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Shear-strength degradation model for RC columns subjected to cyclic loading

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ABSTRACT

An analytical model was developed to estimate the shear-strength degradation and the deformation capacity of slender reinforced concrete columns subjected to cyclic transverse loading. The shear capacity of the concrete compression zone was defined as a function of the inelastic flexural deformation of the column, based on the material failure criteria of concrete. The shear capacity is degraded as the inelastic flexural deformation increases. The deformation capacity of a column is determined when the degraded shear capacity reaches the shear force demanded by flexural yielding of the column. Other failure mechanisms including rebar-buckling and -fracture and flexural failure were also considered to estimate the deformation capacity. The proposed model was applied to test specimens possessing various design parameters. The result showed that the proposed model estimated the shear-strength degradation and deformation capacity of the test specimens with reasonable precision.

1. Introduction

The use of a performance-based design method for ensuring the safety of structures subjected to earthquakes provides a strong impetus for an accurate estimation of the deformation capacity of reinforced concrete members. Particularly, an accurate evaluation of the deformation capacity is required for columns, because they have a relatively low deformation capacity, due to axial compression; their failure frequently brings about catastrophic damage to the overall structure.

According to evidence from past strong earthquakes, reinforced concrete columns are susceptible to diagonal tension cracking that frequently leads to a brittle shear failure. Therefore, a major portion of previous studies for the earthquake resistance of columns has focused on investigating their shear strength. Experimental studies by Ang et al. [1], Aschheim and Moehle [2], Wong et al. [3], Moretti and Tassios [4], Ho and Pam [5], and Lee and Watanabe [6] showed that columns subjected to cyclic lateral loading may fail early, in shear, after flexural yielding. Based on test results, these studies reported that the shear strength of columns is heavily dependent on their inelastic deformations, and the shear strength degrades more quickly than flexural strength under cyclic loading. Priestley et al. [7] reported the shear-strength degradation and early shear failure is attributed to the development of diagonal tension cracks in the plastic hinge regions.

In previous studies, several shear-capacity models have been proposed to account for the shear-strength degradation of columns subjected to cyclic lateral loading. The ATC seismic design guideline [8] proposed a shear-capacity curve, and it describes shear-strength degradation in terms of displacement ductility (Fig. 1). Martin-Perez and Pantazopoulou [9] proposed a shear-capacity curve similar to the ATC model considering the effect of bond, aggregate interlock, and dowel action on the shear strength degradation of RC columns. Priestley et al. [7] proposed an improved shear-capacity curve for columns by considering the contributions of concrete, transverse reinforcement, and axial load (Fig. 2). In the latter model, the shear strength of concrete and the shear contribution of the truss mechanism are defined as functions of the member's inelastic deformation demand. In FEMA 273 [10], a ductility-related factor was introduced to describe the degradation of concrete's shear capacity. Sezen and Moehle [11] followed a similar approach, but they applied the ductility-related factor to reinforcing bars as well as concrete (Fig. 2). Mullapudi and Ayoubm [12], and Sima et al. [13] developed a fiber beam-column element formulation and a constitutive model using smeared crack approach to simulate the seismic behavior of concrete columns subjected to cyclic load, respectively.

In current design codes, decrease in shear strength under cyclic loading has been well recognized. However, strength degradation is not explicitly defined in terms of member's deformation level, and the strength degradation is expressed in a more conservative way. ACI318-08 [14] neglects concrete shear strength for the members subjected to low compressive force in Special Moment

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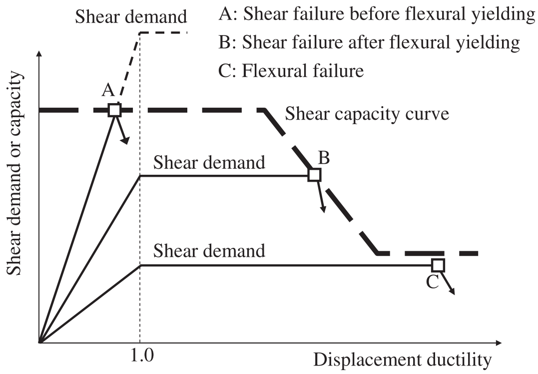

Fig. 1. ATC model [8] for shear-strength degradation.

Resisting Frame defined in the special provisions for seismic design. The NZC [15] also ignores the concrete contribution to the members' shear resistance. Similarly, FEMA 273 [10] ignores the shear contribution of concrete members at moderate or high ductility demand levels.

Due to the complexity of shear-strength degradation, which varies with flexural deformation, most previous models have estimated degradation of shear capacity, depending on practical experiences obtained from laboratory testing and field observations of earthquake-damaged buildings. If a more rigorous model is developed, based on the fundamental failure mechanism of reinforced concrete, it may improve the understanding of the mechanism behind shear-strength degradation; such understanding may eventually enable a more accurate assessment of the deformation capacity of reinforced concrete columns.

Recently, Park et al. [16] developed a strain-based shear-strength model based on the material failure criteria of concrete. This model reasonably describes variations in the shear capacity of reinforced concrete beams, according to their flexural deformation. Originally, it was developed to estimate the shear strength of beams that fail in shear, before flexural yielding. However, this model is also applicable to estimating the shear strength of members after flexural yielding. In addition, Choi and Park [17] expanded this approach to concrete beams subjected to cyclic loading, and successfully the developed and verified the analytical model to evaluate the envelope of the load-deformation behavior up to the failure by using test results with a variety of range of test parameters.

Based on their approach, in the present study, an analytical model was developed for estimating the seismic shear behavior of reinforced concrete columns (shear span ratio, $2.0 < a/d < 4.0$) addressing the various failure mechanisms: the concrete shear failure, the buckling and fracture of longitudinal reinforcing bars, and flexural failure (i.e., concrete crushing in the compression zone).

2. Shear demand of columns

In a slender column where shear failure occurs after flexural yielding, the load-carrying capacity of the column is determined by its flexural yield strength. Therefore, the shear demand, which the column should resist, is determined as the shear force required for flexural yielding. The shear demand can be calculated from flexural moment-curvature analysis, using geometric data, material properties, and applied axial load.

In a column confined by lateral ties, the confinement effect should be considered when describing the post-yielding flexural behavior of the column. In the present study, the compressive stress-strain relationship of the confined concrete was defined with an ascending branch of a second-order parabolic function and a linearly descending branch (Fig. 3) (Hognestad [18]; Vecchio and Collins [19]; Collins et al. [20]; Légeron and Paultre [21]).

$$\sigma_a(\varepsilon) = f'_{cc}\left[2\left(\frac{\varepsilon}{\varepsilon_1}\right) - \left(\frac{\varepsilon}{\varepsilon_1}\right)^2\right] \quad \text{for} \quad \varepsilon \leqslant \varepsilon_1 \tag{1a}$$

$$\sigma_d(\varepsilon) = f'_{cc} - Z_m(\varepsilon - \varepsilon_1) \quad \text{for} \quad \varepsilon_1 < \varepsilon \leqslant \varepsilon_{ult}, \tag{1b}$$

where $\sigma_a(\varepsilon)$ and $\sigma_d(\varepsilon)$ represent the stress-strain relationships for the ascending and descending branches, respectively; $Z_m[= 0.15f'_{cc}/(\varepsilon_{85} - \varepsilon_1)]$ denotes the slope of the descending branch; f'_{cc} is the compressive strength of the confined concrete; ε_1 is the compressive strain corresponding to the peak compressive strength, f'_{cc}; and ε_{85} is the compressive strain corresponding to 85% of the peak compressive strength on the descending branch. f'_{cc}, ε_1, and ε_{85} are defined according to Saatcioglu and Razvi's model [22]:

$$f'_{cc} = f'_c + k_1 f_{le} \tag{2}$$

$$\varepsilon_1 = \varepsilon_{01}(1 + 5K) \tag{3}$$

$$\varepsilon_{85} = 260\rho\varepsilon_1 + \varepsilon_{085} \tag{4}$$

In these equations, f'_c, ε_{01}, and ε_{085} denote material parameters for unconfined concrete: the peak compressive strength, strain at the peak strength, and post-peak strain corresponding to 85% of the peak strength, respectively. The parameters k_1, f_{le}, K, and ρ, as used in the above equations, are calculated from the geometry

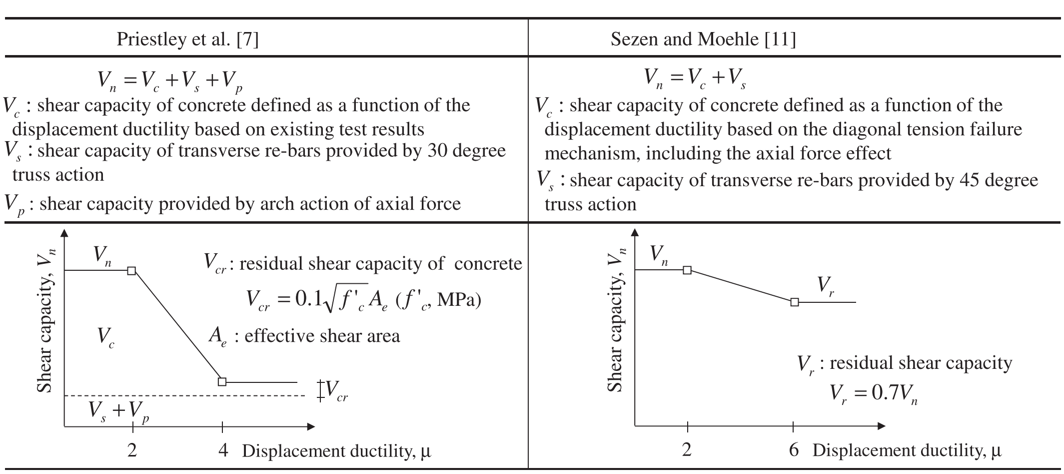

Fig. 2. Existing models for estimating shear capacity degraded by inelastic deformation.