and unconfined cover. Cover model includes an unconfined stress-strain relation with zero strength after spalling at a strain of 0.006.

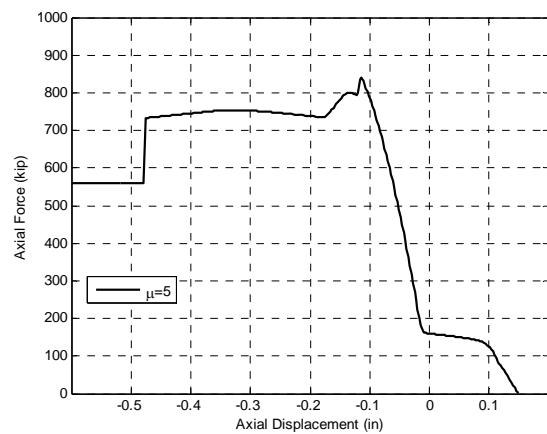
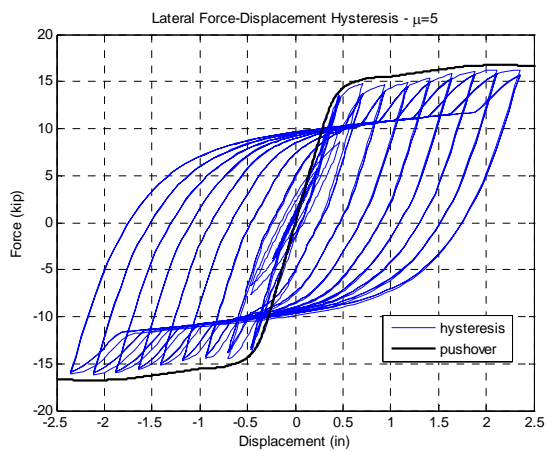
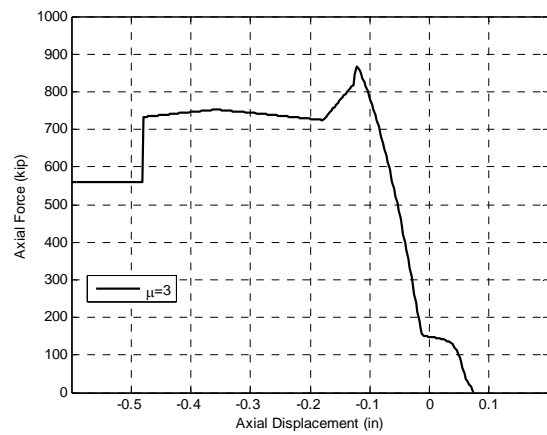
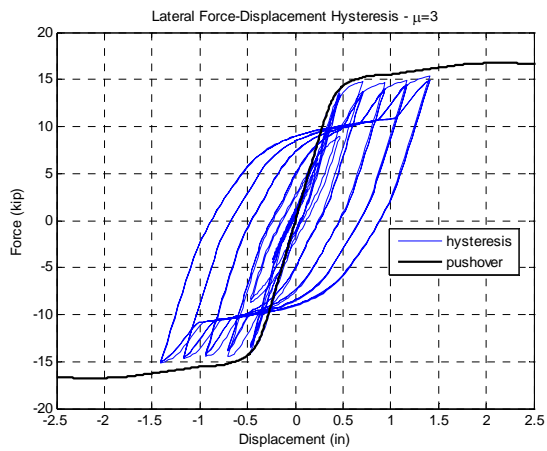
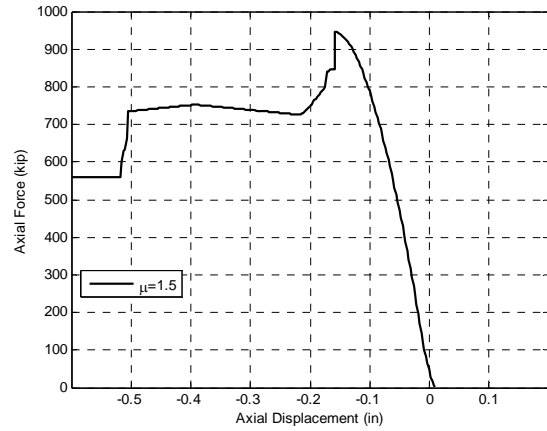
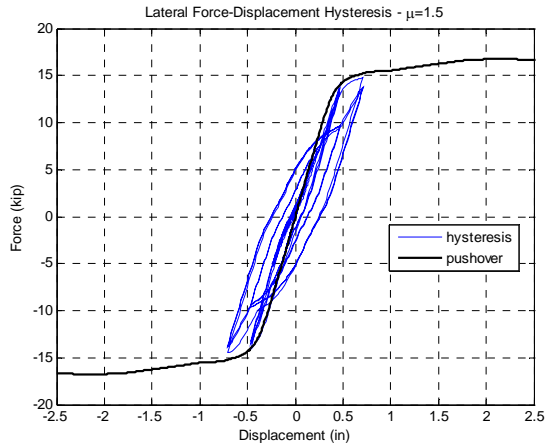
Analysis

The analytically-modeled specimen was subjected to uni-directional displacement histories up to pre-determined target ductility levels listed in TABLE I. The increments in displacement magnitude followed the standard ACI ITG 1.99. The analytical model was then cycled at low amplitude to reduce the restoring force at zero displacement to a specified tolerance. In Figure 4(a) results of the analysis are presented for three specified levels of lateral ductility demand. The lateral load-displacement hysteretic response is accompanied by a monotonic pushover response, in order to compare results of two different loading techniques (with cyclically and monotonically increasing loading pattern). They both provide about the same lateral force-displacement response of the column.

In the absence of lateral loads, the column was then compressed axially to mimic the axial load-carrying capacity test. In the Figure 4(b), axial force-displacement responses for three specified levels of ductility are shown. As the specimens elongated while they were cycled laterally, a small toe on the axial force-displacement curve in the positive displacement region occurred under the axial compressive load. In this region, response of the specimens originates from reinforcement stiffness and strength. As axial loading increases, the "gap" closes and the core stiffness is activated. Since the specimens are very well confined, cycling laterally doesn't fail any of the core fibers, and consequently all the specimens have the same axial stiffness.

Additionally, an undamaged column ($\mu=0$) is loaded axially in order to obtain the maximum predicted axial load-carrying capacity of the specimen. Hereafter, axial load capacity for a certain damage level is normalized with respect to maximum axial load-carrying capacity (Figure 5).

In order to predict the loss of axial strength due to the accumulation of damage, a curve of the normalized axial force versus ductility can be used. Such a curve for the analytical results is presented in Figure 6. For considered range of ductility, maximum loss of axial carrying capacity is about 12 %. It should be noted, that this curve does not represent loss of axial strength of a real bridge column, but of the considered specimen in specified experimental conditions. Other effects that influence response of a bridge column: type of the soil, stiffness of the deck, residual displacement and tributary weight on the column, will be modeled analytically and added to experimentally derived response.



(a)

(b)

Figure 4 – (a) Lateral force-displacement hysteresis for different ductility levels; (b) Axial force-displacement response for different ductility levels

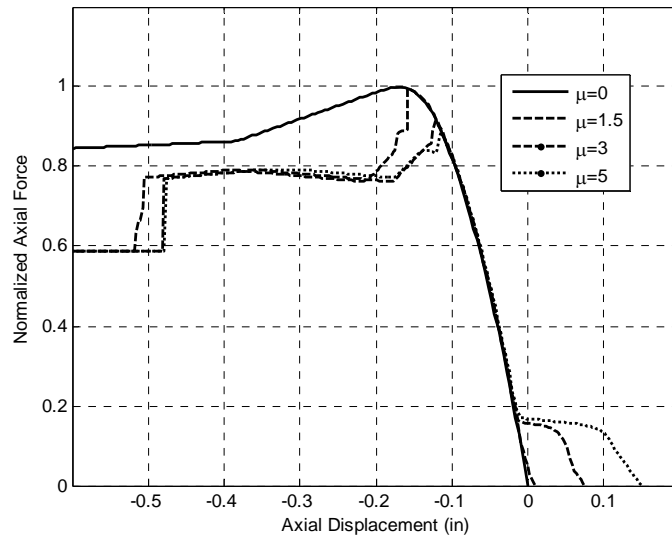


Figure 5 – Normalized axial force-displacement response for different ductility levels

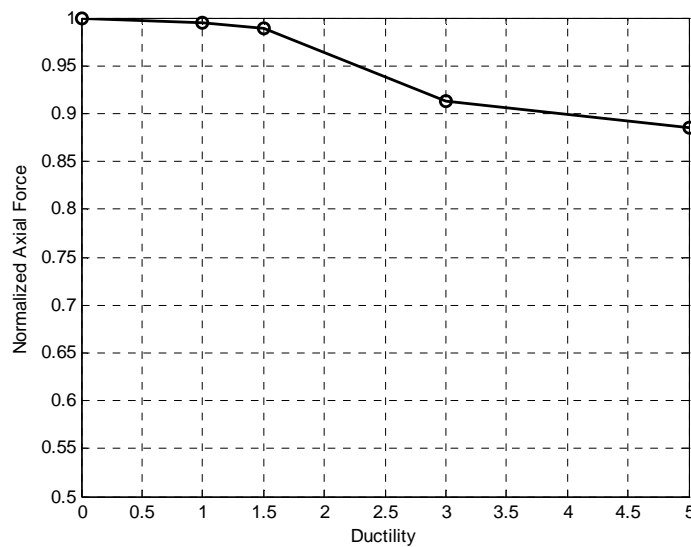


Figure 6 – Loss of axial capacity of the *base* specimen

PRELIMINARY ANALYSIS OF *SHEAR-SHORT* COLUMN SPECIMEN

Models

Behavior of a specimen that is not shear-critical, but that could fail in shear after some inelastic action in the plastic hinge region, is explored here. To evaluate how behavior of such a specimen affects its axial load-carrying capacity, analytical modeling is performed using OpenSees. Furthermore, the total capacity model (TCM), developed by Elwood (Elwood, 2005) is utilized. TCM provides an estimate of the axial capacity of a column that has previously experienced shear

failure. In TCM, the classical shear friction model is modified to include only information about the transverse reinforcement. This is then added to the expected strength obtained from the longitudinal reinforcement. The TCM, although developed for rectangular reinforced concrete sections, is modified and applied to the circular sections of this study. Since the friction coefficient for rectangular sections was calibrated from experimental data, it is left unchanged. A similar approach using the truss analogy for residual axial capacity was employed by Tasai (2000). However, this approach requires knowledge of the stresses in the truss mechanism at some deteriorated capacity, making the TCM prediction more attractive.

The analytical model developed in OpenSees contains flexural-axial interaction with the fiber cross section of the beam-column elements. The same material models were used as for the *base* column specimen. In addition, the model incorporates shear stress-shear strain relationships aggregated at the integration points of the nonlinear elements.

Specimen geometry

Specimen geometry and dimensions are detailed in Figure 7. The specimen has a 16-inch diameter circular column 39 inches in height. The specified unconfined compressive strength of the concrete is 3.25 ksi. Grade 60 steel was used for the longitudinal reinforcement. Twelve longitudinal #4 reinforcing bars are placed around perimeter of the column. Transverse steel reinforcement is continuous spiral W3.5 at 1.45-inch on center. The cover is 1/2" all around.

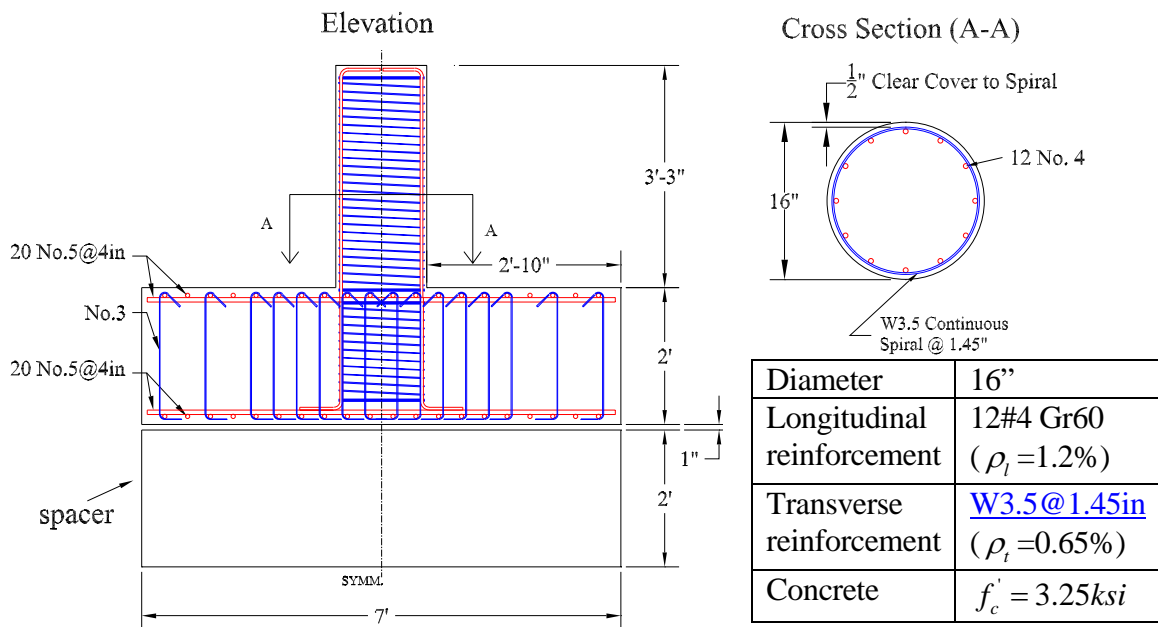


Figure 7 – Geometry and dimensions of *shear-short* column specimen

Analysis

The analytically modeled *shear-short* specimen was subjected to the same regime of lateral and axial loading as the *base* specimen. Loss of axial load-carrying capacity with the accumulation of

damages from both the analysis results and using the TCM are presented in Figure 8. The analytically obtained data points from OpenSees model suggest that there is more residual axial load-carrying capacity than predicted by TCM.

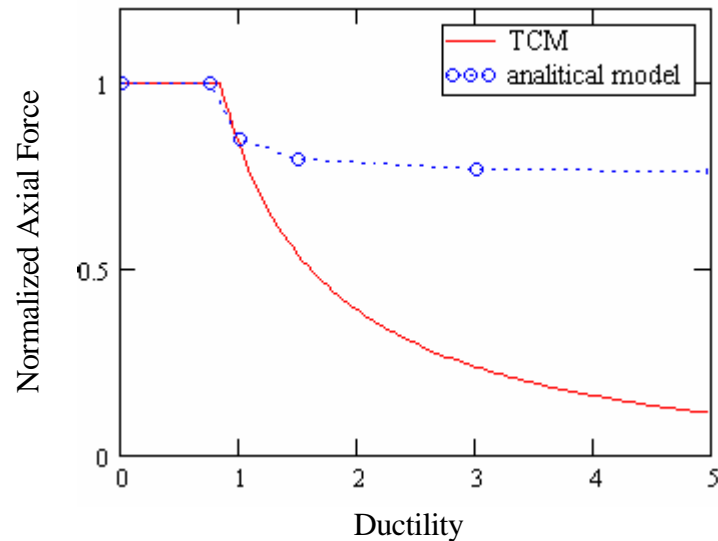


Figure 8– Loss of axial capacity of the *shear-short* column specimen

PERFORMANCE-BASED EARTHQUAKE ENGINEERING CONTEXT

The ability to rationally predict the post-earthquake load carrying capacity of reinforced concrete bridge columns is an important step in the performance-based earthquake engineering decision making process. The original two-phase experimental procedure presented in this paper involves lateral excitation up to a pre-determined ductility or earthquake hazard level followed by a monotonic axial compression test of the damaged specimens. This procedure is designed to provide the data needed to calibrate an analytical beam-column finite element with respect to both flexural and shear damage, and the ability to model residual axial load capacity and collapse under gravity load. Thus, it will be possible to accurately predict the loss of axial load-carrying capacity of bridge structures and, thus, give decision makers a tool to quickly decide on necessary bridge closures and prioritize repairs after an earthquake. The calibrated and validated finite element models of bridge structures are an essential element of the probabilities performance-based tools for evaluating the state of highway networks after an earthquake.

REFERENCES

- Cornell, A., and Krawinkler, H., 2000, Progress and Challenges in Seismic Performance Assessment, *PEER Center News* 3 (2), pp. 1-2.
- Elwood, K.J. 2002. Shake table tests and analytical studies on the gravity load collapse of reinforced concrete frames. *PhD Dissertation*, University of California Berkeley.
- Elwood, K.J. & Moehle, J.P. 2005. Axial Capacity Model for Shear-Damaged Columns. *ACI Structural Journal*, V.102, No.4, July-August 2005, pp.578-587.

- Kato, D. & Ohnishi, K. 2002. Axial load carrying capacity of reinforced concrete columns under lateral load reversals. *Technical report PEER 2002/02: 247-255*, PEER Center.
- Ketchum, M, Chang, V. and Shantz, T. 2004. Influence of Design Ground Motion Level on Highway Bridge Costs, *Technical Report PEER 6D01*, PEER Center.
- Mackie, K. 2004. Degradation of reinforced concrete column axial strength, In Proceedings of the *5th International Symposium in Civil Engineering*, June 16-19, 2004. Delft, Netherlands.
- Mackie, K & Stojadinovic, B. 2005, Fragility Basis for California Highway Overpass Bridge Decision Making, *Technical Report PEER 2005/02*, PEER Center.
- Shin, Y.B. & Moehle, J.P.M. 2002. Quarter-scale reinforced concrete specimen test. *Internal technical report*, UC Berkeley.
- Stojadinovic, B., Mosqueda G., and Mahin, S., 2006, Event-Driven Control System for Geographically Distributed Hybrid Simulation, *ASCE Journal of Structural Engineering*, Vol. 132, No. 1, January.
- Tasai, A. 1999. Residual axial capacity and restorability of reinforced concrete columns damaged due to earthquake. *Technical Report PEER 1999/10: 191-202*, PEER Center.
- Tasai, A. 2000. Residual axial capacity of reinforced concrete columns during shear degradation. *Technical Report PEER 2000/10: 257-267*, PEER Center.
- Yoshimura, M. & Nakamura, T. 2002. Axial collapse of reinforced concrete short columns. *Technical Report PEER 2002/21: 187-198*, PEER Center.