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Seismic analysis and design of steel-plate concrete composite shear wall piers

Siamak Epackachi *, Andrew S. Whittaker, Amjad Aref

Dept. of Civil, Structural and Environmental Engineering, University at Buffalo, NY, United States

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ABSTRACT

This paper presents results of numerical studies on the in-plane monotonic response of steel-plate concrete (SC) composite shear wall piers. Results of finite element analysis of 98 SC wall piers are used to investigate the effects of wall aspect ratio, reinforcement ratio, slenderness ratio, axial load, yield strength of the steel faceplates, and uniaxial compressive strength of concrete on in-plane response, and to formulate (a) predictive equations to establish the trilinear lateral force versus lateral displacement response of SC wall piers up to peak strength, sufficient for seismic analysis of structures including SC wall piers and (b) a mechanics-based design equation for peak flexural strength, which addresses the interaction of co-existing shear and axial force. Design of Experiments is used to select the 98 piers. The baseline finite element model was formally validated using data from reversed cyclic, inelastic in-plane tests of four large-scale SC wall piers.

1. Introduction

Steel-plate concrete (SC) composite shear walls used or proposed for construction in the United States are constructed using steel faceplates, infill concrete, and connectors used to anchor the steel faceplates together and to the infill concrete. Although the seismic behavior of SC walls has been studied in some detail over the past 25+ years [1–20], the number of applications to date has been limited. Empirical equations to predict the initial stiffness and lateral load capacity of SC walls have been proposed, but effects of key design variables, including wall aspect ratio, reinforcement and slenderness ratios, axial load, and material properties have not been systemically accounted for. Herein, these design variables are addressed explicitly to

- Develop predictive equations to fully characterize the trilinear seismic response of an SC wall pier up to peak strength, suitable for inclusion in an analysis standard.
- Verify and validate a mechanics-based equation for the peak flexural strength of an SC wall pier, suitable for inclusion in a seismic design standard.

The following sections of this paper provide the technical bases for the predictive equations to characterize trilinear response and the mechanics-based equation for peak flexural strength. The literature review that follows immediately below focuses on those studies that address the behavior of SC wall piers considering one or more of the key design variables listed above.

2. Literature review

Fukumoto et al. [21] tested 1/4-scale steel plate, plain concrete, and composite shear walls under axial and shear loads to study the effects of composite action between the steel faceplates and the infill concrete, slenderness ratio, and stiffening methods for the steel faceplates, on the response of SC walls. The composite walls were constructed by assembling welded steel boxes and infilling them with concrete: different from the construction discussed above. Qualitative conclusions were drawn but they were by-and-large specific to the construction used.

Takeda et al. [22] subjected seven composite wall panels to in-plane cyclic loading in pure shear. The primary focus of their study was the effect of thickness of steel faceplates, partitioning webs, and the use of studs, on the shear response of SC panels. The specimens were composed of two steel faceplates, infill concrete, headed steel studs anchoring the faceplates to the infill, and the partitioning webs joining the steel faceplates: somewhat different to the construction discussed above. The results of the

* Corresponding author.
E-mail address: siamakep@buffalo.edu (S. Epackachi).

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Nomenclature

A_c	cross-section area of infill concrete
A_c^{eff}	effective cross-sectional area of the infill concrete (= $A_c/1.2$)
A_g	total cross-section area of SC wall
A_s	cross-section area of steel faceplates
A_s^{eff}	effective cross-sectional area of the steel faceplates (= $A_s/1.2$)
c	depth to the neutral axis of the steel faceplates
c'	depth to the neutral axis of the infill concrete
E_c	elastic modulus of concrete (MPa)
E_s	elastic modulus of steel (MPa)
f'_c	uniaxial compressive stress of concrete (MPa)
f_t	nominal tensile strength of concrete (MPa)
f_t^*	effective tensile strength of concrete (MPa)
f_y	yield stress of steel faceplates (MPa)
f_s^*	effective stress in steel faceplates (MPa)
G_c	elastic shear modulus of concrete (MPa)
G_f	specific fracture energy (the energy required to propagate a tensile crack of unit area)
G_s	elastic shear modulus of steel (MPa)
H	wall height
H^*	moment to shear ratio (= wall height for single story wall panels)
I_c	moment of inertia of the cross section of the infill concrete
I_s	moment of inertia of the cross section of the steel faceplates
K_{el}	theoretical initial stiffness of SC wall
K_{el}^c	theoretical initial stiffness of infill concrete
K_{el}^s	theoretical initial stiffness of steel faceplates
K_{fc}	flexural stiffness of infill concrete
K_{vc}	shear stiffness of infill concrete
K_{fs}	flexural stiffness of steel faceplates
K_{vs}	shear stiffness of steel faceplates
K_{el}^s	theoretical initial stiffness of steel faceplates
K_y	pre-yield stiffness of SC wall
K_P	post-yield stiffness of SC wall
L	length of wall
M	bending moment
N	axial load
V_c^y	shear force resisted by infill concrete at the onset of steel faceplate yielding
V_s^y	shear force resisted by steel faceplates at the onset of steel faceplate yielding
V_y	lateral force resisted by SC wall at the onset of steel faceplate yielding
V_c^p	shear force resisted by infill concrete at peak lateral load
V_s^p	shear force resisted by steel faceplates at peak lateral load
V_p	lateral load capacity of SC wall
V_{flex}^*	shear force associated with the ultimate moment capacity of SC wall cross-section
t_c	thickness of infill concrete
t_s	thickness of each steel faceplate
w	crack width
ε_c	concrete strain at extreme fiber in compression
ε_{cu}	ultimate concrete strain
ε_y	steel strain at yielding
ρ_s	reinforcement ratio
β_1	stress block coefficient
β_2	stress block coefficient

Takeda study indicated that stud spacing, in the range considered, had no effect on peak strength. These authors parsed the pre-peak-strength response into four regions: (1) elastic, (2) post-concrete cracking, (3) post-buckling of steel faceplates, and (4) post-yielding of steel faceplates. The shear response of these SC panels was idealized using a perfectly plastic force-displacement relationship because their lateral load capacity did not deteriorate at shear strains less than 2%.

Sasaki et al. [23] tested seven flanged walls with aspect ratios ranging between 0.33 and 0.5 to investigate the effects of aspect ratio, reinforcement ratio, axial load, and the use of headed studs attached to the end plates of the web wall on the flexural-shear response of SC walls. A faceplate slenderness ratio of 33 was used. They reported the lateral stiffness and strength of a flanged SC walls increase with decreasing shear span-to-depth ratio and increasing reinforcement ratio, which is somewhat intuitive. Increases in axial load led to an increase in lateral strength but not initial stiffness.

Ozaki et al. [14] tested flanged walls with different aspect and reinforcement ratios under lateral loading to investigate the in-plane response of shear-critical and flexure-critical SC walls. Five shear-critical SC specimens with aspect ratios ranging from 0.5 to 0.85 and reinforcement ratios ranging from 0.7% to 2% were tested. The reinforcement ratio had a small effect on the initial stiffness and cracking strength of the shear-critical SC walls but it significantly affected the yield and the peak lateral loads. The displacements corresponding to the yield and lateral loads were not affected by reinforcement ratio. Four flexure-critical SC walls with aspect ratios of 0.7 and 0.85, and a reinforcement ratio of 2%, were also tested. The design parameters considered in this part of their study were aspect ratio, axial force, and type of SC wall connection to the foundation. Ozaki et al. proposed that the bending strength of flexure-critical SC walls be calculated using the results of plastic cross-section analysis. The interaction of axial force and bending moment was ignored.

Nie et al. [24] subjected twelve walls to axial and cyclic lateral loads to investigate the effects of reinforcement ratio, concrete strength, thicknesses of the steel face and flange plates, concrete reinforcement, and wall aspect ratio on the in-plane response of SC walls. The reinforcement and aspect ratios varied from 4.6% to 7.1%, and from 1 to 2, respectively. The twelve specimens failed in flexure, characterized by local buckling and fracture of the steel faceplates. Their test results showed that peak strength increased as shear span-to-depth ratio decreased. Changes in the concrete compressive strength had little effect on the stiffness of the SC specimens.

Kurt et al. [12] reported the effects of wall aspect ratio, wall thickness, and reinforcement ratio on the monotonic response of SC wall piers. The finite element codes ABAQUS [25] and LS-DYNA were used for the numerical simulations. Data from tests of eight SC wall piers [10,12] and the numerical simulations were used to derive design equations for the lateral load capacity of SC wall piers. The proposed equation for in-plane flexural capacity is parsed by aspect ratio (ratio of height to length): (1) for aspect ratios of 0.5 and smaller, the capacity is equal to the moment corresponding to the onset of yielding of the steel faceplates at the compression end of the wall and (2) for aspect ratios of 1.5 and greater, the capacity is equal to the plastic moment capacity of the wall cross-section. The flexural capacity for intermediate aspect ratios is determined by linear interpolation but accounts for wall thickness. The effects of co-existing axial and shearing forces on flexural capacity are not addressed.