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Hysteretic model for steel–concrete composite shear walls subjected to in-plane cyclic loading

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ABSTRACT

Steel–concrete composite (SC) shear walls are being widely used as an alternative to reinforced concrete walls. Investigations on seismic behavior of SC walls have been conducted to develop design specifications for safety-related nuclear facilities. However, there is a lack of hysteretic models that can be used to predict structural performance as the structure approaches collapse. This paper presents (a) the analysis of experimental results of 32 SC wall specimens, and (b) the derivation and calibration of a quadri-linear backbone with negative post-peak stiffness and associated hysteretic rules. Different cross section shapes and loading configurations were used to test the SC wall specimens. Based on the experimental results, equations for stiffnesses and loads are derived from a mechanics based model, and basic hysteretic rules are employed to describe the response of SC walls subjected to in-plane cyclic loading. Calibrations are conducted to suggest the reduction factors for the Young's moduli of concrete and steel that reflect the plasticity extension and damage accumulation.

1. Introduction

Steel–concrete composite (SC) shear wall typically consists of steel faceplates and plain concrete infill. The steel faceplates are attached to the concrete with headed shear studs to ensure deformation compatibility. Tie-bars, stiffeners or partitioning webs connecting the two steel faceplates are designed to provide out-of-plane shear resistance and confinement to the concrete (see Fig. 1).

The concept of SC wall was initially proposed for nuclear power plants. In 1977, Japanese researchers Ichikawa et al. [1] suggested using SC walls instead of reinforced concrete (RC) walls in the containment vessel to provide sufficient out-of-plane shear capacity at the bottom cross section. Due to the high bearing capacity, excellent impermeability, and construction efficiency, SC walls have been widely used in high-rise buildings, nuclear power plants, offshore structures, and impact resistance protective structures.

Since the 1990s, Japanese researchers have conducted a large number of experimental and theoretical studies on SC walls subjected to in-plane cyclic loading (e.g. Akiyama et al. [2], Takeuchi et al. [3], Ozaki et al. [4,5]). Based on the results, a technical guideline (JEAG 4618-2005 [6]) for SC walls in safety-related nuclear facilities was developed. Additional research was carried out in South Korea (e.g. Eom et al. [7]), and a design guideline (KEPIC-SNG [8]) was also developed. In the US, a series of studies on SC structures were conducted by Varma et al. [9–13], and the American Institute of Steel Construction (AISC) is currently drafting a design specification for modular construction of SC walls. Over the past five years, researchers in China have conducted similar experimental research works (e.g. Nie et al. [14,15], Ji et al. [16], Wu et al. [17], and Cheng et al. [18]), aiming at developing design codes in compliance with the Chinese design standard system.

For the performance-based design of SC wall components, hysteretic models are critical to the demand prediction as the structure approaches collapse. Previously, several hysteretic models have been developed for reinforced concrete components (e.g. bilinear model developed by Clough and Johnston [19], and trilinear model developed by Takeda et al. [20]).

For the case of SC walls, Akita et al. [21] developed trilinear backbone curves for both the relationship between shear force and shear strain (Q–γ) and the relationship between bending moment and curvature (M–Φ). Associated hysteretic rules were presented in the design guideline JEAG 4618-2005. By considering the deformations caused by bending and shear at the same time, the load–displacement (Q–Δ) relationship can be described by a smooth curve with five turning points [3]. However, this method cannot describe the negative stiffness of post-peak response in the whole loading process. Also, it is inconvenient for application

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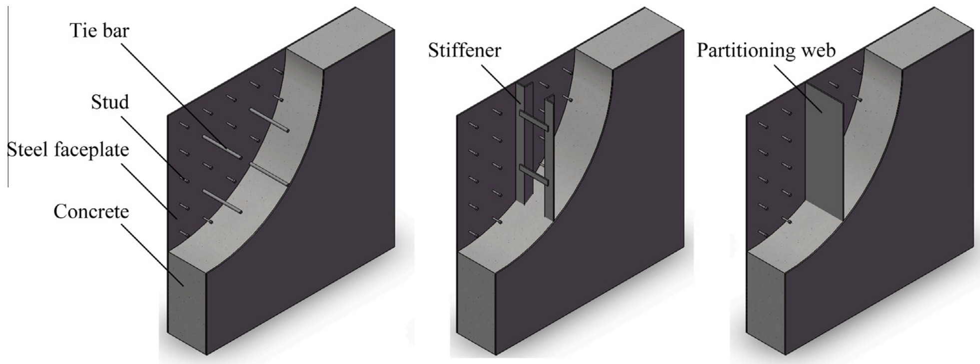

Fig. 1. Typical types of SC walls.

Table 1
Details of the SC wall specimens.

Reference	Cross section	Loading type	Specimen	t_s (mm)	t_w (mm)	h_w (mm)	t_f (mm)	b_f (mm)	H (mm)	B/t_s	E_c (GPa)	E_s (GPa)	f_c (MPa)	f_y (MPa)
Akiyama et al. [2]	(a)	BS	SS050	3.2	160	1440	–	–	1800	50	19.9	206.0	24.0	305.0
			SS100	3.2	160	1440	–	–	1800	100	19.7	206.0	24.0	305.0
			SS150	3.2	160	1440	–	–	1800	150	18.6	206.0	24.0	305.0
Takeuchi et al. [3]	(b)	BS	H10T05	2.3	115	1775	115	830	2060	33	20.7	203.0	29.7	286.0
			H10T10	2.3	230	1890	230	830	2060	33	23.4	203.0	32.7	286.0
			H10T10V	2.3	230	1890	230	830	2060	33	23.4	203.0	32.7	286.0
			H10T15	2.3	345	2005	345	830	2060	33	20.7	203.0	29.7	286.0
			H07T10	2.3	230	1890	230	830	1650	33	20.7	203.0	29.7	286.0
			H15T10	2.3	230	1890	230	830	2900	33	23.4	203.0	32.7	286.0
Ozaki et al. [4]	(b)	BS	BS70T05	4.5	230	1890	115	945	1323	30	24.6	191.0	33.9	352.5
			BS70T10	2.3	230	1890	115	945	1323	30	24.6	199.0	33.9	389.2
			BS70T14	1.6	230	1890	115	945	1323	30	24.8	209.0	36.2	448.4
			BS50T10	2.3	230	1890	115	945	945	30	24.8	199.0	36.2	389.2
			BS85T10	2.3	230	1890	115	945	1607	30	24.6	199.0	33.9	389.2
Ozaki et al. [5]	(c)	US	S2-00NN	2.3	200	1200	–	–	1200	30	27.2	197.0	42.2	340.0
			S2-15NN	2.3	200	1200	–	–	1200	30	27.7	197.0	41.6	340.0
			S2-30NN	2.3	200	1200	–	–	1200	30	27.9	197.0	42.0	340.0
			S3-00NN	3.2	200	1200	–	–	1200	31	27.1	199.0	41.9	351.0
			S3-15NN	3.2	200	1200	–	–	1200	31	26.7	199.0	41.6	351.0
			S3-30NN	3.2	200	1200	–	–	1200	31	27.0	199.0	40.1	351.0
			S3-00PS	3.2	200	1200	–	–	1200	31	27.1	199.0	41.9	351.0
			S3-00PN	3.2	200	1200	–	–	1200	31	27.2	199.0	39.9	351.0
			S4-00NN	4.5	200	1200	–	–	1200	30	27.6	207.0	42.8	346.0
Cheng et al. [18]	(d)	BS	SCW1-1a	3.0	150	1000	–	–	1000	13	33.0	206.0	28.6	330.0
			SCW1-1b	3.0	150	1000	–	–	1000	13	33.0	206.0	28.6	330.0
			SCW1-2a	3.0	150	1000	–	–	1500	13	33.0	206.0	28.6	330.0
			SCW1-2b	3.0	150	1000	–	–	1500	13	33.0	206.0	28.6	330.0
			SCW1-3	3.0	150	1000	–	–	2000	13	33.0	206.0	28.6	330.0
			SCW1-4	2.0	150	1000	–	–	1000	20	33.0	206.0	28.6	307.0
			SCW1-5	4.0	150	1000	–	–	1000	10	33.0	206.0	28.6	361.0
			SCW1-6	3.0	150	1000	–	–	1000	27	33.0	206.0	28.6	330.0
			SCW1-7	3.0	150	1000	–	–	1000	20	33.0	206.0	28.6	330.0

BS: bending shear, US: uniform shear.

because the displacement caused by bending must be calculated through the integration of the curvature Φ over the height of the wall.

Based on the design force and moments demands, the mechanics based model proposed by the Japanese researchers was modified by Varma et al. [10], and an interaction surface in principle force space was developed. The calculated trilinear backbone was verified by the experimental results of pure in-plane shear behavior; however, no hysteretic response was studied, and the verification for bending shear behavior should be included.

Wu and Zhang [22] conducted an experimental study on three SC wall specimens and discussed the influence of the steel faceplate thickness on ductility and energy-dissipation capacity. Wu and Zhang developed a hysteretic model based on the experimental results; however, the sample number was insufficient, and no theoretical derivations were presented.

This paper compiles the experimental results of 32 in-plane cyclic loading test on SC wall specimens. Based on the analysis of the experimental results, a quadri-linear backbone curve with negative stiffness branch of post-peak response and simple hysteretic rules are employed. The mechanics-based model proposed by the Japanese