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Analytical prediction of the pinching mechanism of RC elements under cyclic shear using a rotation-angle softened truss model

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Abstract

The response of a reinforced concrete (RC) element under cyclic shear is characterized by the hysteretic loops of the shear stress–strain curves. These hysteretic loops can exhibit strength deterioration, stiffness degradation, and a pinched shape. Recent tests [Mansour MY, Hsu TTC. Behavior of reinforced concrete elements under cyclic shear. I: Experiments. ASCE Journal of Structural Engineering 2005;131(1):44–53] have shown that the orientation of steel grids in RC shear elements has a strong effect on the "pinching effect" in the post-yield hysteretic loops. When the steel grid was set at a 45 degree angle to the shear plane, there was no pinching effect and no strength deterioration. However, when the steel grid was set parallel to the shear plane, there was a severe pinching effect and severe strength deterioration with increasing shear strain magnitude. It was thus obvious that the undesirable "pinching effect" and strength deterioration that were attributed to the presence of high shear forces can be eliminated by properly orienting the steel grid in RC elements subjected to cyclic shear.

In this paper, two RC elements subjected to reversed cyclic shear stresses are considered to study the effect of the steel grid orientation on the shape of the cyclic shear stress–strain curves. The presence and absence of the pinching mechanism in the post-yield shear hysteretic loops is studied using the Rotating Angle Softened Truss Model (RA-STM) theory [Hsu TTC. Softened truss model theory for shear and torsion. ACI Structural Journal 1988;85(6):624–35]. It is found that the RA-STM when combined with newly proposed cyclic material constitutive relationships can rationally predict the presence and absence of the pinching effect in the shear hysteretic loops of RC shear elements but is still incapable of predicting the descending envelopes.

Keywords: Pinching effect; Energy dissipation; Ductility; Cyclic loading; Shear; Stress; Strain

1. Introduction

Structures located in earthquake regions are designed to withstand moderate seismic loading within the elastic range, and to absorb the energy of severe seismic loading using the plastic range. Consequently, it becomes necessary to evaluate the inelastic responses and energy dissipation capacities of such structures and to determine methods to enhance their seismic behavior under earthquake loading. In the case of structures that deform primarily in the flexural mode, the response is governed by well-rounded hysteretic load–deformation curves because the response of such elements is governed mainly by the properties of the reinforcing steel bars. By comparison, reinforced concrete elements that deform primarily in the shear mode frequently show significant pinching around zero load, and severe strength deterioration in their hysteretic loops.

Thus, when the shear force governs the response of a reinforced concrete (RC) element, as in the case of a low-rise shear wall, the effect of shear on the element's response is thought to be responsible for the "pinching effect" in the hysteretic loops, resulting in the degradation of stiffness, deterioration of strength and the reduction of

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Nomenclature

E_{cr} and E_s modulus of elasticity of concrete and steel bars, respectively
f'_c compressive strength of concrete cylinder
f_{cr} cracking stress of concrete
f'_{ct4} stress at point TD between Stage C1 and Stage T4
f_i and ε_i average steel stress and strain at the load reversal point, respectively
f_ℓ, f_t smeared stresses of steel bars in the ℓ and t directions, respectively
f_s and ε_s average stress and strain of mild steel bars, respectively,
f_y and ε_y yield stress and strain of bare mild steel bars, respectively
k loading coefficient
α angle between the direction of the principal concrete stress and the direction of the longitudinal steel
$\gamma_{\ell t}$ smeared shear strain in the ℓ–t coordinate system
γ_{45° smeared shear strain in the 45° direction
ε_c and σ_c average strain and stress of concrete
ε_{ci} and σ_{ci} concrete strain and stress at the load reversal point
ε_{ci+1} concrete strain at the end of the stage under consideration
ε_d, ε_r smeared principal strains in the r and d directions, respectively
ε_ℓ, ε_t smeared strains in the ℓ and t directions, respectively
ε_H, ε_V smeared strains in the H and V directions, respectively
ε_o peak cylinder compressive strain of concrete
ξ_σ and ξ_ε softening coefficient of stress and strain, respectively
ρ reinforcement steel ratio
ρ_ℓ, ρ_t steel ratios in the ℓ and t directions, respectively
σ_d and σ_r principal stresses in the cracked concrete in the d and r directions, respectively
σ_ℓ, σ_t applied cyclic normal stresses in the ℓ and t directions, respectively
σ^c_ℓ, σ^c_t stresses on the concrete element alone in the ℓ and t directions, respectively
$\tau_{\ell t}$ applied cyclic shear stress in the ℓ–t coordinate system
$\tau^c_{\ell t}$ shear stress on the concrete element alone in the ℓ–t coordinate system

energy dissipation capacity, as the cyclic loading increases beyond the yielding level. However, it was recently shown that this undesirable pinching effect [1] can be eliminated in the hysteretic load–deformation curves of a shear-dominant element if the steel grid orientation is properly aligned in the direction of the applied principal stresses. In this case, RC shear-dominant elements can be designed to possess high energy dissipation capacities, just like RC flexural-dominant elements.

The effect of the steel bar orientation on the structural response of RC structures was first experimentally investigated by Paulay [3] and Paulay and Binney [4] who showed that the pinching effect in the hysteretic loops of coupling beams can be controlled by adding inclined shear reinforcement, as shown in Fig. 1(a). Fig. 1(b), on the other hand, shows the severe pinched shape in the hysteretic loops of the same beam considered in Fig. 1(a), when no inclined shear reinforcement is used. Their test results also revealed that the ductility, energy dissipation and strength of coupling beams were considerably improved by arranging steel diagonally.

The mechanisms behind the presence of the pinching effect in the hysteretic loops of shear-dominant structures were studied by several researchers, like Kinugasa and Nomura [5] and Fenwick et al. [6] to name a few, who showed that the pinching effect was mainly due to the opening and closing of concrete cracks under cyclic loading. According to their findings, when subjected to cyclic shear, two out of phase orthogonal sets of diagonal concrete struts and cracks form in an RC element. After steel yielding, the shear deformation significantly increases and hence the crack width also increases. When the applied shear force is reversed in direction, the opened cracks are closed in one direction and the closed cracks start to open in the orthogonal direction at very low level of shear forces. As a consequence, the strength and the stiffness of the cracked concrete are remarkably reduced during this period of load reversal, creating the pinching effect. The presence of the pinching effect was also attributed to the deterioration of the bond between concrete and the steel bars. Several bond–slip models [7–9] were in turn proposed to analytically model the pinching effect in the hysteretic loops of the load–deformation curves of shear-dominant elements.

Even though previous researchers [5,6] were able to describe physically the pinching mechanism in shear dominant structures, to date no study has been able to show analytically the variation of the concrete and steel stresses and strains as the pinching effect progresses for the hysteretic loops of the shear stress–strain curves of RC elements. In this paper, the Rotating Angle Softened Truss Model [2] (RA-STM) is used to explain rationally the presence and absence of the pinching mechanism in the hysteretic loops of the shear stress–strain curves of two out of twelve RC elements previously tested by Mansour and Hsu [1]. The tested panels were subjected to reversed cyclic shear. The RA-STM which was previously proposed by Hsu [2] to predict the shear behavior of RC elements subjected to monotonic loading is extended in this paper to predict the cyclic behavior of two RC