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A validated numerical model for predicting the in-plane seismic response of lightly reinforced, low-aspect ratio reinforced concrete shear walls

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ABSTRACT

A finite element model is developed in LS-DYNA to simulate the in-plane cyclic behavior of lightly reinforced, low-aspect ratio reinforced concrete (RC) shear walls. Data from tests of 22 low-aspect ratio RC shear walls in three laboratories are used to validate the numerical model. The design variables in the testing programs included aspect ratio, day-of-test concrete compressive strength, vertical and horizontal web reinforcement ratio, reinforcement ratio in boundary elements, and yield and ultimate strengths of reinforcement, and these are addressed in the numerical model.

The finite element predictions and test results, including the force–displacement relationships and damage to the RC shear walls, are presented and contrasted. Numerical methods are proposed to model the effect of early stage cracking on the initial stiffness of RC walls and to capture post-peak strength degradation. The numerical simulations are in good agreement with the measured responses. The validated LS-DYNA model is used in a parametric study to investigate the effects of wall aspect ratio, reinforcement ratios in web and boundary elements, and compressive axial load on the monotonic response of RC walls. The accuracy of four equations used to predict the peak shear strength of low-aspect ratio walls is assessed using results of the numerical analyses.

1. Introduction

Low-aspect ratio reinforced concrete (RC) shear walls, herein defined as walls with an aspect ratio of less than or equal to 1.5, are widely used as gravity and lateral load resisting components in low-rise buildings and safety-related nuclear structures. Walls with an aspect ratio of less than 1.0 are generally shear-critical unless the web reinforcement ratios are very small. The peak shear resistance of walls with aspect ratios between 1.0 and 1.5 can be limited by flexure, shear or a combination thereof, again dependent on the volume and distribution of reinforcement.

A significant number of *experimental* studies have been performed over many decades to characterize the behavior of low aspect ratio RC walls. Gulec and Whittaker [1] compiled a comprehensive database of 434 low-aspect ratio RC walls tested by other researchers prior to 2009. Luna et al. [2] summarized experimental data collected between 2010 and 2015. Analytical and numerical studies have also been performed but there are no validated models for the analysis of shear-critical walls capable of reproducing cyclic response to levels of lateral drift corresponding to failure, measured here in terms of a significant loss of strength and stiffness.

A numerical model is developed in this paper to predict the in-plane cyclic inelastic response of planar, lightly reinforced, RC walls. Herein, *lightly reinforced* is associated with web horizontal and vertical reinforcement ratios of less than or equal to 1.5%. The general-purpose finite element code LS-DYNA [3,4] is used for this purpose. The LS-DYNA model is validated using data from tests of 22 low-aspect ratio RC walls performed at three laboratories, with different reinforcement and aspect ratios, and concrete strengths, subjected to in-plane cyclic lateral loading and compressive axial loading. The validated model is used to investigate the effects of wall aspect ratio, reinforcement ratio in web and boundary elements, and axial compressive load on the monotonic response of low-aspect ratio walls for displacements up to peak shear strength.

2. Numerical modeling of low aspect ratio walls: literature review

The nonlinear cyclic response of RC shear walls has been simulated using micro (finite element) and macro (spring-based) models. Finite element models, which are suitable for research but not for use in design, have been used to capture the nonlinear nature of concrete, including tensile cracking, tension stiffening, compression softening,

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Table 1
Properties of the test specimens.

No.	Researcher	Specimen ID	h_w/l_w	f_c (MPa)	$\frac{P}{A_g f_c}$	Web		Boundary		Reinforcement	
						ρ_l^w (%)	ρ_t^w (%)	ρ_l^b (%)	ρ_t^b (%)	f_y (MPa)	f_u (MPa)
1	Luna 2015 [2,54]	SW1	0.94	24.8	0	0.67	0.67	–	–	460	703
2		SW2	0.54	48.3	0	1.00	1.00	–	–	435	600
3		SW3		53.8	0	0.67	0.67	–	–		
4		SW4		28.9	0	0.33	0.33	–	–	460	703
5		SW5	0.33	29.6	0	1.00	1.00	–	–		
6		SW6		26.2	0	0.67	0.67	–	–		
7		SW7		26.2	0	0.33	0.33	–	–		
8		SW8	0.54	24.1	0	1.50	1.50	–	–		
9		SW9		29.6	0	1.50	0.67	–	–		
10		SW10		31.7	0	1.50	0.33	–	–		
11		SW11		34.5	0	0.67	0.67	1.50	1.50		
12		SW12		34.5	0	0.33	0.33	2.00	2.00		
13	Salonikios 1999 [55]	MSW1	1.60	26.1	0	0.57	0.57	1.70	1.10	610	–
14		MSW3	1.60	24.1	0.07	0.28	0.28	1.30	1.10		
15		LSW1	1.10	22.2	0	0.57	0.57	1.70	1.70		
16		LSW2	1.10	21.6	0	0.28	0.28	1.30	1.70		
17		LSW3	1.10	23.9	0.07	0.28	0.28	1.30	1.70		
18	Li 2015 [56]	LW1	1.13	40.2	0	0.50	0.50	1.40	0.97	427	497
19		LW2	1.13	41.6	0.05	0.50	0.50	1.40	0.97		
20		LW3	1.13	34.8	0.05	0.50	0.50	1.40	0.37		
21		LW4	1.13	39.8	0	0.50	0.50	1.40	0.97		
22		LW5	1.13	35.6	0.05	0.50	0.50	1.40	0.97		

bond slip, dowel action, and shear stress transfer across the cracks. For low-aspect ratio walls, whose behavior is generally dominated by shear, the modeling of both tensile cracking and shear stress transfer across crack surfaces is crucial to capture failure modes (including damage) and to accurately simulate macro-level cyclic response. Simplified macro models, which are suitable for use in design, cannot adequately capture the failure modes of low-aspect ratio walls (including diagonal tension and diagonal compression, and combinations thereof) and cannot describe damage in sufficient detail to develop fragility functions that are used for performance-based design and probabilistic risk assessment.

A significant number of macro models have been proposed to simulate the nonlinear response of RC shear walls. These models can be grouped into three bins: (1) beam or beam-column (e.g., [5–11]), (2) truss (e.g., [12–16]), and (3) multiple spring (e.g., [17–38]). The first finite element model relevant to analysis of RC shear walls was developed by Ngo and Scordelis [39] in 1967: a two-dimensional plane-stress model to simulate the flexural behavior of a simply supported reinforced concrete beam subjected to two-point loading. The reinforcement and concrete elements were modelled using constant strain triangular elements with linear elastic material properties. Bond between the reinforcement and the concrete was modelled using link elements. The proposed model accurately predicted nodal displacements, concrete and steel stresses, and forces in the bonded elements. Since that time, concrete structures have been analysed using plane stress, plane strain, shell, axisymmetric solid, and three-dimensional solid elements with a wide range of assumptions for modeling cracking, dowel action, compression softening, bond, aggregate interlock, and tension stiffening. The literature review below addresses only those publications relevant to numerical modeling of low aspect ratio RC walls subjected to in-plane loading.

Participants [40] in the *Seismic Shear Wall International Standard Problem* (SSWISP) project organized by the Nuclear Power Engineering Corporation (NUPEC) simulated the dynamic response of two low-aspect ratio, flanged RC shear walls (U-1 and U-2) using Abaqus [41], ADINA [42], and DIANA [43]. Analyses investigated the effects of different modeling assumptions on response. Of the 15 analyses, 12 predicted initial stiffness within 15% of that measured. The ratio of the predicted to measured peak lateral strength varied between 0.65 and 1.15, and the predicted displacement at peak lateral strength varied between 25% and 185% of the corresponding measured displacements. NUPEC wall U-1 [44] was analysed by Asfura and Bruin [45] using three finite element codes: IDARC2D [46], FEM-I [47], and ADINA [42]. Nonlinear static and dynamic analyses were performed. An effective flange width of 24% of the total width was used in the analysis, as recommended by Paulay and Priestley [48]. Nonlinear static analysis was performed in IDARC2D using a single fiber-based two-dimensional panel, in FEM-I using plane-stress elements and a smeared model to represent the concrete and reinforcement, respectively, and in ADINA using four-node plane stress elements to model the concrete and inelastic truss elements to model the reinforcement. Tension stiffening, compression softening, and tension cracking were considered. The lateral force–displacement response of wall U-1 was captured reasonably well by the three models up to the lateral displacement associated with initial yielding of the reinforcement; the force at greater displacement was significantly overestimated.

Brun et al. [49] developed a two-dimensional finite element model to simulate the response of a shear-critical rectangular wall (denoted T5) tested at the European Laboratory for Structural Assessment using the general purpose synthetic accelerogram. The numerical analysis was conducted using a general purpose finite element code CASTEM [50,51]. The aspect ratio of wall T5 was 0.4; the horizontal and vertical reinforcement ratios were 0.8%. A fixed smeared-crack model was used for the concrete and a bilinear kinematic model was used for the reinforcement. Four-node membrane elements and two-node bar elements were used to represent the concrete and reinforcement, respectively. Perfect bond between the concrete and the reinforcement was assumed. The predicted force–displacement relationship up to peak strength (hereafter termed the peak point) agreed well with the experimental results. The predicted and measured post-peak responses were not presented. The authors noted that the predicted displacement at failure agreed with the experimental results but they did not define failure. Palermo and Vecchio [52] tested two low aspect ratio, flanged RC shear walls (denoted DP1 and DP2) with a similar geometry to the NUPEC walls and analysed them using VecTor2 [53]: a 2D nonlinear finite element program used to simulate the in-plane response of RC structures. An axial load of $0.05A_g f_c$ was applied to DP1; where A_g is the cross-sectional area of the RC wall and f_c is the reported concrete