Criteria for Evaluating the Effect of Displacement History and Span-to-Depth Ratio on the Risk of Collapse of R/C Columns

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LISBOA 2012

SUMMARY:
Physical simulations of seven slender columns and five short columns subjected to shear reversals until axial failure were performed as part of a research program to develop a better understanding of the behavior of poorly detailed reinforced concrete columns and the risk that they pose to the collapse of older reinforced concrete buildings during strong earthquakes. Detailing of the columns was chosen to be representative of older building construction in the west coast of North America. Parameters in the study were axial load, amount and arrangement of the transverse reinforcement, span-to-depth ratio, and displacement history. Data generated from this recent test program and previous studies was analyzed in the context of rehabilitation standards and used to develop new criteria to account for the effect of displacement history and shear span-to-depth ratio on the performance parameters and acceptance criteria that can be implemented in the ASCE-41 standard.

Keywords: reinforced concrete; building columns; collapse; biaxial loading; displacement history.

1. INTRODUCTION

Performance and evaluation criteria for reinforced concrete columns developed as part of rehabilitation standards and guides such as FEMA-273 (1997), FEMA-356 (2000), ASCE-41 (2007), the ASCE-41 supplement No. 1 (Elwood et al., 2007), and the ACI 369 Rehabilitation Guide (2011) were based on limited experimental data. Test data was particularly scarce for severely damaged columns subjected to shear reversals. Given the complexity involved in testing full scale components with unstable behavior and the inherent potential for damage to the testing equipment and sensors, very few column tests had been carried out to column axial failure when those provisions were developed, forcing experts to rely on their judgment to overcome information gaps. Due to the uncertainty caused by the lack of data, the result was a set of rehabilitation criteria that was limited in scope and conservative in nature.

A recent effort funded by the National Science Foundation and undertaken under the umbrella of the PEER center was aimed at improving the understanding of the risk of collapse in older reinforced concrete buildings and to use that information to improve rehabilitation standards used by practicing engineers. One of the thrusts of this research program focused on the risk of collapse posed by reinforced concrete columns with reinforcing details considered to be inadequate in modern seismic codes. The column research thrust consisted of 12 physical simulations (Henkhaus, 2010, Woods and Matamoros, 2010) and computer simulations (Sammarco and Matamoros, 2010) investigating the effect of several parameters on column behavior and on the drift ratio at axial failure. The parameters investigated were displacement history, axial load, amount and spacing of transverse reinforcement, and aspect ratio. Several of the columns in the experimental program were proportioned to be shear critical (columns in which shear failure is expected to occur before yielding of the longitudinal reinforcement due to the combined effects of flexure and axial load) to address the paucity of experimental results about this type of columns. These physical simulations provided new insight into the behavior of nonductile reinforced concrete columns at severe stages of damage which can be used for refining the performance and acceptance criteria in supplement No. 1 to the ASCE-41 (Elwood et al., 2007) seismic rehabilitation standard.

The analysis described in this paper was carried out as part of the last stage of the PEER-NSF research program. It is intended to summarize some of the trends observed in the column tests, and to draw a comparison between the experimentally observed behavior of the columns and the provisions in supplement No. 1 to the ASCE-41 rehabilitation standard (Elwood et al., 2007), with the goal of identifying areas in which changes in the standard are warranted in light of the findings from the tests. The paper focuses specifically on provisions related to column stiffness of shear-critical columns, the effect of aspect ratio on the drift ratio at axial failure, and the effect of displacement history on the drift at axial failure.

2. STIFFNESS PROVISIONS FOR SHEAR-CRITICAL COLUMNS

According to Section 6.3.1.2 of supplement No. 1 to the ASCE-41 rehabilitation standard (Elwood et al., 2007) the stiffness of columns shall be modeled considering flexural, shear, and axial stiffnesses according to the parameters presented in Table 6-5 of this document. For all types of elements listed in Table 6-5 of supplement No. 1 to the ASCE-41 standard, including columns, the shear rigidity is specified as 0.4 E_c A_w, where E_c represents the modulus of elasticity of concrete and A_w represents the area of the web cross section, defined as the product b_w d. The shear rigidity parameter specified in Table 6-5 is consistent with an elastic shear modulus $G = E_c / 2 (1 + \nu)$, where Poisson's modulus ν = 0.25.

Experimental data from shear critical columns in this testing program showed that near the point of lateral loss capacity (shear failure), deformations related to shear were significantly higher than those calculated using the provisions in supplement No. 1 to the ASCE-41 standard. Figure 1a shows the normalized shear modulus measured within the maximum moment region of column 3 (Woods and Matamoros, 2010), a shear-critical slender column with a shear span-to-depth ratio of approximately 3.6 tested as part of the PEER-NEES research program. Figure 1b shows the hysteretic response of the column. The red line in Fig. 1b corresponds to the envelope curve developed following the provisions in supplement No.1 to the ASCE-41 standard.

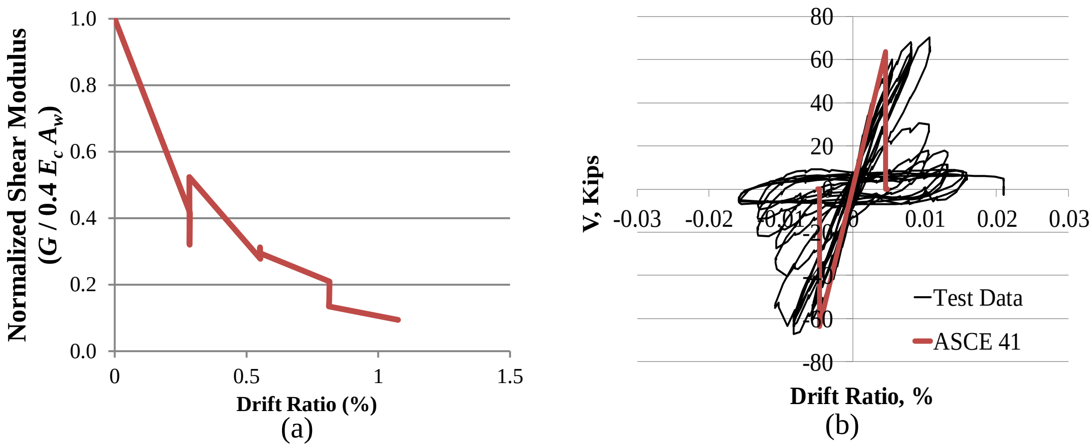
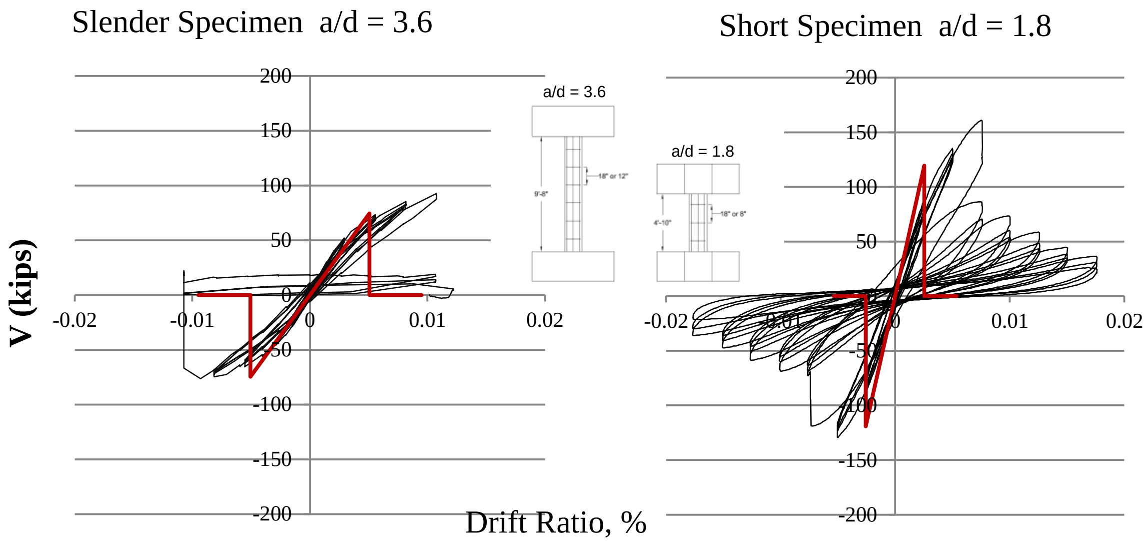


Figure 1. Normalized shear modulus and hysteretic response of column 3.

The shear modulus shown in Fig. 1a was calculated based on a grid of led taggers that was attached to the maximum moment region of the column and tracked using an optical system (Woods and Matamoros, 2010). The deformations within the grid region were used to calculate deformation components related to flexure and shear following the procedure described by Woods (2009). Deformations related to shear at the peak of each displacement cycle were used to calculate the effective shear modulus. The value at the beginning of the test corresponds to the theoretical shear modulus calculated following the provisions in supplement No. 1 to the ASCE-41 standard. As shown in Fig. 1b, a drift ratio of 1.25% corresponds approximately to the point at which the column experienced loss of lateral loss capacity. Figure 1 clearly illustrates that for relatively slender shear-critical columns the deformations related to shear at the point corresponding to loss of lateral load capacity were approximately 10 times the values calculated using elastic theory.

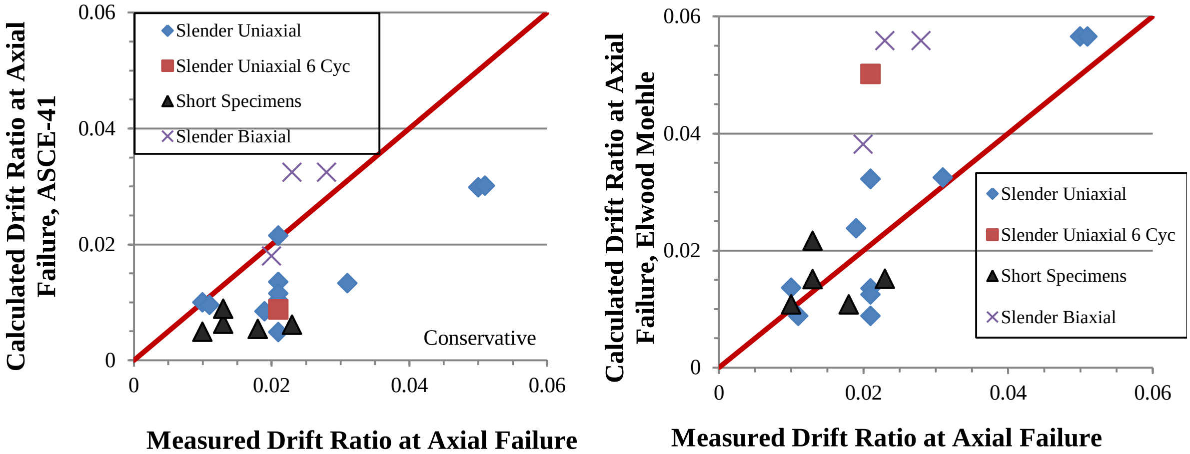
The difference between experimental and theoretical values was much more significant in specimens with smaller shear span-to-depth ratio. A comparison between the hysteretic response of two similar specimens with different shear span-to depth ratios (Matamoros et al., 2008, Henkhaus, 2010) is presented in Fig. 2.



(a) (b)

Figure 2. Hysteretic response for column specimens with different shear span-to-depth ratio. Both specimens had a longitudinal reinforcement ratio of 2.5%, #3 hoops with 90 deg. ties at 18 in. and an axial load of 500 kips.

As shown in Fig. 2 the specimen with the smaller span-to-depth ratio experienced loss of lateral load capacity at approximately 80% of the drift ratio of the slender specimen, while the calculated deformations related to shear based on elastic theory were approximately 25%.



(a) (b)

Figure 3. Comparison between measured and calculated drift ratio at axial failure for column specimens tested at UC-Berkeley and as part of the PEER-NSF project.

3. DRIFT AT AXIAL FAILURE FOR SPECIMENS WITH SHORT SPAN-TO-DEPTH RATIO

Another important finding from the experimental program was that specimens with short shear span-to-depth ratios had drifts at axial failure that were much larger than those estimated using the provisions in supplement No. 1 to the ASCE-41 standard.

This can be observed in Fig. 3, which shows a comparison between measured and calculated drift ratios at axial failure for the specimens tested as part of the PEER-NSF project and similar specimens previously tested by Lynn (2001) and Sezen (2000). Figure 3 shows that for specimens with low shear span-to-depth ratio (black triangles) estimates of drift ratio at axial failure obtained using the provisions in supplement No. 1 to the ASCE-41 standard were much lower than those observed in the tests. This observation is also evident from Fig. 2, which shows a comparison between the hysteretic response and the corresponding envelope curve for one of the specimens tested in the PEER-NSF project. The envelope described by the red line was calculated using the performance criteria in the provisions of supplement No. 1 to the ASCE-41 standard. Because the specimen was shear critical, the drift ratio at axial failure was estimated conservatively to be approximately 0.5%, while the physical specimen was able to sustain a drift ratio of approximately 1.75% before axial failure.

Figure 3 also shows that the estimates of drift ratio at axial failure were conservative for slender columns subjected to uniaxial loading. This was to be expected given that the stated criteria used to develop the limits in Table 6-8 of supplement No. 1 to the ASCE-41 standard (Elwood et al., 2007) were to achieve a probability of failure of 15% for columns that experience shear failures and a probability of failure of 35% for columns expected to achieve flexural failure.

Because supplement No. 1 to the ASCE-41 standard was intended to be conservative, a more appropriate estimate of the mean drift ratio at axial failure was obtained using an established model to calculate the drift ratio at axial failure. Elwood and Moehle proposed used a shear-friction model to develop the following expression for the drift ratio at axial failure:

$$\frac{\Delta}{L} = \frac{4}{100} \frac{1+tan^2 65°}{tan 65° + P\left(\frac{s}{A_{st} \, f_{yt} \, d \, tan 65°}\right)} \tag{3.1}$$

where Δ/L represents the drift ratio at axial failure, P is the axial load, A_{st} is the cross area of transverse reinforcement crossing the plane of failure, s is the spacing of the transverse reinforcement, and f_{yt} is the yield stress of the transverse reinforcement.

A comparison between estimated values of the drift ratio at axial failure using the model proposed by Elwood and Moehle (Elwood, 2003) and experimentally observed values is shown in Fig 3. It is evident from Fig. 3 that although the Elwood-Moehle model was calibrated on the basis of slender flexure-shear critical columns, it provided a good estimate of the mean drift ratio at axial failure for both short and slender shear-critical columns subjected to uniaxial loading. Figure 4 shows the relationship between axial load and drift ratio at axial failure and for a family of columns with similar transverse reinforcement ratios and cross section dimensions. The blue line in Fig. 4 represents the drift ratio at axial failure as a function of the axial load calculated using Eqn. 3.1 (Elwood, 2003) model. The data in Fig. 4 reiterates that the Elwood-Moehle model provided a reasonable estimate of the mean drift ratio at axial failure for columns with different shear span-to-depth ratios and axial loads.

4. EFFECT OF DISPLACEMENT HISTORY ON DRIFT AT AXIAL FAILURE

One of the most important parameters evaluated in the PEER-NSF study was the effect of displacement history on the drift ratio at axial failure. The subset of columns used to evaluate the effect of displacement history had the highest transverse reinforcement ratio and lowest axial load demand of the set of columns tested in the study. Most of the columns in this subset were flexure-shear critical, although some of the columns with the low values of concrete compressive strength were shear critical due to the low shear capacity of the concrete.

The effect of displacement history was evaluated in two different ways. Similar columns were subjected to uniaxial loading varying the number of cycles per drift ratio in the displacement protocol. These tests were intended to evaluate the significance of long-duration ground motions on the drift ratio at axial failure of nonductile columns. A second group of columns tested by Henkhaus (2010) was subjected to biaxial loading.

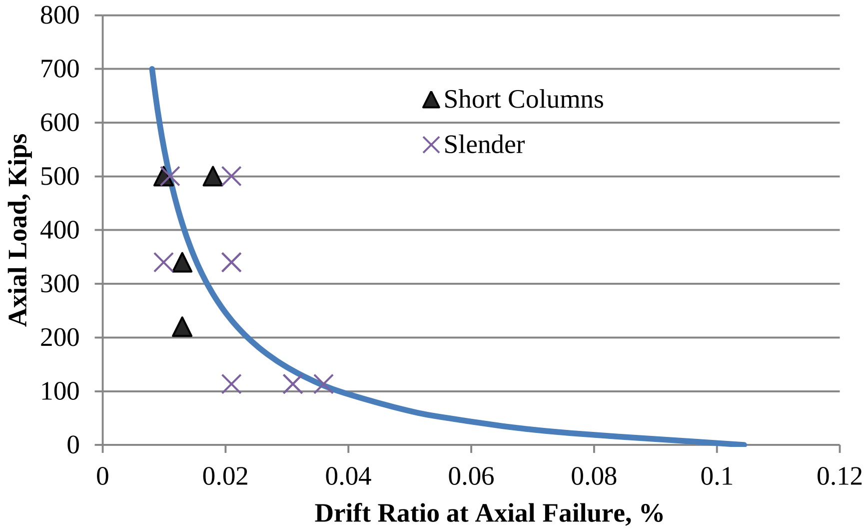


Figure 4. Comparison between measured and calculated drift ratio at axial failure for column specimens tested at UC-Berkeley and as part of the PEER-NSF project.

The effect of the number of cycles is illustrated in Fig. 5. Of the three columns shown, the first two were tested by Sezen (2000) and had displacement histories with 1 and 3 cycles per drift ratio. The third column was tested as part of the PEER-NSF project (Woods, 2009) and had a displacement history with a total of 6 cycles per drift ratio.

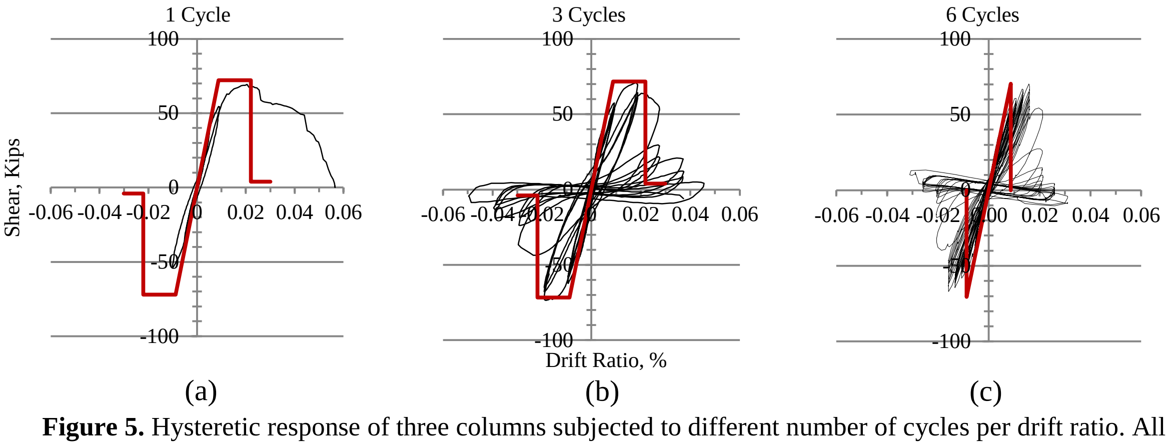


Figure 5. Hysteretic response of three columns subjected to different number of cycles per drift ratio. All columns had a longitudinal reinforcement ratio of 2.5%, diamond and rectangular ties spaced at 12 in., and an axial load of 150 Kips.

The red lines in Fig. 5 represent the corresponding envelope curves calculated using the provisions in supplement No. 1 to the ASCE-41 standard. While the first two columns had very similar envelopes, the third one had a lower concrete compressive strength which caused it to fall into the shear-critical category. The difference in the envelope curves illustrates very well the lower probability of failure that was given to shear-critical columns in supplement No. 1 to the ASCE-41 standard. A relatively small difference in shear strength caused the third column to shift to the shear-critical category, which resulted in a much more conservative envelope curve.

There is a noticeable difference between the hysteresis curves in Fig. 5 due to the number of cycles per drift ratio. It is clear that as the number of cycles per drift ratio increased, the drift ratio at axial failure decreased, with the third column failing at approximately half the drift ratio of the first one. It is also clear from the figure that the larger number of cycles caused a more rapid decrease in the stiffness of the column after the point corresponding to loss of lateral load capacity was surpassed.

The effect of the number of cycles on the drift ratio at axial failure can also be noticed in Fig. 3. While the estimate of drift ratio at axial failure was still very conservative, in great part due to the fact that the column was shear-critical, the estimates of drift ratio at axial failure calculated with the Elwood-Moehle model were significantly higher than the measured values. The Elwood-Moehle model was calibrated for the most part based on columns subjected to uniaxial loading with three cycles per drift ratio. Because this model was applied making no distinction between flexure-shear critical columns and shear-critical columns, the probability of failure assigned to both is the same, indicating that the displacement history with six cycles per drift ratio caused more severe damage to the column and caused it to reach axial failure at a lower drift ratio.

The effect of displacement history was evaluated also by subjecting a set of columns to biaxial loading protocols (Henkhaus, 2010). The loading protocol was such that the columns were subjected to three displacement cycles with deformations along one of the principal directions followed by three displacement cycles in the orthogonal principal direction (Henkhaus, 2010). At no point during the test the columns were subjected to deformations along the two principal directions simultaneously.

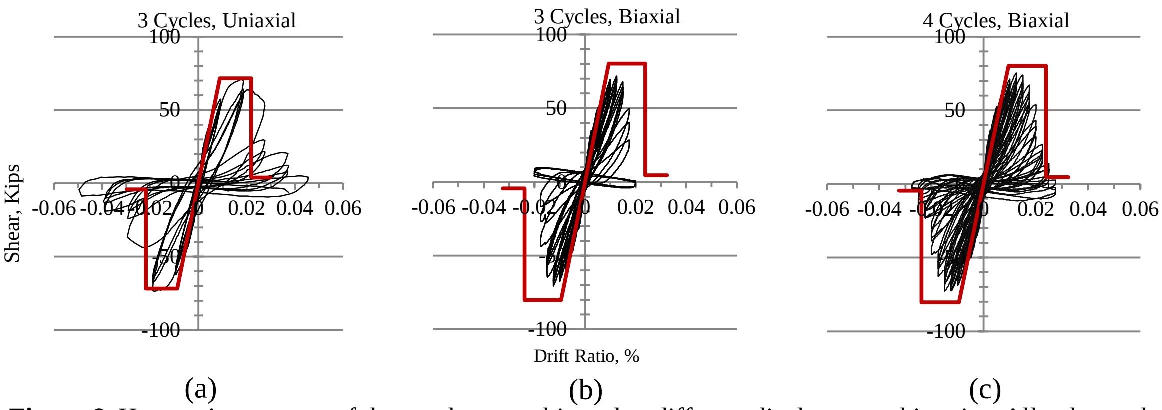


Figure 6. Hysteretic response of three columns subjected to different displacement histories. All columns had a longitudinal reinforcement ratio of 2.5%, diamond and rectangular ties spaced at 12 in., and an axial load of 150 Kips.

Figure 6 shows that the effect of biaxial loading was much more severe than that of the number of cycles. While the red line corresponding to supplement No.1 to the ASCE-41 standard provided a conservative envelope for the hysteretic response of the column subjected to uniaxial loading, the ASCE-41 envelope curves were unconservative for the case of the two columns subjected to biaxial loading. Figure 6 also shows that the difference between 3 cycles per drift level and 4 cycles per drift level was not very significant for columns subjected to biaxial loading.

This trend was consistent with the results illustrated in Fig. 3. Estimates of the drift ratio at axial failure calculated using supplement No. 1 to the ASCE-41 standard for columns subjected to a biaxial displacement protocol were found to be unconservative. A comparison between estimates of drift ratio at axial failure of columns with biaxial displacement protocols and the corresponding drift ratios at axial failure calculated using the Elwood-Moehle showed that the estimates obtained with the Elwood-Moehle model were more unconservative than those obtained using supplement No. 1 to the ASCE-41 standard, indicating that columns subjected to biaxial displacement protocols experienced more severe damage and experienced axial failure at lower drift ratios than columns subjected to uniaxial displacement protocols.

4. SUMMARY AND CONCLUSIONS

Results from an experimental program investigating the response of columns with inadequate seismic details subjected to repeated load reversals were presented. The experimental program was intended to investigate the effect of transverse reinforcement, axial load, shear span-to-depth ratio, and displacement protocol on the drift ratio at axial load failure.

Test data showed that deformation components related to shear at the point corresponding to loss of lateral load capacity were significantly higher than those calculated based on linear elastic material properties. Experimental data showed that for slender shear critical columns the deformation component related to shear at loss of lateral load capacity was approximately 10 times greater than the value estimated based on linear elastic material properties. An even greater discrepancy was found for the case of columns with a lower shear span-to-depth ratio, representative of captive columns. On the basis of the test data it is recommended that deformations related to shear be calculated with an effective shear modulus, significantly lower than that calculated on the basis of linear elastic material properties.

Experimental results showed that, as intended, performance criteria in supplement No. 1 to the ASCE-41 standard provided conservative estimates of the drift ratio at axial failure for columns with shear span-to-depth ratios of approximately 1.8 and 3.6. Test results also showed that the Elwood-Moehle model provided adequate estimates of the mean drift ratio at axial failure for columns evaluated in the PEER-NSF study regardless of shear span-to-depth ratio. The Elwood-Moehle model was found to be equally applicable for columns that were shear critical and flexure-shear critical. Based on these findings it is suggested that Elwood-Moehle model be implanted as the basis for the provisions in the ASCE-41 standard, which would have the added benefit of simplifying the provisions in the standard significantly.

Because columns subjected to biaxial displacement protocols and larger number of deformation cycles experienced lowed drift at axial failure than similar columns subjected to uniaxial displacement protocols with three cycles per displacement, it is recommended that reduction factors be implemented in the ASCE-41 standard when these types of displacement protocols are expected.

AKCNOWLEDGEMENT

This work was supported primarily by the National Science Foundation under award number 0618804 through the Pacific Earthquake Engineering Research Center (PEER). The authors would like to acknowledge the collaboration with Professors Santiago Pujol and Julio Ramirez from Purdue University and Jack Moehle from the University of California who have been active participants of the PEER–NSF and have actively contributed to the development of recommendations for the improvement of the ASCE-41 standard and the ACI-369 rehabilitation guide.

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