Evaluation of the AISC Seismic Design Method for Steel-Plate Concrete Shear Walls

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Abstract Steel-plate concrete (SC) shear walls are used as the lateral-load resisting system in high-rise buildings as they can offer faster construction and reduced construction cost compared with their conventional reinforced concrete counterparts. This paper aims to predict the moment capacity of SC shear walls using the finite element analysis method and evaluate the current method by the AISC Seismic Provisions. Numerical parametric study of SC walls is used to develop a predictive equation for the moment capacity of such walls. The numerical analyses are then used to evaluate the method currently prescribed by the AISC Seismic Provisions. It is shown that the AISC design equation may not accurately predict the moment capacity of SC walls and should be improved.

Keywords AISC · Seismic design · Shear walls

1 Introduction

Steel–Concrete (SC) composite shear walls consist of plain infill concrete covered by steel faceplates on both sides. Tie rods are used as connectors between two steel face-plates to prevent their buckling, and shear-headed studs attach the concrete to steel faceplates to develop composite action between them [9], see Fig. 1.

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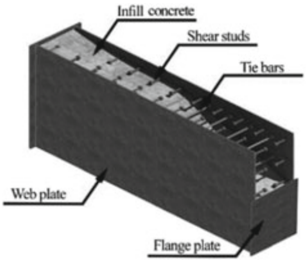
R. Gupta et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2022*, Lecture Notes in Civil Engineering 348,
https://doi.org/10.1007/978-3-031-34159-5_2

Fig. 1 SC wall configuration [9]



To obtain the moment capacity of SC walls, Kurt et al. proposed equations to calculate the moment capacity of double skin plate SC walls without boundary elements using parametric studies in LS-DYNA, based on tested squat walls [8]. They recommended the use of yield moment capacity, M_y, for walls with an aspect ratio of 0.5, and use of plastic moment capacity, M_p, for walls with an aspect ratio larger than 1.5, and interpolation with consideration of wall thickness for walls with an aspect ratio between 0.5 and 1.5. The yield moment capacity, M_y, corresponds to the yielding of steel under tension with its specified minimum yield strength, F_y, and the first yield in steel under compression with strength, F_y, also considering linear elastic distribution for concrete under compression with the maximum compressive stress equal to 0.7 f_c'. The plastic moment capacity, M_p, corresponds to the full minimum yield strength of steel, F_y, on both tension and compression parts and rectangular Whitney block with compressive stress equal to 0.85 f_c', for concrete under compression. The methodology presented by Kurt et al. was validated for only double skin plate shear walls with limited design variables [8]. The standard AISC 341-16 recommends the use of yield moment capacity, M_y, for SC walls without boundary elements and the use of plastic moment capacity, M_p, for SC walls with boundary elements [1]. For calculation of M_p in AISC 341-16, use of f_c' instead of 0.85 f_c' is recommended. Epackachi et al. conducted a set of monotonic numerical studies in LS-DYNA on SC walls, considering different design variables, including aspect ratio, axial compression ratio, slenderness ratio, reinforcement ratio, axial compression ratio, infill concrete compressive strength, and minimum yield strength of steel faceplates [5]. They considered three values for each design variable and used the design of experiment (DOE) method to reduce the number of analyses effectively. Considering the interaction of shear and axial loading, they proposed an equation for calculating the moment capacity of SC walls with respect to mentioned design variables. The equation proposed by Epackachi et al. was complex and limited to walls without end plates and boundary elements. Moreover, Eapackachi et al. show that all SC walls, including squat and slender are flexural-critical [5].

A robust FE model is required before conducting a large number of numerical analyses, which provides a dataset for the development of predictive equations for the moment capacity of SC walls. Asgarpour et al. presented a comprehensive validation study for numerical modeling of different shapes of SC walls tested in the literature [3]. For modeling the infill concrete, the Winfrith material model is used in LS-DYNA, as it was shown to be an appropriate material model for capturing the fundamental characteristics of concrete in past studies [2, 3, 4, 6, 7]. All assumptions of numerical modeling used in this paper, including material modeling, the element selected, and interactions are included in [3] and not repeated here for brevity.

Although some efforts have been made for proposing an accurate equation for the moment capacity of SC walls, further investigation is needed for developing an equation for the moment capacity of SC walls, which would be applicable for a variety of SC walls, considering different design variables, especially the wall shape and has an easy-to-use formulation, which is the primary goal of this study. In this paper, a simple and accurate formulation is implemented for SC walls with four cross-sectional shapes, including double skin rectangular, rectangular with end plates, rectangular with boundary elements, and flanged SC walls, considering six design variables, including aspect ratio, slenderness ratio, reinforcement ratio, axial load ratio, infill concrete compressive strength, and minimum yield strength of steel faceplates.

2 Predictive Equation Development

A six design variables that significantly affect the local and global response of SC walls are: aspect ratio, H/L_w, reinforcement ratio, A_s/A_g, slenderness ratio, S/t_s, axial load ratio, $P_u/(A_sF_y + A_cf_c')$, yield strength of the steel faceplates, F_y, and concrete compressive strength, f_c'. This study selects three values (min, max, and mean values used in practice) for each design parameter. The values in the parentheses are coded values indicating low (−1), intermediate (0), and, high (1) values of the design parameters. The values of the design parameters are summarized in Table 1. Based on the AISC 341-16, identical dimensions (10 mm diameter) and properties are assumed for the connectors, i.e., tie rods for all models. However, the distance between tie rods is considered an important design variable.

In this study, four cross-section shapes are considered for SC walls, including double skin plates SC wall (DS-SC wall), double skin plates with end plates SC wall (DSE-SC wall), SC wall with boundary elements (BE-SC wall), and flanged SC wall (FBE-SC wall), see Fig. 2. Based on the number of design variables and considering three values for each shape, 729 analyses need to be conducted for walls with each cross-sectional shape. To effectively consider the effects of design

Table 1 Levels of the design variables

Variable	Low	Intermediate	High
Aspect ratio (AR)	0.5 (−1)	1 (0)	3 (1)
Reinforcement ratio (RR) [%]	4 (−1)	6 (0)	10 (1)
Slenderness ratio (SR)	15 (−1)	25 (0)	40 (1)
Axial load (AL) [%]	0 (−1)	10 (0)	20 (1)
Yield strength of the steel faceplates (SS) [MPa]	235 (−1)	350 (0)	460 (1)
Concrete compressive strength (CS) [MPa]	27.5 (−1)	42 (0)	55 (1)

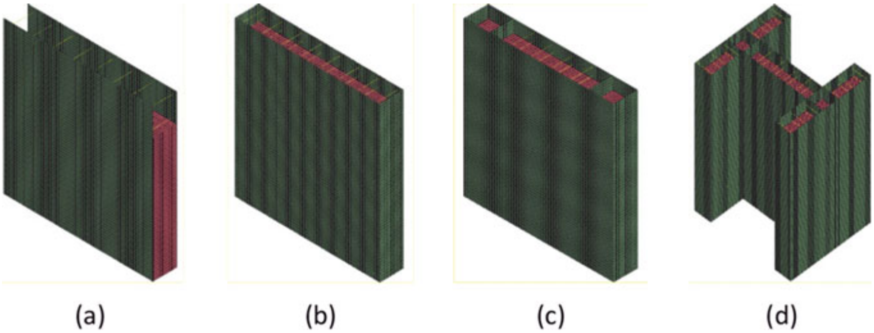


Fig. 2 Four cross-section shapes: **a** Double skin plates SC wall (DS-SC wall), **b** Double skin plates with end plates SC wall (DSE-SC wall), **c** SC wall with boundary elements (BE-SC wall), **d** Flanged SC wall (FBE-SC wall)

variables on the moment capacity of SC walls, a design of experiments (DOE) is used, which reduces the number of analyses from 729 to 88. In the FE models, fixed restraints are considered for the bottom of the SC walls, and lateral load is applied at the top monotonically. Then, the moment capacity of each model is monitored as the corresponding peak lateral load multiplied by its height.

Equations 1–3 are developed to calculate the moment capacity of SC walls considering six design variables and four configurations. Based on Eq. 1, moment capacity of SC walls is based on plastic moment capacity introduced by AISC 341-16 formulation and is modified to consider the effect of these design variables. To identify the importance of each design variable on the moment capacity of SC walls, their coefficient of variation (COV) is determined first. Then, the design variable with the largest COV is eliminated, and the accuracy of the revised equation is evaluated. Although design variables considered in equations significantly impact the accuracy of proposed equations, their importance is different. For instance, the importance of reinforcement ratio is less than other design variables for BE-SC Wall (see Table 2), but it is not ignorable.

$$M_n = \lambda M_P^{\gamma} \tag{1}$$

$$\lambda = \frac{c\lambda_1^{\alpha_1}}{\lambda_2^{\alpha_2}\lambda_3^{\alpha_3}\lambda_4^{\alpha_4}\lambda_5^{\alpha_5}} \tag{2}$$

$$\lambda_1 = \frac{h}{l_w};\quad \lambda_2 = \frac{S}{t_s};\quad \lambda_3 = \frac{A_s}{A_g};\quad \lambda_4 = \frac{f_y}{f_c'};\quad \lambda_5 = (1 - N),\quad N = \frac{P_u}{f_c' A_c + f_y A_s} \tag{3}$$

Table 2 Parameter values for Eqs. (1–3)

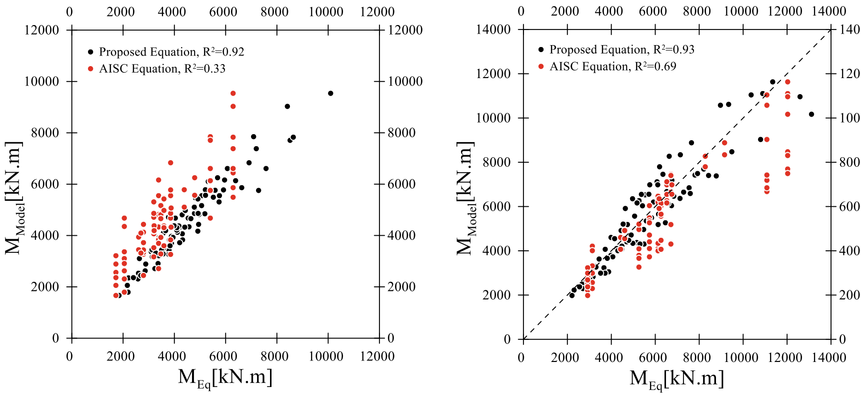
Shape	c	γ	α_1	α_2	α_3	α_4	α_5
DS-SC wall	6.63	0.83	0.15	0.17	0.08	0.13	0.82
DSE-SC wall	2.04	0.95	0.18	0.09	0.10	0.15	0.44
BE-SC wall	3.50	0.90	0.18	0.04	0.004	0.19	0.65
FBE-SC wall	3.99	0.84	0.54	0.09	0.10	0.14	0.35

3 Evaluation of the Proposed Equation

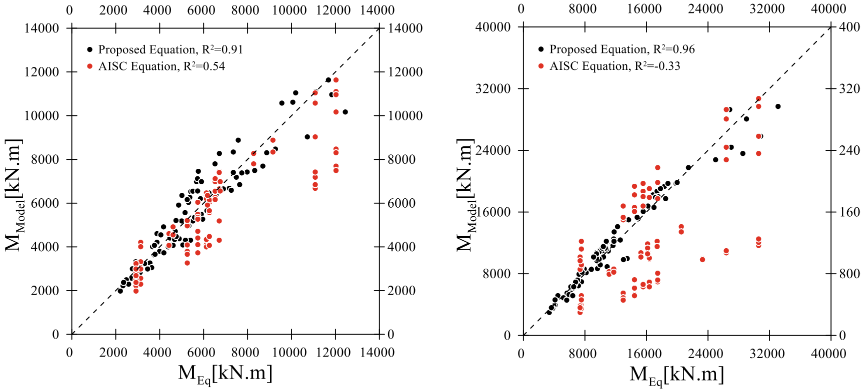
AISC 341-16 design method for SC walls does not consider the effects of design variables including aspect ratio, slenderness ratio, reinforcement ratio, axial load ratio, and cross-sectional shape on the moment capacity of SC walls. The simple plastic stress distribution method might not lead to an accurate prediction of the actual moment capacity of SC walls. To investigate whether and to what extent ignorant of these design variables changes the results, the moment capacity based on the proposed equation and AISC 341-16 methodology is compared with all cross-sectional shapes, as shown in Fig. 3. The black and red points in Fig. 3 depict the moment capacity values based on the proposed equation and AISC 341-16 method, respectively. The more the predicted values get closer to the bisector line, shown as a dashed line, the more accurate that formulation is. The proposed equation in this study predicts the actual moment capacity of all SC walls with high accuracy and low dispersion. Among four studied cross-sectional shapes, the AISC 341-16 method results in the minimum and maximum errors in DSE-SC and FBE-SC walls, respectively. Figure 3a shows that the AISC 341-16 method underestimates the moment capacity of rectangular SC walls without boundary elements. In particular, in the models with a high aspect ratio, low reinforcement ratio, and high axial load ratio, the moment capacity of the walls is much higher than M_y and close to $2M_y$ in some cases. It is concluded that the use of M_y in DS-SC walls leads to reasonable results only for low aspect ratio walls, moderate values for slenderness ratio and reinforcement ratio, and zero axial load value.

Figure 3b–d show that the AISC 341-16 method overestimates the moment capacity of most SC walls with rectangular end plates and boundary elements and, in particular, flanged walls, which leads to nonconservative results. As shown in Fig. 3b, DSE-SC walls with low aspect ratios have the maximum errors, exhibiting up to 50% overestimating the effects in DSE-SC walls with low aspect ratios and high axial load ratios. Figure 3c shows that AISC 341-16 design equation overestimates the capacity of BE-SC walls with low aspect ratios and underestimates that of walls with a high axial load ratio.

It is inferred that the use of M_p in the walls with end plates and boundary elements leads to reasonable results only for high aspect ratio walls, moderate values for slenderness ratio and reinforcement ratio, and zero axial load value. In general, AISC 341-16 method resulted in a less accurate prediction of the moment capacity



(a) DS-SC Wall (b) DSE-SC Wall



(c) BE-SC Wall (d) FBE-SC Wall

Fig. 3 Calculated moment capacity based on the proposed equation and AISC 341-16

for the studied here, suggesting the importance of considering different key design variables in the design of the moment capacity of SC walls.

4 Conclusions

A new equation was developed to predict the moment capacity of Steel–Concrete (SC) shear walls using the results of extensive numerical analyses performed in LS-DYNA. The proposed equation was then used to evaluate the current AISC 341-16 design equation. A perfect prediction of the SC wall moment capacity was obtained using the proposed equation. It was also confirmed that the AISC 341-16 method might underestimate the moment capacity of DS-SC walls, in particular when the wall has a high aspect ratio and high axial load ratio, while it may overestimate the moment capacity of DSE-SC walls, BE-SC walls, and BE-SC walls, in particular those with low aspect ratio. Further numerical simulations and experimental testing are required to improve seismic design provisions used to design SC walls.

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