

EFFECTIVE LATERAL STIFFNESS OF STEEL-PLATE CONCRETE COMPOSITE SHEAR WALL PIERS

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ABSTRACT

Building codes and standards of practice recommend reductions in the flexural and shear rigidities of uncracked reinforced concrete shear walls for estimation of effective stiffness for the purpose of static and dynamic analysis. There are no comparable recommendations for composite shear wall piers consisting of steel faceplates, infill concrete, and connectors used to anchor the steel faceplates together and to the infill concrete.

Results of a parametric study of 77 SC wall piers are used to develop equations to estimate reduction factors for the shear and flexural rigidities of SC wall piers as a function of design variables including wall aspect ratio, reinforcement ratio, slenderness ratio, axial load, yield strength of the steel faceplates, and uniaxial compressive strength of concrete. The predictive equations are suitable for inclusion in seismic design standards such as ASCE/SEI 4, 7, 41 and 43.

INTRODUCTION

Steel-plate concrete (SC) composite shear walls consists of steel faceplates, infill concrete, and connectors used to anchor the steel faceplates together and to the infill concrete. In the past four decades, a number of experimental, analytical, and numerical studies have investigated the behavior of SC walls. Empirical equations to predict the initial stiffness and peak shear strength of SC walls have been proposed using either limited test data available in the literature or mechanics-based equations based on simplifying assumptions (e.g., Epackachi et al. 2014b, Nie et al. 2014, Varma et al. 2014). However, the effects of SC wall design variables, including wall aspect ratio, reinforcement and slenderness ratios, axial load, and material properties on the effective lateral stiffness of SC wall piers have not been systematically studied.

An NSF-funded research project was completed at the University at Buffalo in 2013 that investigated the seismic performance of SC wall piers for application to buildings and mission-critical infrastructure such as nuclear power plants (Epackachi et al. 2016a)). The SC walls considered in that study were composed of two steel faceplates, infill concrete, headed studs to connect the infill concrete to the steel faceplates, and tie rods to connect two steel faceplates together. The research program included testing of four large four large-size specimens with an aspect ratio (height-to-length) of 1.0 (Epackachi et al. 2014a)) followed by numerical and analytical studies on the in-plane behavior of flexure- and flexure-shear-critical SC wall piers. The design variables in the experimental program were wall thickness, reinforcement, and slenderness ratios, where the reinforcement ratio is defined as the ratio of the cross-sectional area of the steel faceplates to the total cross-sectional area of SC wall and the faceplate slenderness ratio is the spacing of the connectors (studs or tie rods) divided by the steel faceplate thickness. A validated LS-

DYNA (LSTC 2012a, 2012b) model was used to simulate the nonlinear cyclic behavior of the SC walls (Epackachi et al. 2015)). Mechanics-based and simplified equations were also developed for preliminary analysis and design of SC walls (Epackachi et al. 2014b, 2016b).

A comprehensive parametric study was conducted to investigate the effects of key design variables on the inelastic response of SC wall piers using the validated LS-DYNA model. The results of that study are presented in Epackachi et al. (2016b).

Building codes and standards of practice recommend reductions in the flexural and shear rigidities of uncracked reinforced concrete shear walls for estimation of effective stiffness for the purpose of static and dynamic analysis. For example, ASCE/SEI 41-13 (ASCE 2013) recommends a reduction of 50% in the flexural rigidity and no reduction in the shear rigidity for cracked reinforced concrete shear walls. There are no comparable recommendations for composite shear wall piers consisting of steel faceplates, infill concrete, and connectors used to anchor the steel faceplates together and to the infill concrete, and the goal of this paper is to fill this gap. Results of the prior parametric study of 77 SC wall piers are systematically analyzed to investigate the effects of aspect ratio, reinforcement ratio, slenderness ratio, axial load, yield strength of the steel faceplates, and concrete compressive strength on the effective lateral stiffness of SC wall piers.

DESIGN VARIABLES

The design variables considered in this study are wall aspect ratio (AR), reinforcement ratio (RR), slenderness ratio of the steel faceplates (SR), axial force ratio (AL), yield strength of the steel faceplates (SS), and concrete compressive strength (CS). The reinforcement and slenderness ratios were defined in the previous section. The axial force ratio is the ratio of the applied axial compressive force to the product of the concrete compressive strength and the total wall area (i.e., $(2t_s + T)L_w$, where t_s and T are the thickness of each steel faceplate and infill concrete, respectively, and L_w is the length of the wall). The range on each design variable considered in the study is presented in Table 1. The values of -1, 0, and +1 show the coded values used in the analysis.

Table 1. Levels of the design parameters

| Variable | Low | Intermediate | High |
|--|-----------|--------------|-----------|
| Aspect ratio | 0.5 (-1) | 1.25 (0) | 2.0 (+1) |
| Reinforcement ratio (%) | 1.67 (-1) | 3.33 (0) | 5.0 (+1) |
| Slenderness ratio | 10 (-1) | 25 (0) | 40 (+1) |
| Axial force ratio | 0 (-1) | 0.1 (0) | 0.2 (+1) |
| Yield strength of the steel faceplates (MPa) | 235 (-1) | 350 (0) | 460 (+1) |
| Concrete compressive strength (MPa) | 27.6 (-1) | 41.4 (0) | 55.2 (+1) |

Three aspect ratios (= 0.5, 1.0, and 2.0) are considered to study the behavior of low-, intermediate-, and high-aspect ratio wall piers, to address shear- and flexure-critical behaviors. The range for reinforcement ratio was based on Section N9.1.1c of AISC N690s1 (AISC 2015), which limits the reinforcement ratio to a minimum of 1.5% and a maximum of 5%. Section N9.1.3 of AISC N690s1 specifies a maximum slenderness ratio of $1.0\sqrt{E_s / f_y}$ to prevent local buckling of the steel faceplates before yielding, where E_s and f_y are the Young's modulus and nominal yield strength of the steel faceplate, respectively. For the range of the yield strength of the steel faceplates considered in this study (235 to 460 MPa), the AISC-specified maximum slenderness ratio varies between 21 and 29. This range was extended in the numerical study: 10 to 40. Plate steel of ASTM A36 ($f_y = 235$ MPa), A588 ($f_y = 350$ MPa), and A852 ($f_y = 460$ MPa) were used to represent low, intermediate, and high values of yield strength, respectively.

Design of Experiments (DOE) concepts were used to consider any potential interactions of the design variables. A three-level, six-factor, fractional factorial design was selected to build different combinations of the design variables for the numerical analysis of SC walls (Montgomery 1982). The levels of the design variables for each run are listed in Table 2.

Table 2. Coded values of the design variables for the parametric study

| Run | Factor levels | | | | | | Run | Factor levels | | | | | |
|-----|---------------|----|----|----|----|----|-----|---------------|----|----|----|----|----|
| | AR | RR | AR | RR | SR | AL | | AR | RR | AR | RR | SR | AL |
| 1 | -1 | -1 | -1 | -1 | -1 | -1 | 41 | 1 | -1 | 1 | -1 | -1 | -1 |
| 2 | -1 | -1 | -1 | -1 | -1 | 1 | 42 | 1 | -1 | 1 | -1 | -1 | 1 |
| 3 | -1 | -1 | -1 | -1 | 1 | -1 | 43 | 1 | -1 | 1 | -1 | 1 | -1 |
| 4 | -1 | -1 | -1 | -1 | 1 | 1 | 44 | 1 | -1 | 1 | -1 | 1 | 1 |
| 5 | -1 | -1 | -1 | 1 | -1 | -1 | 45 | 1 | -1 | 1 | 1 | -1 | -1 |
| 6 | -1 | -1 | -1 | 1 | -1 | 1 | 46 | 1 | -1 | 1 | 1 | -1 | 1 |
| 7 | -1 | -1 | -1 | 1 | 1 | -1 | 47 | 1 | -1 | 1 | 1 | 1 | -1 |
| 8 | -1 | -1 | -1 | 1 | 1 | 1 | 48 | 1 | -1 | 1 | 1 | 1 | 1 |
| 9 | -1 | -1 | 1 | -1 | -1 | -1 | 49 | 1 | 1 | -1 | -1 | -1 | -1 |
| 10 | -1 | -1 | 1 | -1 | -1 | 1 | 50 | 1 | 1 | -1 | -1 | -1 | 1 |
| 11 | -1 | -1 | 1 | -1 | 1 | -1 | 51 | 1 | 1 | -1 | -1 | 1 | -1 |
| 12 | -1 | -1 | 1 | -1 | 1 | 1 | 52 | 1 | 1 | -1 | -1 | 1 | 1 |
| 13 | -1 | -1 | 1 | 1 | -1 | -1 | 53 | 1 | 1 | -1 | 1 | -1 | -1 |
| 14 | -1 | -1 | 1 | 1 | -1 | 1 | 54 | 1 | 1 | -1 | 1 | -1 | 1 |
| 15 | -1 | -1 | 1 | 1 | 1 | -1 | 55 | 1 | 1 | -1 | 1 | 1 | -1 |
| 16 | -1 | -1 | 1 | 1 | 1 | 1 | 56 | 1 | 1 | -1 | 1 | 1 | 1 |
| 17 | -1 | 1 | -1 | -1 | -1 | -1 | 57 | 1 | 1 | 1 | -1 | -1 | -1 |
| 18 | -1 | 1 | -1 | -1 | -1 | 1 | 58 | 1 | 1 | 1 | -1 | -1 | 1 |
| 19 | -1 | 1 | -1 | -1 | 1 | -1 | 59 | 1 | 1 | 1 | -1 | 1 | -1 |
| 20 | -1 | 1 | -1 | -1 | 1 | 1 | 60 | 1 | 1 | 1 | -1 | 1 | 1 |
| 21 | -1 | 1 | -1 | 1 | -1 | -1 | 61 | 1 | 1 | 1 | 1 | -1 | -1 |
| 22 | -1 | 1 | -1 | 1 | -1 | 1 | 62 | 1 | 1 | 1 | 1 | -1 | 1 |
| 23 | -1 | 1 | -1 | 1 | 1 | -1 | 63 | 1 | 1 | 1 | 1 | 1 | -1 |
| 24 | -1 | 1 | -1 | 1 | 1 | 1 | 64 | 1 | 1 | 1 | 1 | 1 | 1 |
| 25 | -1 | 1 | 1 | -1 | -1 | -1 | 65 | 0 | 0 | 0 | 0 | 0 | 0 |
| 26 | -1 | 1 | 1 | -1 | -1 | 1 | 66 | -1 | 0 | 0 | 0 | 0 | 0 |
| 27 | -1 | 1 | 1 | -1 | 1 | -1 | 67 | 1 | 0 | 0 | 0 | 0 | 0 |
| 28 | -1 | 1 | 1 | -1 | 1 | 1 | 68 | 0 | -1 | 0 | 0 | 0 | 0 |
| 29 | -1 | 1 | 1 | 1 | -1 | -1 | 69 | 0 | 1 | 0 | 0 | 0 | 0 |
| 30 | -1 | 1 | 1 | 1 | -1 | 1 | 70 | 0 | 0 | -1 | 0 | 0 | 0 |
| 31 | -1 | 1 | 1 | 1 | 1 | -1 | 71 | 0 | 0 | 1 | 0 | 0 | 0 |
| 32 | -1 | 1 | 1 | 1 | 1 | 1 | 72 | 0 | 0 | 0 | -1 | 0 | 0 |
| 33 | 1 | -1 | -1 | -1 | -1 | -1 | 73 | 0 | 0 | 0 | 1 | 0 | 0 |
| 34 | 1 | -1 | -1 | -1 | -1 | 1 | 74 | 0 | 0 | 0 | 0 | -1 | 0 |
| 35 | 1 | -1 | -1 | -1 | 1 | -1 | 75 | 0 | 0 | 0 | 0 | 1 | 0 |
| 36 | 1 | -1 | -1 | -1 | 1 | 1 | 76 | 0 | 0 | 0 | 0 | 0 | -1 |
| 37 | 1 | -1 | -1 | 1 | -1 | -1 | 77 | 0 | 0 | 0 | 0 | 0 | 1 |
| 38 | 1 | -1 | -1 | 1 | -1 | 1 | | | | | | | |
| 39 | 1 | -1 | -1 | 1 | 1 | -1 | | | | | | | |
| 40 | 1 | -1 | -1 | 1 | 1 | 1 | | | | | | | |

NUMERICAL MODELLING OF SC WALL PIERS

The numerical analysis of the SC wall models was conducted using the general-purpose finite element code LS-DYNA. The Winfrith concrete model (MAT085) developed by Broadhouse (Broadhouse (1986)) and the Piecewise-Linear-Plasticity model (MAT024) in LS-DYNA were used for the infill concrete and steel faceplates, respectively. The details of the material models are available in Epackachi et al. (2015). The concrete and steel material properties input to the LS-DYNA model are presented in Tables 3 and 4, respectively.

Table 3. Concrete material properties

| Compressive strength level | Young's modulus (MPa) | Poisson's ratio | Uniaxial compressive strength (MPa) | Uniaxial tensile strength (MPa) | Crack width (mm) | Agg. size (mm) |
|----------------------------|-----------------------|-----------------|-------------------------------------|---------------------------------|------------------|----------------|
| Low | 24856 | 0.20 | 27.6 | 2.8 | 0.052 | 19 |
| Intermediate | 30442 | 0.20 | 41.4 | 3.6 | 0.052 | 19 |
| High | 35151 | 0.20 | 55.2 | 4.4 | 0.053 | 19 |

Table 4. Steel material properties

| Yield strength level | Young's modulus (MPa) | Poisson's ratio | Yield strength (MPa) | Ultimate strength (MPa) | Fracture strain (%) |
|----------------------|-----------------------|-----------------|----------------------|-------------------------|---------------------|
| Low | 200000 | 0.30 | 235 | 390 | 24 |
| Intermediate | 200000 | 0.30 | 350 | 460 | 22 |
| High | 200000 | 0.30 | 460 | 635 | 19 |

The friction between the steel faceplates and infill concrete was modelled using CONTACT-AUTOMATIC-SURFACE-TO-SURFACE formulation available in LS-DYNA. The studs and tie rods were tied to the infill concrete elements. Beam elements were used to model the studs and tie rods. Eight-node solid elements, $25.4 \times 25.4 \times 25.4$ mm, and 25.4×25.4 mm four-node shell elements were used to model the infill concrete and steel faceplates, respectively. The length and the thickness of the walls were set to 1524 mm and 304.8 mm, respectively, and the heights of the low-, intermediate- and high-aspect ratio SC walls were selected to achieve the desired aspect ratios of 0.5, 1.0, and 2.0, respectively.

EFFECTIVE LATERAL STIFFNESS OF SC WALL PIERS

The effective flexural and shear rigidities of a SC wall pier can be calculated as:

$$EI_{eff} = \eta_f (E_c I_c + E_s I_s) \quad (1)$$

$$GA_{eff} = \eta_v (G_c A_c^{eff} + G_s A_s^{eff}) \quad (2)$$

where E_c and E_s are the elastic modulus of the concrete and steel, respectively; G_c and G_s are the shear modulus of the concrete and steel, respectively; I_c and I_s are the moment of inertia of the cross section of the infill concrete and the steel faceplates, respectively; A_c^{eff} and A_s^{eff} are the effective cross-sectional areas of the infill concrete and the steel faceplates, respectively, calculated as the total cross-sectional area

divided by 1.2; and h is the height of the wall, and η_f and η_v are the flexure and shear stiffness reduction factors and can be calculated as:

$$\eta_f = \frac{K_f^{DYNA}}{K_{fc} + K_{fs}}, \eta_v = \frac{K_v^{DYNA}}{K_{vc} + K_{vs}} \quad (3)$$

where K_f^{DYNA} and K_v^{DYNA} are the DYNA-predicted secant flexure and shear stiffnesses at the yield point, respectively, and calculated by dividing the DYNA-predicted yield force to the shear and flexural displacements, respectively.

The flexural displacement at the top of the SC wall, Δ_f , was calculated as:

$$\Delta_f = \zeta \theta H \quad (4)$$

where θ is the rotation at top of the wall, H is the height of the wall, ζ is the distance between the top of the wall and centroid of the curvature diagram, and θ and ζ can be calculated as:

$$\theta = \frac{\Delta_{v1} - \Delta_{v2}}{L} \quad (5)$$

$$\zeta = \frac{\int_{y=0}^{y=h} y \Phi(y) dy}{h \int_{y=0} \Phi(y) dy} \quad (6)$$

where Δ_{v1} and Δ_{v2} are the vertical displacements on the tension and compression faces at the top of the wall, respectively, L is the length of the wall, and $\Phi(y)$ is the curvature of the wall section at a distance of y from top of the wall.

Each wall was discretized into sub-elements along its height to calculate the flexural displacement. The curvature in the i^{th} sub-element was calculated as:

$$\Phi_i = \frac{\delta_{v1}^i - \delta_{v2}^i}{L h_{sub}^i} \quad (7)$$

where δ_{v1}^i and δ_{v2}^i are the relative vertical displacements on the tension and compression faces of the i^{th} sub-element over its height, h_{sub}^i , respectively. The distance ζ was calculated as:

$$\zeta = \frac{\sum_{k=1}^m \Phi_k (k-1/2)}{m \sum_{k=1}^m \Phi_k} \quad (8)$$

where m is the number of sub-elements along the height of the wall. The height of each sub-element was set to 1 in for these calculations.

The shear displacement, Δ_v , was calculated as the difference between the total lateral displacement and the flexural displacement. The values of ζ , the ratio of the shear and flexure displacements to the yield displacement, yield displacement, and flexure and shear stiffness reduction factors are reported in Table 5. The ratio of Δ_f / Δ_y varies between 0.37 and 0.47 with an average of 0.41 for low aspect ratio SC walls ($H/L=0.5$) and between 0.88 and 0.94 with an average of 0.91 for the high aspect ratio SC walls ($H/L=2.0$). The distance between the top of the wall and the centroid of the curvature diagram, ζ , varies between 0.7 and 0.91, with an average of 0.8.

Based on these results, an estimation of the flexural displacement at any drift ratio in a SC panel is:

$$\Delta_f = 0.8(\Delta_{v1} - \Delta_{v2}) \frac{H}{L} \quad (9)$$

where Δ_{v1} and Δ_{v2} are the vertical displacements at the tension and compression faces at the top of the wall at given drift ratio.

The main effect plots of Figure 1 shows that the flexure stiffness reduction factor is significantly affected by all design variables. The effects of slenderness ratio and concrete strength on the shear stiffness reduction factor are negligible but the impact of other design variables is significant.

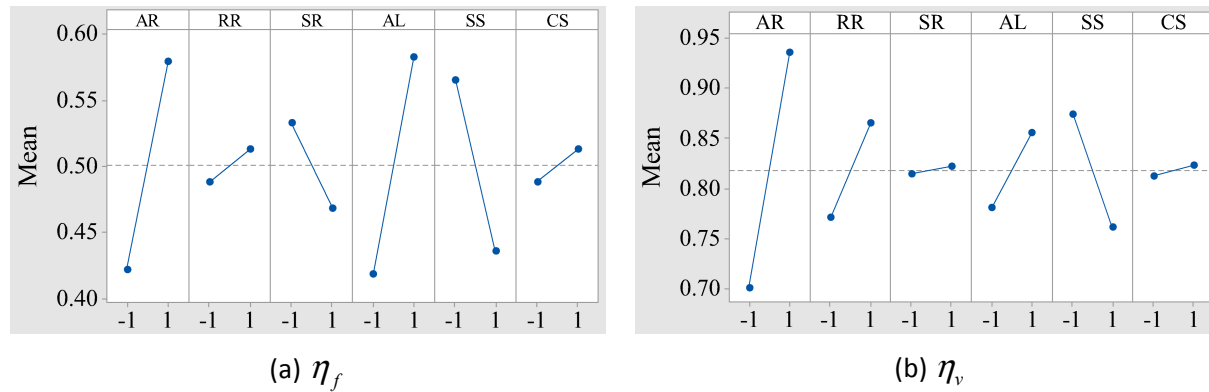


Figure 1. Main effect plots of design variables

Based on the results of ANOVA, two regression equations are proposed for the calculation of the flexure and shear stiffness reduction factors as a function of the coded design variables (i.e., variables varying between -1 and +1):

$$\begin{aligned} \eta_f = & 0.531 + 0.077(AR) + 0.012(RR) - 0.032(SR) + 0.083(AL) - 0.065(SS) + 0.012(CS) \\ & - 0.032(AR^2) - 0.017(AR)(SS) - 0.012(RR)(AL) + 0.017(RR)(SS) - 0.011(RR)(CS) \\ & - 0.019(AL)(CS) \end{aligned} \quad (10)$$

$$\begin{aligned} \eta_v = & 0.836 + 0.111(AR) + 0.040(RR) + 0.038(AL) - 0.059(SS) + 0.011(CS) \\ & - 0.026(AR^2) - 0.011(AR)(AL) + 0.027(AR)(SS) + 0.012(RR)(SR) - 0.017(RR)(AL) \\ & + 0.02(RR)(SS) + 0.013(AL)(CS) \end{aligned} \quad (11)$$

Equations (10) and (11) are used to calculate the effective flexural and shear rigidities of a SC wall pier in the following section.

Table 5. Effective stiffness calculation

| Run | ζ | Δ_f / Δ_y | Δ_v / Δ_y | Δ_y | η_f | η_v | Run | ζ | Δ_f / Δ_y | Δ_v / Δ_y | Δ_y | η_f | η_v |
|-----|---------|-----------------------|-----------------------|------------|----------|----------|-----|---------|-----------------------|-----------------------|------------|----------|----------|
| 1 | 0.83 | 42% | 58% | 0.015 | 0.43 | 0.74 | 40 | 0.73 | 90% | 10% | 0.233 | 0.68 | 0.91 |
| 2 | 0.82 | 43% | 57% | 0.015 | 0.43 | 0.76 | 41 | 0.76 | 92% | 8% | 0.108 | 0.49 | 0.87 |
| 3 | 0.77 | 39% | 61% | 0.045 | 0.28 | 0.44 | 42 | 0.76 | 92% | 8% | 0.108 | 0.48 | 0.84 |
| 4 | 0.78 | 42% | 58% | 0.040 | 0.27 | 0.47 | 43 | 0.79 | 94% | 6% | 0.183 | 0.34 | 0.76 |
| 5 | 0.82 | 38% | 62% | 0.025 | 0.56 | 0.82 | 44 | 0.80 | 94% | 6% | 0.178 | 0.32 | 0.70 |
| 6 | 0.80 | 38% | 62% | 0.025 | 0.62 | 0.90 | 45 | 0.73 | 90% | 10% | 0.158 | 0.70 | 0.94 |
| 7 | 0.86 | 37% | 63% | 0.045 | 0.42 | 0.60 | 46 | 0.71 | 89% | 11% | 0.178 | 0.76 | 0.95 |
| 8 | 0.82 | 38% | 62% | 0.040 | 0.52 | 0.75 | 47 | 0.76 | 92% | 8% | 0.238 | 0.54 | 0.89 |
| 9 | 0.87 | 45% | 55% | 0.020 | 0.34 | 0.67 | 48 | 0.75 | 91% | 9% | 0.258 | 0.59 | 0.91 |
| 10 | 0.86 | 46% | 54% | 0.020 | 0.34 | 0.69 | 49 | 0.72 | 91% | 9% | 0.118 | 0.63 | 0.97 |
| 11 | 0.88 | 45% | 55% | 0.035 | 0.26 | 0.51 | 50 | 0.73 | 91% | 9% | 0.113 | 0.61 | 0.95 |
| 12 | 0.88 | 47% | 53% | 0.035 | 0.25 | 0.52 | 51 | 0.72 | 92% | 8% | 0.228 | 0.53 | 0.90 |
| 13 | 0.85 | 39% | 61% | 0.030 | 0.49 | 0.76 | 52 | 0.74 | 92% | 8% | 0.208 | 0.48 | 0.88 |
| 14 | 0.82 | 39% | 61% | 0.030 | 0.56 | 0.85 | 53 | 0.71 | 89% | 11% | 0.153 | 0.76 | 0.99 |
| 15 | 0.91 | 39% | 61% | 0.050 | 0.37 | 0.56 | 54 | 0.71 | 89% | 11% | 0.168 | 0.80 | 0.98 |
| 16 | 0.87 | 38% | 62% | 0.050 | 0.44 | 0.65 | 55 | 0.73 | 91% | 9% | 0.258 | 0.63 | 0.95 |
| 17 | 0.86 | 42% | 58% | 0.020 | 0.44 | 0.78 | 56 | 0.73 | 90% | 10% | 0.263 | 0.66 | 0.95 |
| 18 | 0.85 | 43% | 57% | 0.020 | 0.42 | 0.78 | 57 | 0.77 | 93% | 7% | 0.128 | 0.53 | 1.00 |
| 19 | 0.86 | 41% | 59% | 0.040 | 0.37 | 0.64 | 58 | 0.77 | 93% | 7% | 0.128 | 0.50 | 0.99 |
| 20 | 0.86 | 43% | 57% | 0.035 | 0.35 | 0.65 | 59 | 0.80 | 94% | 6% | 0.238 | 0.44 | 1.00 |
| 21 | 0.85 | 39% | 61% | 0.030 | 0.52 | 0.80 | 60 | 0.81 | 94% | 6% | 0.228 | 0.39 | 0.99 |
| 22 | 0.82 | 38% | 62% | 0.030 | 0.57 | 0.87 | 61 | 0.74 | 91% | 9% | 0.168 | 0.68 | 1.00 |
| 23 | 0.88 | 38% | 62% | 0.045 | 0.45 | 0.69 | 62 | 0.73 | 90% | 10% | 0.188 | 0.72 | 1.00 |
| 24 | 0.86 | 38% | 62% | 0.050 | 0.47 | 0.70 | 63 | 0.78 | 93% | 7% | 0.283 | 0.55 | 1.00 |
| 25 | 0.89 | 44% | 56% | 0.025 | 0.38 | 0.74 | 64 | 0.77 | 92% | 8% | 0.298 | 0.58 | 1.00 |
| 26 | 0.88 | 45% | 55% | 0.025 | 0.36 | 0.73 | 65 | 0.76 | 80% | 20% | 0.093 | 0.54 | 0.84 |
| 27 | 0.90 | 44% | 56% | 0.040 | 0.34 | 0.65 | 66 | 0.84 | 39% | 61% | 0.038 | 0.42 | 0.64 |
| 28 | 0.89 | 45% | 55% | 0.040 | 0.31 | 0.63 | 67 | 0.76 | 93% | 7% | 0.158 | 0.45 | 0.90 |
| 29 | 0.86 | 39% | 61% | 0.030 | 0.50 | 0.80 | 68 | 0.76 | 80% | 20% | 0.088 | 0.54 | 0.81 |
| 30 | 0.82 | 39% | 61% | 0.030 | 0.56 | 0.86 | 69 | 0.77 | 81% | 19% | 0.103 | 0.52 | 0.88 |
| 31 | 0.91 | 39% | 61% | 0.050 | 0.41 | 0.66 | 70 | 0.76 | 80% | 20% | 0.093 | 0.55 | 0.84 |
| 32 | 0.87 | 39% | 61% | 0.050 | 0.46 | 0.70 | 71 | 0.78 | 81% | 19% | 0.103 | 0.49 | 0.82 |
| 33 | 0.74 | 91% | 9% | 0.080 | 0.62 | 0.93 | 72 | 0.78 | 83% | 17% | 0.083 | 0.42 | 0.79 |
| 34 | 0.73 | 90% | 10% | 0.070 | 0.67 | 0.92 | 73 | 0.75 | 79% | 21% | 0.108 | 0.61 | 0.88 |
| 35 | 0.76 | 93% | 7% | 0.180 | 0.38 | 0.77 | 74 | 0.75 | 79% | 21% | 0.073 | 0.62 | 0.89 |
| 36 | 0.78 | 93% | 7% | 0.140 | 0.42 | 0.83 | 75 | 0.77 | 81% | 19% | 0.118 | 0.48 | 0.80 |
| 37 | 0.71 | 89% | 11% | 0.125 | 0.82 | 0.97 | 76 | 0.75 | 80% | 20% | 0.093 | 0.53 | 0.82 |
| 38 | 0.70 | 88% | 12% | 0.158 | 0.84 | 0.97 | 77 | 0.76 | 80% | 20% | 0.098 | 0.54 | 0.84 |
| 39 | 0.74 | 92% | 8% | 0.233 | 0.43 | 0.77 | | | | | | | |

CALCULATION OF THE EFFECTIVE STIFFNESS OF AN SC WALL PIER

As an example, the effective stiffness of a cantilever SC wall pier on a rigid foundation is calculated using the predictive equations presented in this paper. The properties of the SC wall are presented in Table 6.

Table 6. SC wall properties

| | |
|---------------------------------------|------|
| Height, H (m) | 4.0 |
| Length, L (m) | 4.0 |
| Infill concrete thickness, T (mm) | 305 |
| Steel faceplate thickness, t_s (mm) | 6.35 |
| Stud spacing, S (mm) | 230 |
| Steel strength, f_y (MPa) | 350 |
| Concrete strength, f'_c (MPa) | 41 |
| Axial load, P (kN) | 7560 |

Mechanical Properties of SC Wall

$$E_c = 4700\sqrt{f'_c} = 4700\sqrt{41} = 30094 \text{ MPa}$$

$$G_c = E_c / 2(1 + \nu_c) = 30094 / 2(1 + 0.2) = 12539 \text{ MPa}$$

$$I_c = \frac{1}{12}TL^3 = \frac{1}{12} \times 0.305 \times 4^3 = 1.63 \text{ m}^4$$

$$A_c = TL = 0.305 \times 4 = 1.22 \text{ m}^2$$

$$E_s = 200000 \text{ MPa}$$

$$G_s = E_s / 2(1 + \nu_s) = 200000 / 2(1 + 0.3) = 76923 \text{ MPa}$$

$$I_s = \frac{1}{12}2t_sL^3 = \frac{1}{12} \times 2 \times 0.0064 \times 4^3 = 0.067 \text{ m}^4$$

$$A_s = 2t_sL = 2 \times 0.0064 \times 4 = 0.051 \text{ m}^2$$

The actual and coded values of the design variables are listed in Table 7. The coded values of the design variables were calculated using the actual values and the ranges defined in Table 1.

Table 7. Values of design variables

| Design variable | Actual value | Coded value |
|---|--------------|-------------|
| Aspect ratio, $AR = H / L$ | 1.00 | -0.33 |
| Reinforcement ratio, $RR = 2t_s / T$ | 0.042 | -0.10 |
| Slenderness ratio, $SR = S / t_s$ | 36 | 0.73 |
| Axial load ratio, $AL = P / (A_g f'_c)$ | 0.2 | 1.00 |
| Steel strength, $SS = f_y$ | 350 | 0.00 |
| Concrete strength, $CS = f'_c$ | 41 | 0.00 |

The values of the flexure and shear stiffness reduction factors, η_f and η_v , were calculated to be 0.56 and 0.83, respectively. The flexure and shear stiffness reduction factors were calculated using the values of coded design variables and Equations (10) and (11), respectively.

The values of the effective flexural and shear rigidities are calculated using stiffness reduction factors, elastic flexural and shear rigidities, and Equations (1) and (2).

$$EI_{eff} = 0.56(E_c I_c + E_s I_s) = 35 \text{ kN-m}^2$$

$$GA_{eff} = 0.83(G_c A_c^{eff} + G_s A_s^{eff}) = 13 \text{ kN-m}^2$$

CONCLUSIONS

A parametric study was conducted to systematically investigate the effect of wall aspect ratio, slenderness and reinforcement ratios, axial load, and steel and concrete material strengths on the in-plane response of SC wall piers. The general-purpose finite element code LS-DYNA was used to simulate the nonlinear response of 77 SC wall piers subjected to monotonic loading. The baseline model was validated using data from tests of large-scale SC wall piers. The wall piers studied here had aspect ratios of 0.5 and greater, and none were shear-critical.

The main and interaction effects of the design variables on the effective stiffness of the SC walls were investigated using a three-level fractional factorial design method. The effective stiffness is affected significantly by aspect ratio. Of all the variables considered, the slenderness ratio and concrete strength had the smallest effect on the shear stiffness reduction factor. Equations to calculate reduction factors for shear and flexural stiffness were formulated as a function of key design variables, and these can be used for elastic analysis of structures including SC wall piers. These equations could be implemented in seismic design standards such as ASCE/SEI Standard 4 (ASCE 2017), ASCE/SEI Standard 7 (ASCE 2010), ASCE/SEI Standard 41 (ASCE 2013) and ASCE/SEI Standard 43 (ASCE 2005). Single multipliers (e.g., 0.5) on theoretical values of flexural and shear rigidity are not robust and the effects of design variables should be considered in the calculation of effective lateral stiffness of SC wall piers.

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