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NUMERICAL INVESTIGATION OF THE IN-PLANE BEHAVIOR OF LOW ASPECT RATIO REINFORCED CONCRETE SHEAR WALLS

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ABSTRACT

An experimental study investigated the cyclic behavior of low aspect ratio reinforced concrete shear walls in the SEESL laboratory at the University at Buffalo. The testing program involved 12 shear walls with aspect ratio ranging from 0.33 to 0.94, and horizontal and vertical web reinforcement ratios ranging from 0.33% to 1.5%.

A finite element model is developed in the LS-DYNA domain to simulate the nonlinear cyclic response of these walls. The model is validated using experimental data. Experimentally and numerically derived global and local responses are presented and contrasted. The measured initial stiffness of the RC walls is significantly less than the theoretical and DYNA-predicted stiffness due to the existence of fine cracks at the base of the wall caused by restrained shrinkage. The validated DYNA model is used to investigate the effect of restrained shrinkage on the initial stiffness of RC walls.

LITERATURE REVIEW

Low aspect ratio structural walls (ratio of height to length of two or less) are widely used for gravity and lateral load resistance in safety-related nuclear structures. A significant number of experiments have been conducted to study their behavior. Gulec and Whittaker [13] compiled a comprehensive database of 434 low aspect ratio RC walls tested by other researchers prior to 2009. Key information from the experimental programs were provided in this report. A summary of information from experimental programs on low aspect ratio RC walls conducted between 2010 and the time of this writing is provided in Luna et al. [20]

The response of two flanged low aspect ratio RC shear walls tested by the Nuclear Power Engineering Corporation (NUPEC) has been studied by finite element analysis using ABAQUS, ADINA, and DIANA. The results of the simulations were reported in OECD/NEA/CSNI [21]. On the basis of the analysis results, the majority of the predicted initial stiffnesses were within 15% of the measured values and the predicted peak shear strengths varied between 65% and 115% of the measured values. Asfura and Bruin [5] analyzed the wall tested by NUPEC [14] using three finite element codes: IDARC2D [23], FEM-I [12], and ADINA [1]. The wall was modelled using fiber elements in IDARC and plane stress shell elements in FEM-I and ADINA. The wall response was successfully simulated up to first yielding of the reinforcement. The post-yield stiffness of the RC wall was significantly overestimated by three codes. Kwak and Kim [15] proposed a smeared rotating crack approach to predict the monotonic behavior of RC shear walls. The model included compression softening (i.e., reduction of the concrete compressive strength as a function of tensile lateral strain) as proposed by Vecchio and Collins [27] and an smeared approach based on a tension-stiffening algorithm to account for the effect of horizontal and vertical reinforcement. The proposed model was used to simulate the monotonic response of six low aspect ratio RC walls tested by Lefas et al. [16]. The response of the RC walls was successfully predicted using the model with tension stiffening, which captures the tensile stiffness of intact concrete between cracks. Palermo and Vecchio [22] simulated the response of two flanged RC walls tested at the University of Toronto using VecTor2: a 2-D nonlinear finite element program used to simulate the in-plane response of RC structures. VecTor2 implements the Modified-Field-Compression-Theory (MCFT) [28] and the Distributed-Stress-Field-Model (DSFM) [26]. The DSFM, proposed by Vecchio [26] as an alternative to MCFT, incorporates a smeared rotating crack model that considers slip across crack surfaces and reorientation of cracks during cyclic loading.

In this study, a finite element model is developed for simulation of the cyclic response of RC walls. The model is validated using data from tests of seven RC walls subjected to in-plane cyclic loading at University at Buffalo. A summary of the experimental program, analysis assumptions, and key analysis results are presented in the following sections.

EXPERIMENTAL PROGRAM

Test Specimen Description

Twelve large-size, low aspect ratio, rectangular, RC shear wall specimens (denoted SW1 to SW12) were built and tested as part of a NEES research project on conventional [20] and composite structural walls [8, 9,11] with low aspect ratios at the NEES facility at the University at Buffalo [24]. The construction and testing of the 12 specimens were executed in two phases: Phase I (SW1-SW7) and Phase II (SW8-SW12). The Phase I walls were constructed and tested first. The Phase II walls were designed after preliminary analysis of data from the testing of the Phase I walls. The test results from the phase I walls (SW1 to SW7) are used to validate the numerical model and only the properties of these walls are reported in this paper.

The length and thickness of the test specimens were 10 feet and eight inches, respectively. The design variables were wall aspect ratio (h_w/l_w), where h_w is the distance from the top of the foundation to the centerline of loading and l_w is the length of the wall, day-of-test concrete compressive strength (f_c'), vertical and horizontal reinforcement ratio (ρ_l, ρ_t), yield and ultimate strengths of the reinforcement (f_y, f_u), and splices in vertical reinforcement immediately above the foundation.

Table 1. Properties of test specimens

Specimen	h_w/l_w	ρ_l, ρ_t	Splices	f_c' (ksi)	Reinforcement	
					f_y (ksi)	f_u (ksi)
SW1	0.94	0.67%	No	3.1	67	102
SW2	0.54	1.00%	Yes	5.1	63	87
SW3		0.67%		6.2		
SW4		0.33%	No	3.3	67	102
SW5	0.33	1.00%		2.9		
SW6		0.67%		2.9		
SW7		0.33%		2.9		

Figure 1 presents a photograph of SW5. The foundation of each shear wall was post tensioned to the strong floor in the laboratory using 14 numbers 1.5-inch diameter Dywidag bars. Lateral loads were applied to the walls using two high force-capacity actuators that were horizontally inclined by 9 degrees with respect to the longitudinal axis of the walls, as seen in Figure 2. The actuators imposed displacements on the shear walls via custom-made brackets and thick steel plates that were post tensioned to either side of the specimen. Details of the test setup, loading protocol, and instrumentation are available in Luna et al. [20].

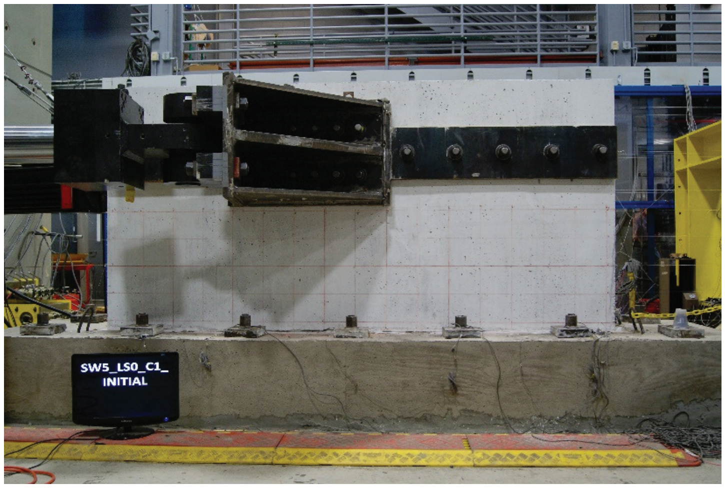


Figure 1. RC wall specimen SW5

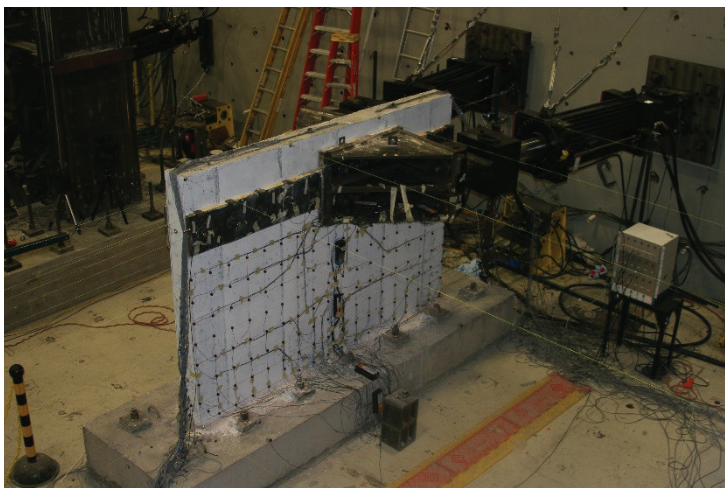
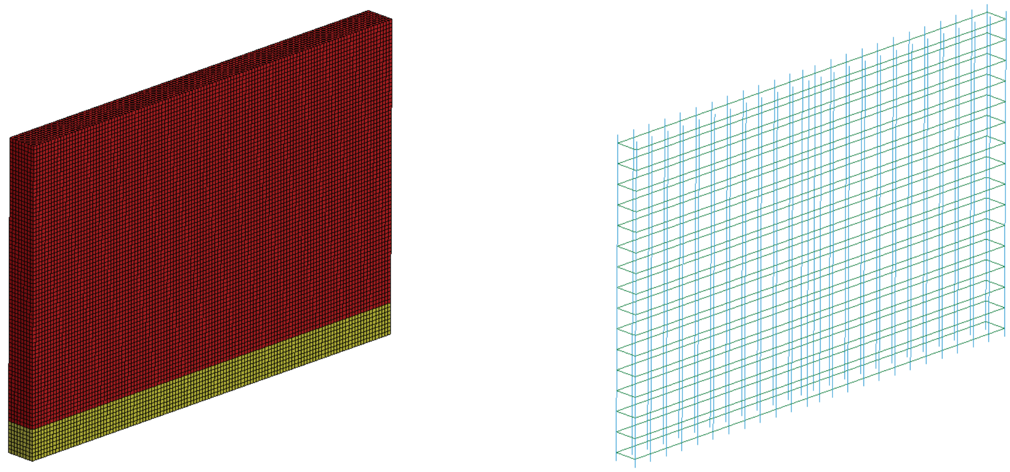


Figure 2. Test setup

NUMERICAL ANALYSIS

A numerical study was conducted to investigate the cyclic in-plane behavior of low aspect ratio RC shear walls using a general purpose finite element code LS-DYNA [17, 18]. The concrete wall was modelled using the smeared crack Winfrith model (MAT085) in LS-DYNA, developed by Broadhouse [6], and the reinforcement were modelled using a plastic model, Mat-Plastic-Kinematic (MAT003), with isotropic, kinematic, and combined kinematic-isotropic hardening. Kinematic, isotropic, or combined kinematic-isotropic hardening can be specified by varying a parameter, β , between 0 and 1 in MAT003 [18]. The details of the concrete and steel material properties are provided in Epackachi [8,9]. Beam elements were used to represent the horizontal and vertical reinforcement. Eight-node solid elements were used to model the concrete wall. The concrete wall was modelled using 1.0 × 1.0 × 1.0 in. solid elements. The reinforcement was tied to the concrete elements. The reversed cyclic loading of the test specimens was simulated by imposing horizontal displacements at the nodes of the concrete wall and reinforcement, located at the level of the centerline of the loading plates. Since the experimental results and preliminary analysis indicated that the foundation block was effectively rigid, it was not included in the finite element model. The LS-DYNA model of SW2 is presented in Figure 3.



(a) Concrete wall (b) Horizontal and vertical reinforcement

Figure 3. DYNA model of SW2

ANALYSIS RESULTS

The predicted damage and a photograph of the recorded damage to SW7 at 0.45% drift ratio are presented in Figure 7. The damage to the RC wall was captured quite well by the finite element model.

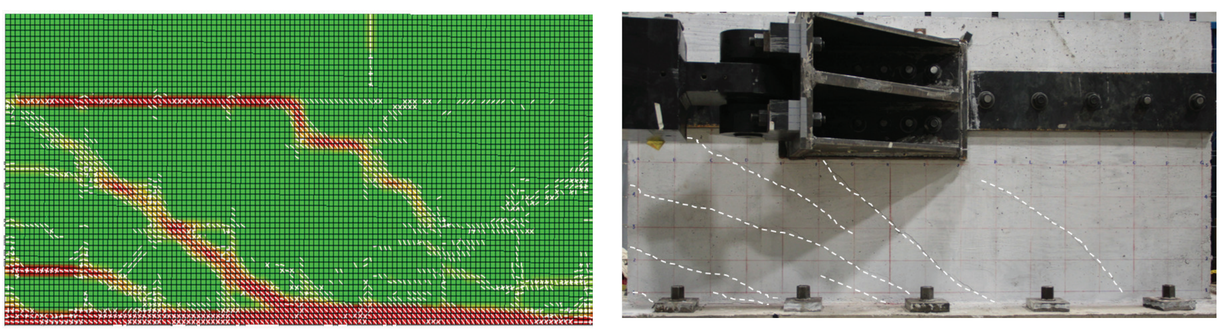


Figure 4. Crack pattern in SW7 at 0.45% drift ratio; DYNA-predicted (left) and experimentally recorded (right)

The DYNA-predicted and measured force-displacement relationships for SW1 through SW7 are presented in Figure 5. In this figure, displacement is the horizontal movement of the wall in its plane at the level of the actuators; drift ratio is defined as the horizontal displacement divided by the distance between the base of the wall and the centerline of horizontal loading. As seen in Figure 8, the cyclic responses of RC walls were successfully captured by the DYNA models. The predictions of the peak shear resistance and the rate of the reloading/unloading stiffness compared favorably with the test results. The ratio of the DYNA-predicted to measured peak shear strengths varies between 0.85 and 1.0. The initial stiffness of the RC walls were significantly overestimated. This outcome was attributed to the effect of restrained shrinkage, which was not addressed in the initial numerical analysis. This issue is investigated using the validated DYNA model in the following section.

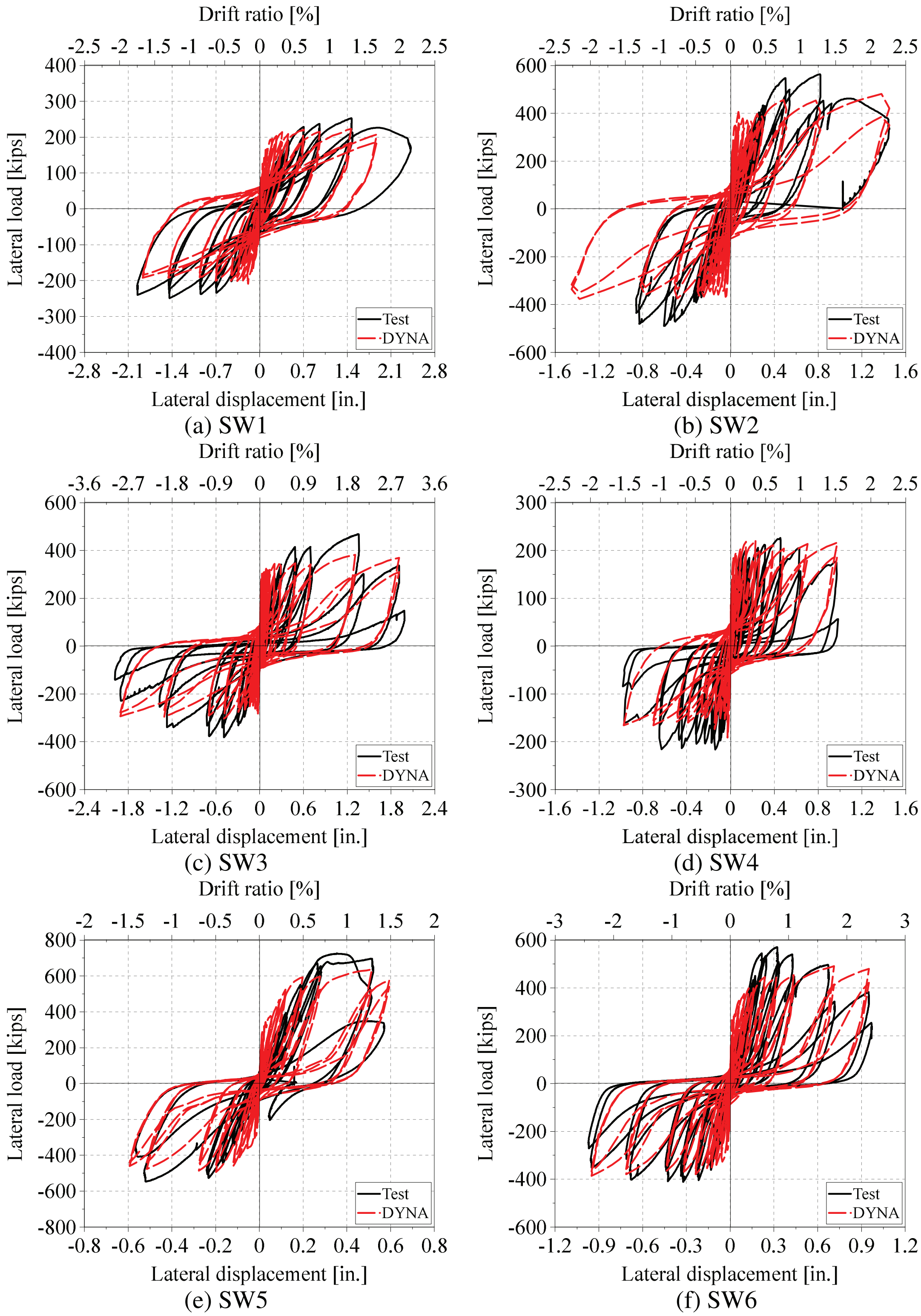
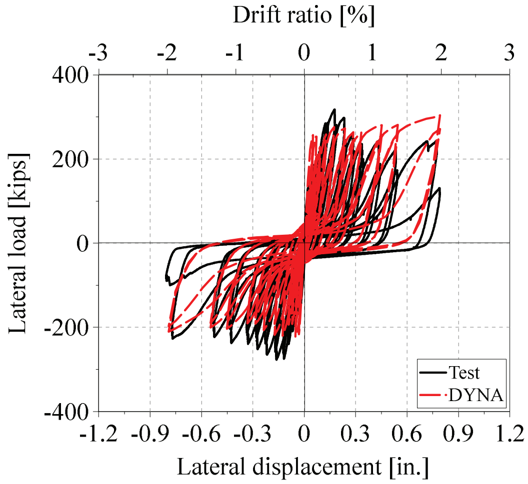


Figure 5. Predicted and measured lateral load - displacement relationships of RC walls



(g) SW7

Figure 5. Predicted and measured lateral load - displacement relationships of RC walls (cont.)

Initial Stiffness

Table 2 presents the measured and predicted lateral stiffness of seven RC walls. Day-of-test concrete compressive strength, presented in Table 1, Equation 19.2.2.1(b) of ACI 318-14 [2] for Young's modulus, and Poisson's ratio equal to 0.2 were used in the calculations. Column 2 lists the measured initial stiffness of the RC walls calculated at the first cycle of the first load step that involved force less than 15% of peak strength and a drift ratio of less than 0.025%. Data for the initial stiffness of SW2 to SW4 are not reported due to noise in the data collected in the first load step. DYNA-predicted initial stiffness is presented in column 3. The theoretical *uncracked* stiffness, presented in column 4, is expressed as:

$$K_T = \frac{1}{\dfrac{1}{K_f} + \dfrac{1}{K_s}}, \text{ where } K_f = \frac{3E_c I_g}{h_w^{\,3}} \text{ and } K_s = \frac{G_c A_w}{h_w} \tag{1}$$

and E_c is the modulus of elasticity of concrete; I_g is the wall moment of inertia; h_w is the height of the wall measured from the top of the foundation to the loading centerline; G_c is the shear modulus of concrete; and A_w is the total cross-sectional area of the wall. In the calculation of the theoretical stiffness, I_g and A_w are approximated by considering only the total concrete section.

The calculated *uncracked* and *cracked* stiffness based on the equations proposed in ASCE 41-06 [4] and ASCE 43-05 [3] are presented in columns 5 to 8 of Table 2. To calculate the *uncracked* stiffness, ASCE 41-06 considers $0.8E_cI_g$ and G_cA_w, whereas ASCE 43-05 recommends no reduction in flexural and shear rigidities. The *cracked* stiffness is calculated using $0.5E_cI_g$ and $0.5G_cA_w$ in ASCE 43-05 and $0.5E_cI_g$ and G_cA_w in ASCE 41-06.

As seen in Table 2, the ratios of K_i^m/K_i^D and K_i^m/K_t vary between 0.26 and 0.46, and between 0.26 and 0.43, respectively, indicating that the initial stiffness of RC walls is significantly less than either the theoretical stiffness or the initial stiffness predicted by DYNA analysis. Sozen and Moehle [25] also reported that the measured initial stiffness of RC walls was less than the calculated theoretical initial stiffness, which they attributed to a) invisible shrinkage cracks at the base of the wall, and b) base girder rotation.

As seen in Table 2, the DYNA-predicted stiffnesses are very close the theoretical values; the ratio of K_i^D/K_t varies between 0.93 and 0.99. The average ratios of $K_{41\text{-}06uc}/K_t$ and $K_{41\text{-}06c}/K_t$ vary from 0.87 to 0.96 and from 0.63 to 0.86, respectively.

Table 2. Properties of test specimens

Spec.	Measured K_i^m	DYNA-predicted K_i^D	Theoretical *uncracked* K_t	ASCE 41-06		ASCE 43-05	
				uncracked $K_{41-06uc}$	*cracked* K_{41-06c}	*uncracked* $K_{43-05uc}$	*cracked* K_{43-05c}
SW1	1840	4533	4890	4250	3060	4890	2445
SW2	-	18502	19710	18210	14835	19710	9855
SW3	-	20488	20810	19230	15660	20810	10405
SW4	-	14226	15270	14110	11495	15270	7635
SW5	8900	29116	30530	29330	26250	30530	15265
SW6	7570	28646	28700	27570	24680	28700	14350
SW7	12260	26515	28700	27570	24680	28700	14350

To investigate the effect of shrinkage on the initial stiffness of RC walls, a shrinkage strain was included in the analysis of RC walls using a numerical technique in LS-DYNA. The restrained shrinkage at the base of the wall was modelled by applying a thermal load to concrete elements over a height, H_T, above the foundation. The value of the temperature increment, ΔT, was calculated as:

$$\Delta T = \frac{\varepsilon_{sh}}{\alpha_c} \tag{2}$$

where α_c is the coefficient of thermal expansion of concrete, and ε_{sh} is the ultimate drying shrinkage strain. The range of drying shrinkage strain under standard conditions is between 400 and 1100 microstrains according to Carino and Clifton [7], where standard conditions were defined as seven days initial curing period, volume-to-surface ratio of 1.5 inches, and ambient relative humidity of 40%.

To investigate the impact of shrinkage strain on the initial stiffness, the DYNA model of SW2 was re-analyzed with different levels of restrained shrinkage. Table 3 presents the values of the temperature increment and the heights of the zone above the foundation subjected to thermal loading. Three values for the ultimate shrinkage strain were selected: 400 and 800 microstrains, within the range of shrinkage strain proposed by Carino and Clifton [7], and 1600 microstrain. Two heights were considered for the zone of thermal loading: 8 in., equal to the wall thickness, and 16 in., equal to the twice the thickness of the wall.

Table 3. Thermal loading properties

Model	ΔT (K)	H_T (in.)	ε_{sh} (microstrain)
SW2-1	-27	8	400
SW2-2	-54	8	800
SW2-3	-54	16	800
SW2-4	-108	8	1600
SW2-5	-108	16	1600

Figure 6 presents the DYNA-predicted cyclic force-displacement relationships for SW2-1 through SW2-5 together with the backbone curves of the cyclic responses of SW2 and SW2-1 through SW2-5 and the measured response up to a drift ratio of 0.2%.

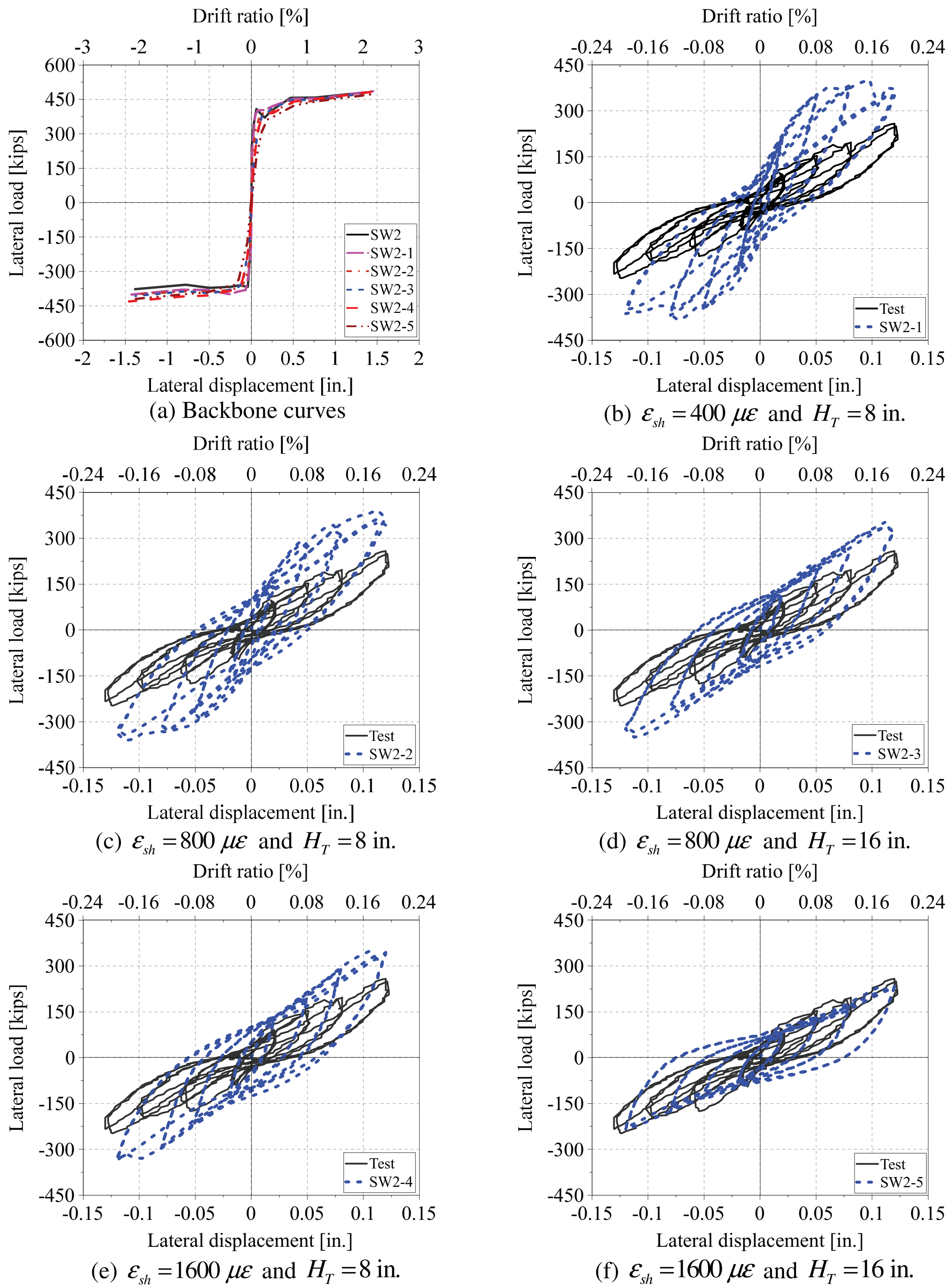


Figure 6. Predicted and measured lateral load - displacement relationships of RC walls

The shrinkage strain has a significant effect on the initial stiffness of the RC walls: the greater the shrinkage strain, the smaller the initial stiffness. As the height of the shrinkage zone is increased, the initial stiffness decreases. As seen in Figure 6f, the DYNA model with a shrinkage strain of 1600 microstrain applied over a height of twice the wall thickness recovers the measured initial stiffness of SW2. Importantly, the results of this study showed that restrained shrinkage has no effect on the peak shear strength and post-peak response, as seen in Figure 6a.

CONCLUSIONS

A reliable finite element model for the cyclic analysis of low aspect ratio RC walls was developed using the general purpose finite element code LS-DYNA. The model was validated using the results of cyclic tests of seven low aspect ratio RC walls at the University at Buffalo. The pinched response, the peak shear strength, and the loading and reloading behavior of the RC walls were predicted well by the DYNA model.

The measured initial stiffness of the RC walls was significantly less than the stiffness predicted by DYNA model and by empirical equations proposed in ASCE 43-05 [3] and ASCE 41-06 [4]. The formation of the fine cracks due to restrained shrinkage, not addressed initially in the analysis and in the derivation of the empirical equations, significantly affected the initial stiffness of the RC walls. This issue was numerically investigated using the validated DYNA model. The measured initial stiffness of SW2 was best recovered by considering a shrinkage strain of 1600 microstrain for the concrete elements within a height of twice the wall thickness above the foundation in the analysis. This study showed that the ignoring shrinkage strain could lead to a significant overestimation of the initial stiffness of RC walls. More information will be available in the PhD dissertation by Luna [19] and a journal article in preparation, from which this paper is excerpted (Epackachi et al. [10]).

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