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Proposal of a complete seismic shear strength model for circular concrete columns

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ABSTRACT

A complete shear strength model is proposed to define the relationship between seismic shear strength and lateral drift ratio of circular concrete columns. The proposed bi-linear model comprises the initial shear strength branch and the shear strength degradation branch, and it can trace the degradation of shear strength along with lateral deformation. The formula to assess the initial shear strength is derived from the equilibrium of the forces acting on the primary shear failure plane and Mohr–Coulomb failure criteria for concrete, while the degradation slope of shear strength is associated with a factor indirectly representing the contribution by the so-called dowel action of longitudinal reinforcements. Another feature of the proposed model is that it can be used to directly calculate the seismic shear strength of circular columns without transforming circular section into an equivalent rectangular or square section. In order to calibrate the proposed model and verify its reliability and accuracy, eighty-eight relatively large scale circular concrete columns that many researchers have reported failing in shear are collected. These previous tests cover a wide range of structural factors such as concrete strength, axial load ratio, yield strength and amount of transverse as well as longitudinal reinforcements, and shear span ratio. Comparisons between the experimental results and the calculated ones indicate that the proposed model can predict the seismic shear strength and trace the shear strength degradation till large deformation more accurately than previous models.

1. Introduction

Structural research community and engineers have well recognized the importance of preventing concrete members under seismic loading from shear failure, since the generally brittle shear failure results in less ductility and causes substantial damage to building structures. Conventionally, structural engineers have avoided brittle shear failure of a concrete column or beam by assuring that the calculated shear force corresponding to ultimate flexure strength of the concrete member is less than the calculated shear strength. This method is based on the concept of capacity design advocated by Park and Paulay [1], and has been adopted in seismic design practice for the ductile concrete frames over the last several decades.

Recent strong earthquakes such as the Kobe earthquake (1995, Japan) and the Sichuan earthquake (2008, China), however, have indicated that ductile concrete frames could survive strong design-earthquake and achieve their goals to prevent the collapse of buildings, but might be left too severe damages and too large residual deformations for the buildings to be repaired. From the viewpoints of immediate re-occupancy and rehabilitation of human society after earthquakes, therefore, ductile concrete frames could no longer be regarded as the only solution for the buildings constructed in earthquake-prone regions. A new alternative which can achieve a higher seismic standard than simple life safety is desirable.

Drift-hardening concrete components have recently gained increasing attention among structural community, and several effective methods have been proposed to make drift-hardening concrete walls and columns [2–4]. Fig. 1 idealizes the typical seismic performances of ductile concrete columns and drift-hardening concrete columns in terms of lateral resistance versus deformation (drift) skeleton curves. As compared with ductile columns, drift-hardening columns can stabilize the seismic response up to much larger deformation and simultaneously reduce the residual deformation significantly [4].

For either ductile concrete columns or drift-hardening concrete columns, the key point lies in that the lateral resistance of the

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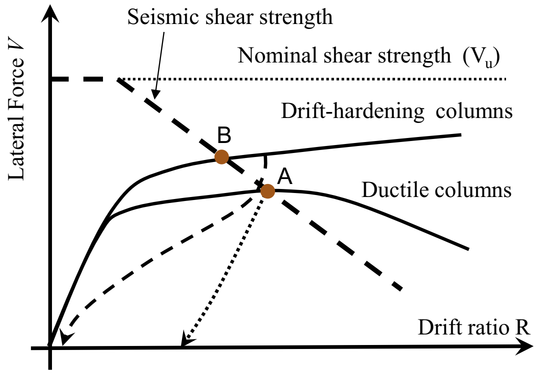

Fig. 1. Comparison of seismic performance of ductile and drift-hardening concrete columns.

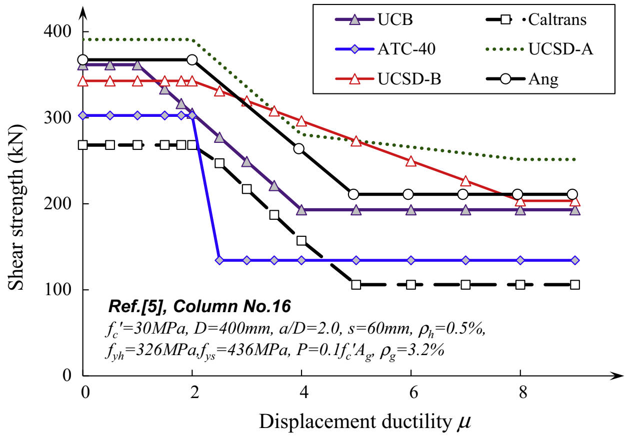

Fig. 2. Outline of the previous seismic shear strength models.

columns must be kept less than the calculated shear strength. It has been well known that the shear strength of a concrete column tends to degrade along with the deformation of the column, because the further extension of shear cracks results in gradual deterioration of the aggregate interlock and the dowel action of longitudinal rebars [5–7]. Therefore, to make a reliable design of either ductile or drift hardening concrete columns, structural engineers need to understand the relationship between shear strength and lateral deformation.

To distinguish from the conventionally-defined nominal shear strength, the shear strength degrading along with deformation of a column will be referred to as seismic shear strength hereafter. Outline of the seismic shear strength is superimposed in Fig. 1. As obvious from Fig. 1, a sound seismic shear strength model is indispensable to the reliable design of either ductile or drift hardening concrete columns. Ignorance of the degradation in shear strength at large deformation may lead an originally ductile or drift hardening column to fail in shear prematurely at much smaller drift level than expected [8]. This inversion of failure mode occurs much easier in circular concrete columns than in square or rectangular ones, since the circular hoops or spirals are more effective in enhancing ductility and drift-hardening effect than in upgrading the shear strength as compared with the rectilinear transverse steels.

However, the current seismic design codes such as ACI 318-11 [9] and AIJ design guideline [10] only provide design equations to indirectly calculate the nominal shear strength of circular concrete columns by applying the design equations recommended for rectangular columns after transforming the circular section into an equivalent rectangular or square one. While NZS-3101 provides design equations to directly calculate the nominal shear strength of circular concrete columns [11], the design equations still adopt the concept of effectives shear area which only considers the concrete core section rather than the gross section.

Although no equations have been recommended to assess the seismic shear strength of circular concrete columns in current design codes, the research on the seismic shear strength has been conducted by many investigators, and can trace back to the work done by Ang [5]. Based on the experimental results of dozens of circular concrete columns, Ang has first developed an equation to define the relation between shear strength and lateral deformation [6]. Since then, Wong et al. [7, Ang/Wong model], Aschheim and Moehle [12, UCB model], Priestley et al. [13, UCSD-A model], California department of transportation [14, Caltran model], Applied Technology Council [15, ATC model], and Kowalsky and Priestley [16, UCSD-B model] have respectively proposed seismic shear strength models for circular concrete columns by revising or modifying Ang's model.

Fig. 2 shows outlines of the previous models that are applied to evaluate the seismic shear strength of a sample column (Unit 16) tested by Ang [5]. Details of the sample column can be found elsewhere [5] and will not be given in the paper. As obvious from Fig. 2, only one model, the UCSD-A model, is a quadric-linear model, and the others are trilinear ones. The models are all ductility-based, and define shear strength as a function of displacement ductility. According to these models, the shear strength remains its initial nominal strength V_{iu} till the displacement ductility (μ) reaches a specific value, which has been assumed to be 1.0 or 2.0. From that displacement ductility on, the shear strength begins to decrease

Table 1
Varying ranges of the primary experimental variables in the database.

Failure mode	Flexure	Shear	Flexure–shear
Number of columns	93	88	94
Overall diameter of column D (mm)	152–1520	250–610	250–610
Shear span ratio a/D	1.0–10.0	0.8–2.5	1.1–6.0
Concrete strength f_c' (MPa)	22.0–90.0	22.4–49.6	23.6–57.0
Axial load ratio η[a]	−0.15 to 0.76	0.00–0.60	−0.10 to 0.60
Transverse steel			
Steel ratio ρ_h (%)[b]	0.12–3.24	0.00–1.58	0.10–3.24
Yield strength f_{yh} (MPa)	240–1417	0–1499	240–1420
Longitudinal rebar			
Steel ratio ρ_g (%)	0.53–5.57	1.33–4.57	0.52–5.21
Yield strength f_{ys} (MPa)	240–894	296–1065	240–803

[a] Compressive axial load is taken as positive.
[b] Volumetric ratio of transverse steel to the concrete core measured between centroids of peripheral hoop or spiral.