Multi-Layer Shell Element for Shear Walls in OpenSees

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ABSTRACT

Reinforced concrete (RC) shear walls is one of the most widely used lateral force-resisting members of high-rise buildings. This research developed a multi-layer shell element on an open-source FE code of OpenSees for shear walls. The multi-layer shell element can simulate the coupled in-plane/out-of-plane bending as well as the in-plane shear and coupled bending-shear behavior of RC shear walls, and it comprehensively reflects the spatial mechanical behavior of the shell structures. The simulation of rectangular walls, flanged walls and coupled walls under pseudo-static loading was conducted. The simulated results agree well with the experimental results, which validates the rationality and reliability of the proposed model. The nonlinear seismic analyses of a super-tall building, namely Shanghai Tower with a height of 632 m, were conducted based on the fiber beam and multi-layer shell elements, and good agreement was achieved between the analytical results of OpenSees and MSC.Marc. The outcome of this study provides an effective tool and a useful reference for the simulation of high-rise buildings using OpenSees.

INTRODUCTION

In recent years, research on the seismic behavior of tall buildings and super-tall buildings has become a popular issue with the frequent occurrence of earthquakes worldwide. Extensive research indicates that numerical simulation is effective for nonlinear seismic analyses of such building gs (Lu et al. 2012; Lu et al. 2011). As an object-oriented open-source finite-element (FE) program for numerical simulation, the Open System for Earthquake Engineering Simulation (OpenSees), has increasingly become one of the most influential open platforms for earthquake engineering research due to its powerful nonlinear numerical simulation capabilities, various effective algorithms, open framework and sustainable integration of the latest

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research outcomes (Mazzoni et al. 2005; McKenna et al. 2009). Despite of the abovementioned numerous advantages, the existing research using OpenSees primarily studied the seismic behaviors of single specimens or small-scale structures. Only a few reports exist on the research of complicated large-scale structures based on OpenSees.

The fiber beam element model has been widely adopted in OpenSees to model the specimens that are predominately controlled by flexural behavior (Spacone et al. 1996). However, this type of element is incapable of simulating the coupled in-plane/out-of-plane bending as well as the in-plane shear and coupled bending-shear behavior of RC shear walls (especially for the complex mechanic behaviors of coupled walls, flanged walls and core tubes), which has hindered the development of the nonlinear analysis of super-tall buildings using OpenSees.

This research proposed a numerical model for shear walls and implemented the multi-layer shell element in the OpenSees environment. The simulation of various types of shear walls under pseudo-static loading was conducted. The simulation results are proven to agree well with the experimental data, thus validating the rationality and reliability of the proposed models.

The nonlinear seismic analyses of Shanghai Tower were performed based on the fiber beam and multi-layer shell elements, and good agreement was achieved between the simulation results of OpenSees and MSC.Marc (Marc 2005), which provides a shared open-source platform for the international collaborative research of seismic behavior of super-tall buildings.

THE FORMULATION OF THE MULTI-LAYER SHELL ELEMENT

Theoretical background of the multi-layer shell element model. The proposed multi-layer shell formulation is implemented in OpenSees using the "ShellMITC4" element, which is a four-node shell element based on the theory of mixed interpolated of tensorial components (MITC) proposed by Dvorkin and Bathe (Dvorkin et al. 1995).

For each of the in-plane integration points, a layered/composites integrated section is implemented to account for the nonlinear behavior of reinforced concrete, i.e., this element simplifies the three-dimensional nonlinear behavior of the shear walls to a shell situation by discretizing them into several fully bonded layers in the thickness direction. Different material properties and thicknesses can be assigned to each layer in accordance with the size of the wall and the distribution of the reinforced bars, as illustrated in Figure 1. The bars are smeared into one or more orthotropic layers according to their physical location and direction, as shown in Figure 2. The axial strains and curvature of the middle layer are initially calculated, the strains of each layer are subsequently obtained based on the plane-section assumption. The stresses of each of the integration points on each layer are calculated in accordance with the constitutive model of the corresponding layer. Lastly, the internal forces are calculated using the numerical integration method (Guan and Loo 1997).

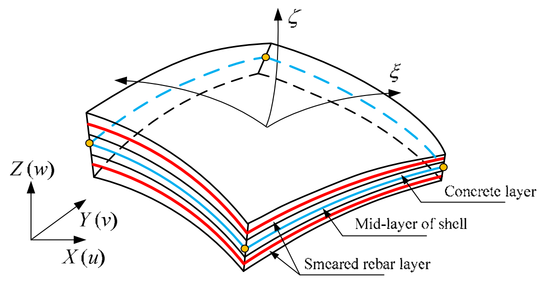


Figure 1. Multi-layer shell element.

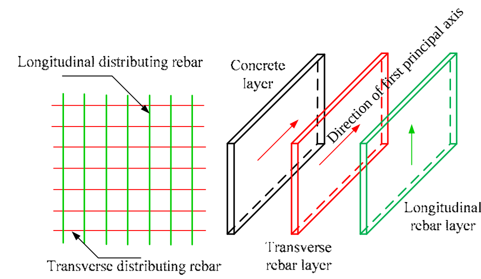


Figure 2. Distribution of the bar layers.

Multi-dimensional material constitutive model. Concrete is assumed to be under planar stress state in the multi-layer shell element; therefore, an accurate and robust two-dimensional concrete constitutive model is required to simulate the complicated mechanical behaviors of shear walls and core tubes induced by an earthquake, it is a great challenge to produce such a reliable and robust model. The analytical model for concrete proposed in this research is based on the damage mechanics and the smeared crack model, which is a model with great computational stability and a simple formulation.

The constitutive equations (Eq. 1) of concrete are expressed as follow:

$$\sigma_c' = \begin{bmatrix} 1-D_1 & \\ & 1-D_2 \end{bmatrix} D_e \varepsilon_c' \tag{1}$$

where $\sigma_c^{'}$, $\varepsilon_c^{'}$ are the stresses and strains, respectively, in the principal stress coordinate system, and D_1, D_2 are the damage parameters for tension and compression, respectively. The damage evolution curve under tension and compression recommended by Løland (Løland 1980) and Mazars (Mazars 1986), respectively, were implemented to calculate the damage parameters.

VALIDATION OF THE MULTI-LAYER SHELL ELEMENT

A series of rectangular walls (Zhang 2007), with different axial load ratios, shear-span ratios, boundary zone widths, reinforcement ratios and stirrup ratios in the boundary elements, are initially simulated. To further validate the adaptability of the multi-layer shell elements, the simulation of H-shaped walls, T-shaped walls (Chen and Qian 2005), coupled walls (Chen and Lv 2003) and symmetric double short-limb walls (Huang et al. 2003) are performed subsequently.

The vertical reinforcing bars inside the main body of the shear wall and the stirrups are smeared into one or more rebar layers, the essentially concentrated reinforcing bars within the boundary zones are simulated with discrete truss elements, which are incorporated into the shell element through the sharing of the same nodes.

To validate the reliability of the simulation of the out-of-plane mechanical behavior, the flanges and webs of H- or T-shaped walls are both simulated by using the shell elements. The element mesh of the shear wall elements is shown in Figure 3. A comparison between the experimental data and the simulation results of the shell elements is presented in Table 1. Most of the results are practically in good agreement with the experimental results, which validates the reliability and robustness of the proposed element.

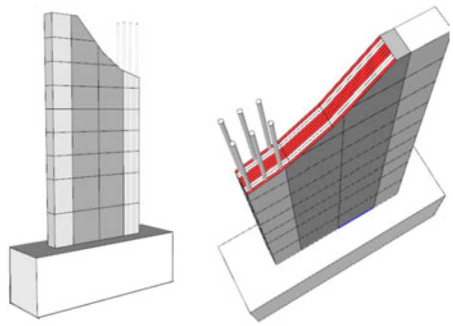
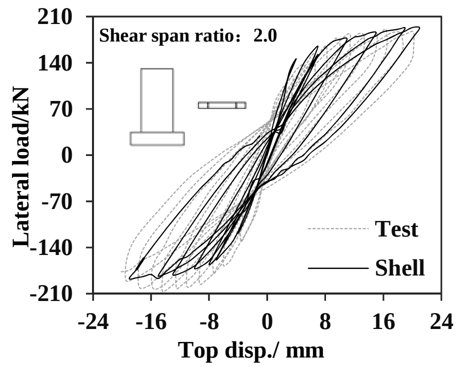


Figure 3. Finite element meshes.

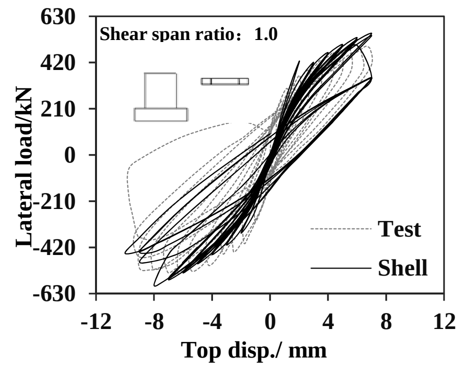
Table 1. Comparison between the experimental results and the simulated results of the shear walls

	Specimen no.	Shear-span ratio	Axial load ratio	Error of the yield load	Error of the yield disp.	Error of the peak load
Rectangular walls (Zhang 2007)	SW1-1	2.0	0.1	2.3%	6.4%	-3.1%
	SW1-2	2.0	0.2	0.8%	0	1.5%
	SW1-3	2.0	0.3	25.3%	9.6%	-4.5%
	SW1-4	2.0	0.4	27%	11.2%	10.2%
	SW2-1	1.0	0.3	3.6%	1.2%	9.6%
	SW2-2	1.5	0.3	19.3%	5.6%	1.2%
	SW4-1	2.0	0.3	7.9%	2.4%	2.9%
	SW4-2	2.0	0.3	4.6%	2.9%	8.4%
	SW5-1	2.0	0.3	2.6%	1.5%	2.1%
	SW5-3	2.0	0.3	-2.2%	2.3%	2.2%
	SW6-1	2.0	0.3	20.1%	3.2%	5.5%
	SW6-3	2.0	0.3	9.6%	2.8%	-1.4%
Flange walls (Chen et al. 2005)	SW-3	1.9	0.26	1.3%	4.5%	10.2%
	SW-4	1.9	0.26	8.6%	5.7%	4.3%
Coupled wall (Chen et al. 2003)	CW-3	-	-	-1.6%	0.6%	7.4%
Symmetric double short-limb walls (Huang et al. 2003)	SW1-1	-	-	9.6%	0	12.9%
	SW1-2	-	-	11.2%	0	-5.8%
	SW1-3	-	-	10.5%	0	9.4%

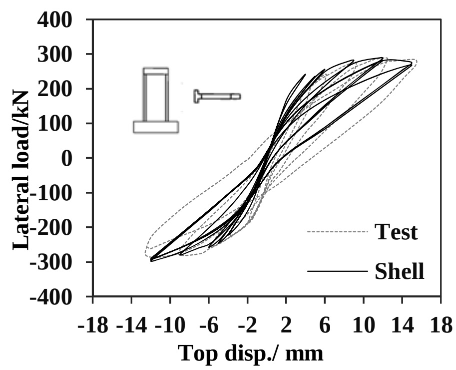
Due to length limitations, only four typical walls are discussed in detail here, the comparisons between the simulation results and experimental data are presented in Figure 4.



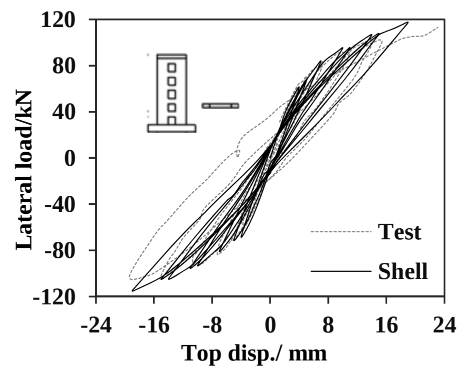
(a) SW1-1



(b) SW2-1



(c) SW-4



(d) CW-3

Figure 4. Top force vs. displacement hysteretic curves of specimens.

For the rectangular wall with sufficient stirrups and high shear-span ratio, such as SW1-1 in Figure 4(a), the multi-layer shell model is capable of capturing the characteristic behaviors of the shear walls predominately controlled by flexural behavior. In contrast, for specimens controlled by shear behavior, such as SW2-1 in Figure 4(b), the results of the multi-layer shell model agree well with the experimental results. For the flange wall in Figure 4(c), the multi-layer shell model can accurately capture the characteristic behavior because such specimens with relatively small flanges are still controlled by flexural behavior, which validates the reliability of the modeling approach for flange walls with shell elements. The hysteretic load-displacement relation curve of the coupled wall in Figure 4(d) is also in good agreement with the test results.

Based on the above validations, it can be concluded that the proposed multi-layer shell element developed in OpenSees is capable of replicating the complex behavior of various types of shear walls.

CONVERSION PROGRAM

The lack of a graphical user interface (GUI) makes it quite difficult to build and check the FE model of high-rise buildings. Because there is a high degree of similarity at the element level between MSC.Marc and OpenSees, and MSC.Marc has a convenient GUI, a conversion program "Marc to OpenSees" was developed to simplify the modeling process in OpenSees. Note that in the conversion program, the fiber beam elements and the multi-layer shell elements in MSC.Marc are converted to OpenSees fiber-by-fiber or layer-by-layer to ensure the absolute consistency between the two models. This will also make the later validation of the OpenSees simulation results with the results of the MSC.Marc very convenient. The corresponding conversion relationship is shown in Figure 5.

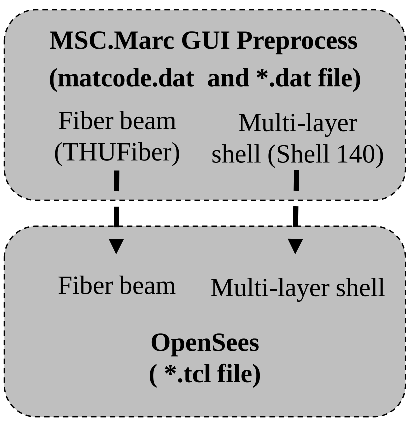


Figure 5. Conversion relationship "Marc to OpenSees".

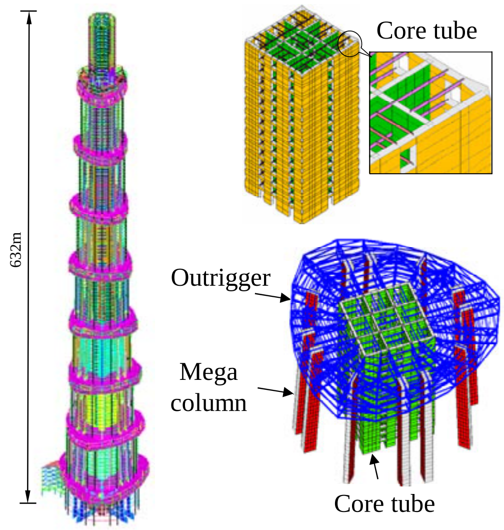


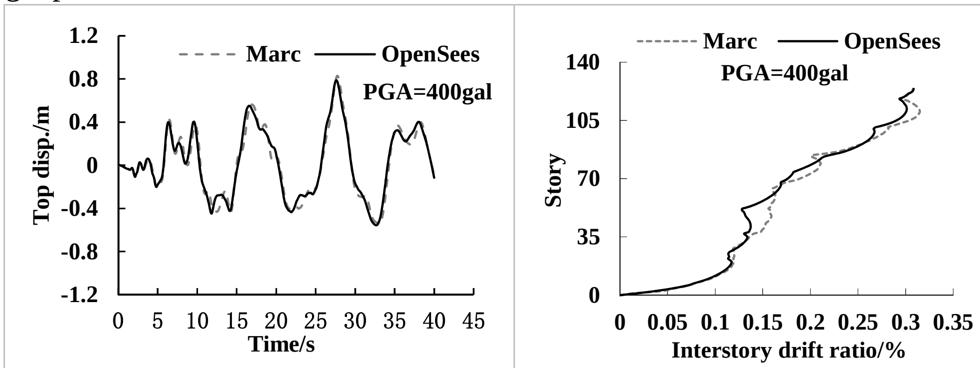
Figure 6. FE model of Shanghai Tower.

APPLICATION TO THE NONLINEAR DYNAMICAL ANALYSIS OF SHANGHAI TOWER

The Shanghai Tower is a 124-story multi-functional office building under construction in Shanghai, China. The total height of the main tower is 632 m. A hybrid lateral-force-resisting system referred to as the "mega-column/core-tube/outrigger" was adopted for the main tower. The details of this super-tall building can be found in Lu et al. (Lu et al. 2011).

The entire model was initially constructed in MSC.Marc and subsequently converted to OpenSees, as shown in Figure 6, which includes 53,006 nodes, 48,774 fiber beam elements and 39,315 multi-layer shell elements. The multi-layer shell element was used to simulate the RC core tube composed by the shear walls and the coupling beams, as well as the perimetric mega-columns. The fiber beam element was used to simulate the H-shape sub-frames and outriggers.

The El-Centro EW ground motion, which is scaled to a value of peak ground acceleration (PGA) of 400 gal, was used as the earthquake input to the structure along the X-axis after the gravity analysis was conducted. Such a ground motion is much larger than the maximal considered earthquake for the design of Shanghai Tower (i.e., PGA = 220 gal). Thus, significant nonlinear behavior will occur during the simulation. During the nonlinear time-history analysis, the 5% Rayleigh damping ratio was adopted. Illustrated in Figure 7 are the comparisons of the time-history curves of the top floor and the envelope curves of the inter-story drift ratio. The results of OpenSees are in strong agreement with the results of MSC.Marc, which validates the feasibility and reliability of simulating real complex super-tall buildings using OpenSees.



(a) Time-top displacement curves (b) Distribution of the drift ratio

Figure 7. Comparison of the time history analysis results.

CONCLUSIONS

A new numerical model, the multi-layer shell element, was formulated and implemented in the OpenSees for the simulation of shear walls, core tubes and eventually super-tall buildings, a series of shear walls with various types of sections were simulated to validate the reliability and robustness of the new element. The nonlinear dynamic analysis under a specified ground motion of Shanghai Tower was conducted. The results of OpenSees are proven to agree well with the results calculated by MSC.Marc with identical models and analyses, which validates the reliability and rationality of the proposed elements and analysis method. The research outcome assists in providing an effective tool and a useful reference for further research on the seismic behavior of tall buildings using OpenSees.

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