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Non-linear Modeling Parameters for Jacketed Columns Used in Seismic Rehabilitation of RC Buildings

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Abstract

Rehabilitation of structures requires knowledge on the anticipated nonlinear behavior of building components. Column retrofitting using jackets made of different materials, designed to counter deficiencies in the original design, can be used to improve the overall performance of an existing building. This paper presents a procedure to obtain the backbone nonlinear response of jacketed columns based on existing experimental results for this class of elements. Column jacketing has been used in the past to increase ductility and strength of reinforced concrete columns. Jacket designs can be varied to selectively improve the lateral-load response of columns depending on the original design deficiency. A uniform methodology or specific recommendations on how to estimate the response of jacketed columns with different jacket materials types do not exist. Existing experimental data are used to determine the backbone nonlinear response of jacketed columns. These data are then used to develop recommendations to determine non-linear force and deformation parameters of jacketed columns. Although the most common types of jackets used are made from: concrete, steel, and FRP, only the last two are included in this paper. The backbone curves thus generated can then be used in performance assessment of reinforced concrete buildings where columns have been jacketed.

Introduction

Performance-based design and seismic rehabilitation of structures requires a thorough understanding of the expected response of a structure under various levels of seismic demand. The elastic and inelastic cyclic behavior of structural components needs to be well understood in order to be able to get better estimates of overall structure response under different ground shaking scenarios. Current practice is to approximate the nonlinear cyclic response of structural components by using force-deformation curves that bound the hysteretic response of these components (backbone curves). To model the nonlinear response of components, average backbone curves are simplified by determining only those points that impact the response of the component importantly. These simplified backbone curves are constructed using values that represent the mean response of components tested in the laboratory. Modeling parameters in *ASCE/SEI Standard 41-06* (2006), for example, allow users to determine force and deformation values at yield, at peak strength, and at residual strength. Multi-linear backbone curves are constructed by joining these three key points. Backbone curves for positive and negative directions of loading are assumed identical for components with symmetrical cross-section and reinforcement.

Modeling parameters included in *ASCE/SEI 41-06* and *ACI 369R-11* were developed for existing structural components. In a seismic rehabilitation project, the ability to estimate the response of the retrofitted structure is important to assess the success of a proposed intervention. Nonlinear modeling of rehabilitated components is therefore needed. A common feature of existing frame structures that predate modern seismic procedures is the presence of columns with details that make them vulnerable to collapse during earthquakes. Columns in these frames may contain short lap splices of longitudinal reinforcement, inadequate shear strength, and/or insufficient confinement to resist the anticipated seismic demands. Column jacketing is a technique that has successfully been used in the past, as shown by experiments, to correct these design and detailing deficiencies. There is little guidance, however, on procedures to determine nonlinear modeling parameters for jacketed columns so the seismic response of retrofitted frames cannot be determined consistently. This paper provides recommendations for construction of backbone curves by determining modeling parameters of columns retrofitted using fiber-reinforced polymer (FRP) jackets or steel jackets. Backbone curves of jacketed columns are first constructed using existing experimental data to determine force-deformation parameters at yield and peak strength. These data are then used for comparison with values determined from models proposed to determine relevant force-deformation parameters of jacketed columns.

Description of Jacketed Column Database

A database of existing laboratory experiments of jacketed reinforced concrete columns was compiled to study the force-deformation response characteristics of these elements. These data were used to construct backbone curves from experimental data, as discussed in the following section, which could be used to estimate yield and ultimate force-deformation values for comparison with proposed models to generate these parameters for other jacketed columns.

All columns in the database were tested under cyclic static loading applied incrementally following a prescribed protocol. Columns were tested in original (un-retrofitted) condition and retrofitted using jackets made with fiber-reinforced polymer materials or steel. The concrete compressive strength of columns in the database ranged between 1300 and 8000 psi (9 and 55 MPa). Columns were tested under either single curvature bending (cantilever) or double curvature bending (fixed-fixed). Although some tests were intended to simulate bridge column behavior, data are still included in the database for these specimens.

The database contains 146 columns of which 52 are circular columns and 94 are rectangular columns. Figure 1 summarizes the classification of columns in the database according to jacket type and type of deficiency encountered in the original design. Figure 2 illustrates the distribution of key parameters of the columns in the database. The parameters presented in this figure are spacing of transverse reinforcement (s) normalized by effective depth to the tension force resultant, d, assumed equal to 0.8 d_c; axial force ratio, defined as the axial load divided by the nominal compressive strength of the concrete (f'_c) and the gross cross-sectional area (A_g); type of jacket used to retrofit each column (steel or FRP); the ratio between shear at plastic hinging (V_o) and nominal shear strength (V_n). Nominal shear strength was calculated using the shear strength equation 4-1 in *ACI 369R-11* using a ductility of 8.

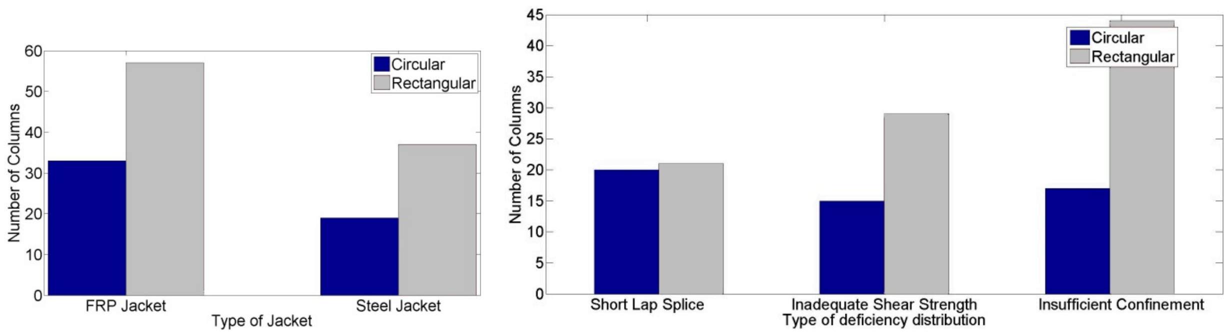


Figure 1 – Classification of columns in database

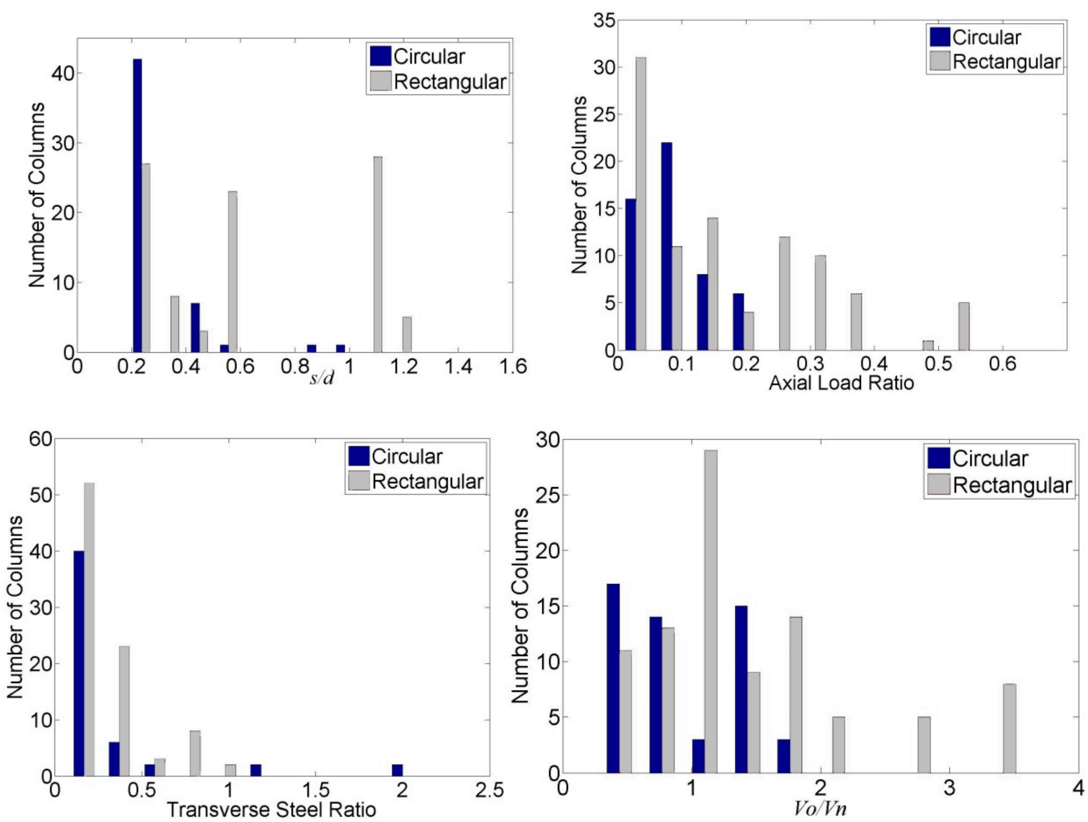


Figure 2 – Distribution of selected parameters of columns in database

A short lap splice condition refers to splicing longitudinal reinforcement within the plastic hinge region of the column over a length of 20 to 36 longitudinal bar diameters. Columns with inadequate shear strength are those that fail in shear prior to developing the plastic hinge capacity of the column at high displacement demands. Inadequate confinement of longitudinal reinforcement is caused by a low volume of transverse reinforcement because of either small diameter hoops and/or hoops at a large spacing. Poor seismic detailing of hoops with 90° hooks at their ends also leads to inadequate confinement after cover concrete spalls at moderate displacement demands.

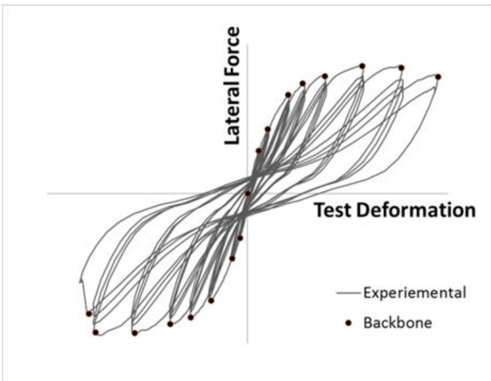
The column database includes information about the material properties and geometry of the jacket. The diameter of circular columns are between 9.5 and 30 in. (241 and 762 mm), while the width of rectangular columns is between 6 and 36 in. (152 and 914 mm) and the depth is between 7.5 and 36 in. (191 and 914 mm). Key jacket properties include jacket material (steel or FRP), jacket thickness, length of jacket, and jacket mechanical properties. The properties of the jacket vary widely depending on the retrofitting objective and the original column deficiency.

Appendix A includes tables that list force-deformation parameters of individual columns in the database. Force-deformation values are provided at three levels: yield force, peak force, and maximum force and deformation. Force is given as applied lateral load, V, at these different levels. Peak values are those measured at the highest force applied to the specimens. Maximum values are those measured at the maximum deformation imposed to the specimens. The deformation parameter used in the tables and throughout this paper was drift, given as lateral displacement divided by specimen height.

Construction of Backbone Curves from Experimental Data

Data available on jacketed columns were used to construct simplified backbone curves that could be used for nonlinear analysis. Results of cyclic tests of jacketed columns are typically presented by different researchers in plots of lateral-load (shear) as a function of displacement (top displacement, drift, or displacement ductility demand). Cyclic force-displacement is available in the literature either in the form of hysteresis curves or response envelopes. Multi-linear backbone curves were extracted using reported hysteresis plots or, if available, force-displacement envelopes for each specimen. These curves were further simplified by identifying and plotting the coordinates of three key points (yield, peak strength, and residual strength) to obtain simplified backbone curves consistent with modeling parameters of *ASCE/SEI 41-06*.

Backbone curves were constructed by digitizing data from figures of hysteresis plots included in the original test references. The data were digitized by obtaining the force and displacement (or drift) at each displacement level applied to the columns. Force and displacement measured during the first cycle at each displacement level were used to construct these curves. If authors directly reported backbone curves, then these plots were digitized to obtain the force-deformation relationships instead of extracting them from hysteresis curves. Generation of a backbone curve from the hysteresis response of one column in the database is illustrated in Figure 3. The key points needed to construct simplified backbone curves were obtained from these curves as illustrated in the figure; they are listed by column specimen in Appendix A.



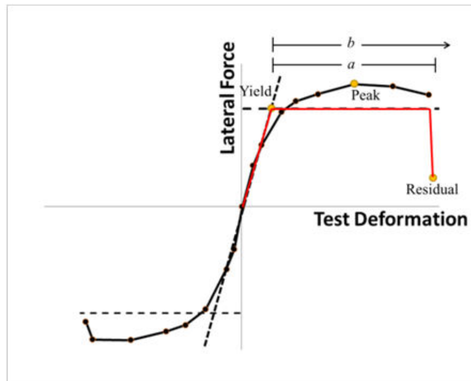


Figure 3 – Backbone curve generated from experimental data

Force and deformation at yield (V_y, Δ_y) were defined at the point of intersection between two secant lines. The first line passes through the origin with the same slope as the experimental force-deformation curve. The force at yield, V_y, was defined in two different ways depending on the drift measured at peak strength. A value $V_y = 0.8V_{peak}$ was used for columns with peak strength at a drift at or below 2% followed by rapid degradation. A value $V_y = 0.7\ V_{peak}$ was used for columns with peak strength at a drift exceeding *3%*. This approach was needed to include retrofitted columns where the jacket enhanced the lateral strength but did not affect the yield capacity significantly.

The coordinates at peak force (V_{Peak}, Δ_{Peak}) were determined by using the average of the peaks measured in the positive and negative directions of loading. The residual force (V_{res}) and maximum displacement (Δ_{max}) are not frequently reported in the literature. Therefore V_{res} was defined as a fraction (20%) of the peak force (V_{peak}) and Δ_{max} was defined conservatively as the maximum displacement reported for each tested column. The definitions of nonlinear modeling parameters (*a*, *b*, and *c*) in *ASCE/SEI 41-06* were used, wherever possible, to construct the simplified backbone curves of jacketed columns. Parameter *a* is defined in *ASCE/SEI 41-06* as the difference between the deformation at lateral strength degradation of 20% and the deformation at yield. In some tests the columns were not displaced to cause a 20% strength degradation. In these cases parameter *a* was defined using the maximum deformation imposed during the test. Parameter *b* is defined in *ASCE/SEI 41-06* as the deformation corresponding to loss of axial capacity, accompanied by a significant drop in lateral-load strength. Most of the jacketed columns were not tested to this level of strength degradation, so parameter *b* was determined as the deformation corresponding to a degradation of 25% from V_{peak}. In cases where columns did not exhibit a strength degradation level of 20% or more, parameter *b* could not be determined and is not reported in Appendix A.

To allow comparison among columns with different geometric characteristics, reinforcement contents, and different material properties, the simplified backbone curves were normalized by dividing all force values by the force at yield. Lateral deflection of the columns was divided by column height (*Δ/H*) to consistently plot drift for all the simplified backbone curves from the database. The mean simplified backbone curves of circular and rectangular columns jacketed using steel or FRP jackets in the database are shown in Figure 4.

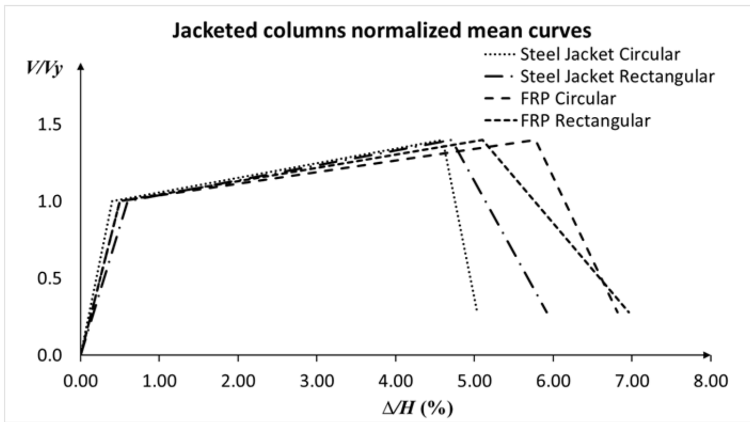


Figure 4 – Mean force-deformation relationships of jacketed columns from database

Effect of Column Jacketing on Yield Force, Peak Strength, and Flexural Stiffness

The key parameters that define simplified backbone curves of jacketed columns need to be calculated reliably for use in nonlinear analyses. Techniques used to determine these parameters for jacketed columns must be developed to allow evaluation of the response of retrofitted frames. Models that can be used to determine the yield force and peak strength of jacketed columns are presented in this section. Because of lack of accurate deformation models, drift at these key points may be based on results collected from the column database, so no model was developed.

Depending on the jacket material used and the way it is connected to the existing concrete column, jackets may also contribute to the flexural and shear strength of the column. The two types of jackets discussed in this paper, steel and FRP, contribute in different degrees to confinement, shear, and flexural strength. Steel jackets may contribute to the shear strength and flexural strength of the columns since steel mechanical properties can be considered as isotropic. FRP jackets, on the other hand, primarily contribute to strength and stiffness in the direction of fiber orientation. Fibers in FRP jackets used for confinement and shear strength increase are applied transversely to the column axis so their contribution to flexural strength is negligible. Only the effects of jacket confinement are considered here; contribution of jackets to shear strength is not discussed in detail.

Steel jackets contribute to bending stiffness of the columns due to the increase in cross-sectional dimensions (grout between original column and steel jacket) and the contribution of the external steel jacket to bending stiffness. The contribution of FRP jackets to bending stiffness is negligible so it was therefore not considered. Stiffness reductions to account for concrete cracking (*ACI 369R-11*, Table 3.1) were used to modify the gross cross-sectional stiffness of jacketed columns.

Confining Effects of Column Jacketing

The main effect of column jacketing is to provide confinement to the concrete in columns with insufficient transverse reinforcement because of the presence of small diameter or widely spaced hoops. Jacket confinement is activated after the concrete expands because of micro-cracking. Increased concrete confinement will allow development of higher stresses and strains in the confined concrete resulting in an increase in flexural strength. If inadequately short lap splices exist within the plastic hinge region, the concrete splitting stresses that generate along the splice at large displacement demands cause the concrete to expand. This expansion causes the column jackets to develop lateral confining stresses (clamping stresses) that prevent failure at low ductility because of splitting along the lap splice. Therefore, models intended to capture jacketed column behavior must consider the confining effects that the jackets provide to the column cross section.

Short lap splices or inadequate confinement of existing older columns may cause localized failures primarily within the plastic hinge region at low ductility demands. The global response of a column with these deficiencies is dominated by the behavior within the plastic hinge region. In these cases it is appropriate to use a sectional model within the plastic hinge zone to capture the global column behavior. The goal of localized column jacketing is to eliminate a brittle splice failure from occurring within the plastic hinge region so that the global response of the column becomes ductile. The jackets, however, may not necessarily provide the level of clamping force necessary to develop yielding of longitudinal bars in the spliced region. The stress developed in the spliced reinforcement was therefore reduced using equation 3-2 of the *ACI 369R-11*, which considers the effect of bar slip in stress reduction. This modification resulted in better agreement with the measured backbone behavior.

Column yield and peak force were estimated by including the effects of concrete confinement using existing models with some modification to account for the properties of the jackets. The cross–sectional behavior of a jacketed column was calculated by dividing the section into fibers. The contribution of each fiber to flexural capacity at various deformations (curvatures) was calculated using the uniaxial stress-strain behavior of the material composing the fiber. For a jacketed column fibers representing reinforcing steel, confined concrete, and jacket were used. Unconfined concrete fibers were not included since jackets are applied externally so all the concrete in the cross section is confined.

Similar to confinement provided by closely spaced hoops, jacket confinement efficiency depends on the jacket and column cross-sectional properties. The lateral confining stress (f_l) generated by steel or FRP jackets for circular columns was estimated using equations proposed by Priestley et al. (1994) and ACI 440.2R-08 (2008), respectively. For circular steel jackets the lateral confining stress was estimated using:

$$f_l = \frac{2 f_{yj} t_j}{(D_j - 2t_j)} \tag{1}$$

and for circular FRP jackets, the lateral confining stress was calculated as:

$$f_l = \frac{2 E_{FRP} n t_f \varepsilon_{fe}}{D} \tag{2}$$

where,

f_{yj} = yield stress of the steel jacket
t_j = steel jacket thickness
D_j = diameter of column to outside face of jacket
E_{FRP} = modulus of FRP jacket
n = number of FRP plies (layers)
t_f = thickness of FRP jacket
ε_{fe} = effective strain in FRP jacket, assumed equal to $0.57\varepsilon_{fu}$
ε_{fu} = maximum strain at failure of FRP jacket material
D = diameter of existing column

To allow use of the popular confinement model developed by Mander et al. (1988), lateral confining stressed developed by steel or FRP jackets was converted to an equivalent quantity of transverse reinforcement that would result in the same lateral confining stress. The jacket confining stresses were equated to the lateral confining stress equation in the Mander et al. (1988) model to determine the spacing required of No. 3 bar hoops that would result in the same confining stress using:

$$f_l = \frac{1}{2}\, k_e \cdot \frac{4(A_{tr})}{D\, s} \cdot f_y \tag{3}$$

where k_e equals

$$k_e = \frac{\left(1 - \frac{s'}{2D}\right)^2}{1 - \rho_{cc}} \tag{4}$$

k_e represents the confinement efficiency factor that accounts for the reduced confining effect of discretely spaced transverse hoops at spacing s. The spacing s' refers to the clear spacing between transverse hoops. The ratio between the area of longitudinal reinforcement (A_s) to concrete area (A_c), denoted as ρ_{cc}, may be taken equal to zero in the case of jacketed columns.