Seismic Simulation of RC Wall-type Structures using Softened Shell Model

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Summary:
Reinforced concrete (RC) wall-type structures are crucial to the safety and serviceability of buildings subject to earthquakes. The shear capacity of elements in walls depends strongly on the softening of concrete struts in the principal compression direction due to the principal tension in the perpendicular direction. By studying the shear behavior of isolated membrane elements, this softening phenomenon has been clarified in the Cyclic Softened Membrane Model. However, they can't be used to predict the three dimensional behavior of structures. In the present paper, the softened shell model is first formulated and then implemented in a finite element program which is based on the framework of OpenSEES. The accuracy of the modeling technique is validated by comparing simulated responses with experimental data from a framed wall subjected to shear and a wall subjected to torsion.

Keywords: Reinforced Concrete Structures; Shear Walls; Finite Element Method; OpenSEES

1.INTRODUCTION

Reinforced concrete (RC) thin walls are crucial to the safety and serviceability of structures subjected to shear. The shear capacities of elements in walls depend strongly on the softening of concrete struts in the principal compression direction due to the principal tension in the perpendicular direction. The past three decades have seen a rapid development of knowledge in shear of RC structures. Various rational models have been proposed that are based on the smeared-crack concept and can satisfy Navier's three principles of mechanics of materials (i.e., stress equilibrium, strain compatibility and constitutive laws). The Cyclic Softened Membrane Model (CSMM) is one of such rational models developed at the University of Houston (UH), which is being efficiently used to predict the behavior of RC structures critical in shear. CSMM for RC has already been implemented into an object-oriented software framework called OpenSEES (McKenna *et al.* 2000) to develop a finite element program called Simulation of Concrete Structures (SCS) (Mo *et al.* 2008; Hsu and Mo 2010).

Since each node of the membrane element has only two degree of freedoms in plane, that means it can only provide the in-plane stiffness, the CSMM cannot be used to simulate the three dimensional behavior of structures. The CSMM is integrated with plane stress element (two degree of freedom per node), so it also meets a difficult coupling with edge beam because beam elements have six degree of freedom per node (Zienkiewicz and Taylor 2005). The introduction of shell element is the naturally choice to deal with this problem. Hence, a Softened Shell Model (SSM) is proposed in this paper. This model can predict in-plane and out-of-plane behavior, including bending, shear and even torsion, of RC wall-type structures. Moreover, the proposed model is able to predict the overall load-deflection behavior of RC structures. This work includes two main parts:

In the first part, the developed theory of SSM and its corresponding shell element will be presented. As well known, a shell element generally can be considered as the assembly of membrane element and plate element. For the membrane part, the CSMM is extended by considering the drilling degree of freedom.

For the plate part, the first order shear deformation theory is adopted to consider the out-of-plane shear and bending deformation. A four-node shell element with six degree of freedom per node is then obtained.

The second part of this work involves the development of computer programs for nonlinear finite element analysis of RC wall-type structures. Constitutive laws of reinforced concrete, developed through previous research at UH have been added into SCS. Based on the SSM, a new module for RC shell section has been created. This new material module has been integrated with the existing material modules in OpenSEES. The computer program thus developed has been used for predicting the behavior of RC framed shear walls tested under reversed cyclic loading at UH (Gao 1999). Finally, the developed computer program has been applied to analyze the seismic behavior of RC wall under torsion tested at Hong Kong Polytechnic University (Peng and Wong 2011).

2.FORMULATION OF SSM

In general, there are three kinds of shell elements: curved shell element, isoparametric shell element and flat shell element. For many practical purposes the flat element approximation gives adequate accuracy and also permits an easy coupling with edge beam and rib members, a facility sometimes not present in a curved element formulation (Zienkiewicz and Taylor 2005). According to the properties of engineering structures, the flat shell element is also the most widely applied to simulate flat specimens such as panels, floor slabs and shear walls. For these reasons, the flat shell element will be used here to analyze RC wall-type structures. Ignoring the interaction of in plane and out plane response, shell element generally can be considered as the assembly of membrane element and plate element.

2.1 Assumption of shell element

The general assumptions of shell element are: (*a*) The special form of domain Ω :

$$\Omega = \left\{ (x, y, z) \in R^3 \text{ such that } z \in \left[-0.5h, 0.5h \right] \,\&\, (x, y) \in A \subset R^2 \right\} \quad (1)$$

where h is the thickness and A is the mid-surface; (*b*) The plane stress hypothesis: $\sigma_z = 0$; (*c*) The Reissner-Mindlin assumption: a plane section remains a plane before and after deformation with allowing the cross-section to be non-perpendicular to the mid-surface. The last assumption allows that the three dimensional displacement fields (u, v, w) in the *x*, *y* and *z* directions are expressed as (Maekawa *et al.* 2003; Reddy 2004)

$$u(x, y, z) = u_0(x, y) - z\phi_x,\ v(x, y, z) = v_0(x, y) - z\phi_y,\ w(x, y, z) = w_0(x, y) \quad (2)$$

where (u_0, v_0, w_0) denotes the displacements of a point on the mid-surface ($z = 0$). ϕ_x and ϕ_y are the rotations of a transverse normal about the *y* and *x* axes, respectively. If θ_x and θ_y denote the rotations about the *x* and *y* axes, respectively, that follow the right-hand rule, then $\theta_x = \phi_y$ and $\theta_y = -\phi_x$. The shell element has six degrees of freedom per node: three translation (u_0, v_0, w_0) , two rotations θ_x and θ_y , and one more degree of freedom, rotation about the *z*-axis, which is known as the "drilling degree of freedom" θ_z (Hughes and Brezzi 1989). Therefore the displacement field of the element can be express as

$$\mathbf{d} = [u_0, v_0, w_0, \theta_x, \theta_y, \theta_z] \quad (3)$$

2.2 Generalized strains

We don't need to calculate ε_z because $\varepsilon_z = \partial w / \partial z = 0$ according to Eq.(2). Other strains can be computed by differentiating the displacement based on the following relationship

$$\varepsilon_x = \frac{\partial u}{\partial x},\ \varepsilon_y = \frac{\partial v}{\partial y},\ \ \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x},\ \ \gamma_{xz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x},\ \ \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \tag{4}$$

Substituting Eq.(2) into Eq.(4), we have

$$\varepsilon_x = \bar{\varepsilon}_x - z\kappa_x,\ \varepsilon_y = \bar{\varepsilon}_y - z\kappa_y, \gamma_{xy} = \bar{\gamma}_{xy} - z\kappa_{xy}, \gamma_{xz} = \frac{\partial w_0}{\partial x} - \phi_x,\ \gamma_{yz} = \frac{\partial w_0}{\partial y} - \phi_y \tag{5}$$

where $\bar{\varepsilon}_x$, $\bar{\varepsilon}_y$ and $\bar{\gamma}_{xy}$ are the mid-surface membrane strains and κ_x, κ_y and κ_{xy} are the curvatures

$$\bar{\varepsilon}_x = \frac{\partial u_0}{\partial x},\ \ \bar{\varepsilon}_y = \frac{\partial v_0}{\partial y},\ \bar{\gamma}_{xy} = \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x}, \kappa_x = \frac{\partial \phi_x}{\partial x},\ \kappa_y = \frac{\partial \phi_y}{\partial y}, \kappa_{xy} = \frac{\partial \phi_y}{\partial x} + \frac{\partial \phi_x}{\partial y} \tag{6}$$

that indicates that we have eight general strains: three membrane strains ($\bar{\varepsilon}_x$, $\bar{\varepsilon}_y$ and $\bar{\gamma}_{xy}$), three curvatures (κ_x, κ_y and κ_{xy}) and two transverse shear strains (γ_{xz} and γ_{yz}). They are related to eight stress resultants, as described in the next section and we will find these relationships in section 2.4.

2.3 Stress resultants

The stress resultants can be divided into the membrane stress resultants (*N*), the bending moments (*M*) and the transverse shear force (*Q*) as shown in Fig. 1, which can be computed by integrating the stress over the thickness of the element as

(*a*) Membrane $N_x = \int_{-h/2}^{h/2} \sigma_x dz,\ N_y = \int_{-h/2}^{h/2} \sigma_y dz,\ N_{xy} = \int_{-h/2}^{h/2} \tau_{xy} dz$ (7)

(*b*) Bending $M_x = \int_{-h/2}^{h/2} z\sigma_x dz,\ M_y = \int_{-h/2}^{h/2} z\sigma_y dz,\ M_{xy} = \int_{-h/2}^{h/2} z\tau_{xy} dz$ (8)

(*c*) Transverse shear $Q_x = k_s \int_{-h/2}^{h/2} \tau_{xz} dz,\ Q_y = k_s \int_{-h/2}^{h/2} \tau_{yz} dz$ (9)

where $k_s = 5/6$ or $\pi^2/12$ is the shear correction factor (Crisfield 1996). As shown in Eqs. (7) and (8), $N_{yx} = N_{xy}$ and $M_{yx} = M_{xy}$ because $\tau_{xy} = \tau_{yx}$. Therefore, there are only eight independent stress resultants.

2.4 Constitutive relationships in SSM

Ignoring the interaction of in plane and out plane response, a shell element generally can be considered as the assembly of a membrane element and a Reissner-Mindlin plate element. The basic principle is demonstrated in Fig. 1. Both bending and transverse shear behaviors are included in the plate element. The softened membrane element have been developed at UH. Logically as a next step, we will develop the SSM based on the CSMM used in the membrane element.

2.4.1 Secant form

The constitutive relationship between stress resultants and general strains include two parts: in-plane and out-of-plane relationships.

(*a*) *In-plane forces and bending moments*

We can obtain the in-plane membrane stresses $\boldsymbol{\sigma}_m = (\sigma_x, \sigma_y, \tau_{xy})^T$ from CSMM as follows:

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} = \hat{\mathbf{D}}_0 \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ 0.5\gamma_{xy} \end{pmatrix} = \mathbf{D}_0 \left[\begin{pmatrix} \bar{\varepsilon}_x \\ \bar{\varepsilon}_y \\ \bar{\gamma}_{xy} \end{pmatrix} - z \begin{pmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{pmatrix} \right] \tag{10}$$

or in matrix form as $\boldsymbol{\sigma}_m = \mathbf{D}_0 \boldsymbol{\varepsilon}_z$ where $\boldsymbol{\varepsilon}_z = \boldsymbol{\varepsilon} - z \cdot \boldsymbol{\kappa}$, $\boldsymbol{\varepsilon} = (\bar{\varepsilon}_x, \bar{\varepsilon}_y, \bar{\gamma}_{xy})^T$ and $\boldsymbol{\kappa} = (\kappa_x, \kappa_y, \kappa_{xy})^T$. The principal stress directions of the applied stresses have an angle θ_1 with respect to the x-axis. The '*i*-th' group of rebars are located in the direction with an angle θ_{si} to the x-axis. The in-plane material constitutive matrix for reinforced concrete is formulated as (Zhong 2005)

$$\hat{\mathbf{D}}_0 = \mathbf{T}(-\theta_1)\cdot\mathbf{D}_c\cdot\mathbf{V}\cdot\mathbf{T}(\theta_1)+\sum_i \mathbf{T}(-\theta_{si})\cdot\mathbf{D}_{si}\cdot\mathbf{T}(\theta_{si}-\theta_1)\cdot\mathbf{V}\cdot\mathbf{T}(\theta_1) \tag{11}$$

where $\mathbf{D}_c = diag(E_1^c, E_2^c, G_{12}^c)$ and $\mathbf{D}_{si} = diag(\rho_{si}E_{si}, 0, 0)$ is the uniaxial constitutive matrix of concrete and steel, respectively. The shear modulus $G_{12}^c = (\sigma_1^c - \sigma_2^c)/(\varepsilon_1 - \varepsilon_2)$. $\mathbf{V}$ is a matrix, which converts the biaxial strains into uniaxial strains using the Hsu/Zhu ratios. $\mathbf{T}$ is the transformation matrix between different coordinates. The detail information about this formula and the uniaxial constitutive laws of concrete and steel can be found in (Zhong 2005; Hsu and Mo 2010).

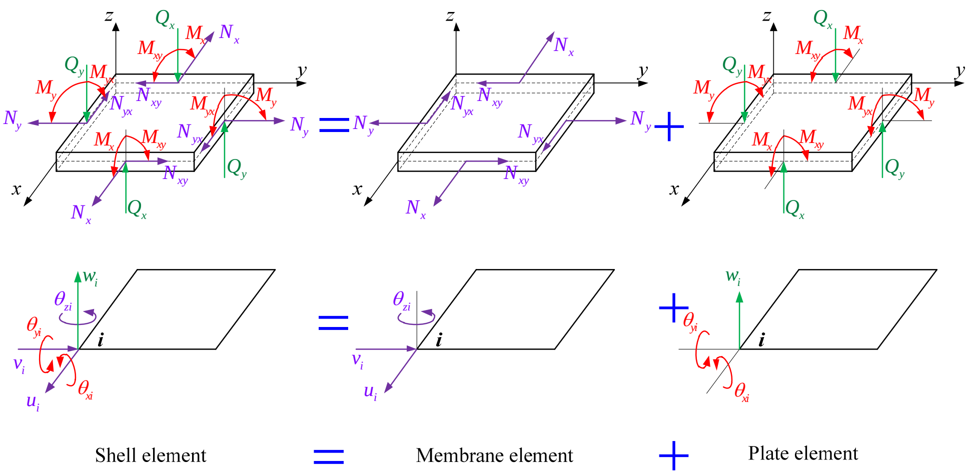

Figure 1. Stress resultants, degree of freedom and the formulation of shell element

Note that the in-plane constitutive matrix $\mathbf{D}_0$ is slightly different from $\hat{\mathbf{D}}_0$ because we use the strain γ_{xy} instead of $0.5\gamma_{xy}$ and $\mathbf{D}_0 = \hat{\mathbf{D}}_0\cdot\mathbf{\Lambda}$ where $\mathbf{\Lambda} = diag(1,1,\ 0.5)$. For a nonlinear material, $\mathbf{D}_0$ is a function of $\boldsymbol{\varepsilon}_z$, which is equal to $\boldsymbol{\varepsilon} - z\cdot\boldsymbol{\kappa}$, so $\mathbf{D}_0$ is a function of z. A numerical integration should be adopted to get the relationship between stress resultant and strain. To do so, the shell is divided into several layers along its depth. Assume the mid-plane and thickness of the *i*-th layer is z_i and t_i, respectively. The two-dimensional in-plane constitutive law Eq. (10) is applied at the mid-plane of each layer. One can easily get

$$(\mathbf{N},\mathbf{M}) = \int_{-h/2}^{h/2}(1,z)\boldsymbol{\sigma}_m(z)dz = \sum_{i=1}^{n} t_i(1,z_i)\boldsymbol{\sigma}_m(z_i) = \sum_{i=1}^{n} t_i(1,z_i)\mathbf{D}_0(\boldsymbol{\varepsilon}_{zi})\boldsymbol{\varepsilon}_{zi} \tag{12}$$

where $\mathbf{N} = (N_x, N_y, N_{xy})^T$, $\mathbf{M} = (M_x, M_y, M_{xy})^T$, $\boldsymbol{\varepsilon}_{zi} = \boldsymbol{\varepsilon} - z_i\cdot\boldsymbol{\kappa}$ and n is the number of layers. Precisely the integrals of any function $f(z)$ defined along the depth can be numerically evaluated using the Gauss-Lobatto quadrature formulas

$$\int_{-h/2}^{h/2} f(z)dz \xrightarrow{z=0.5\eta} 0.5h\int_{-1}^{1} f(\eta)d\eta = 0.5h\sum_{i=1}^{n} w_i f(\eta_i) \tag{13}$$

where n denotes the number of Gauss-Lobatto quadrature points, η_i denotes the Gauss-Lobatto point coordinates, and w_i denotes the corresponding Gauss-Lobatto weights (Reddy 2004). Therefore, the stress resultants are

$$(\mathbf{N},\mathbf{M}) = \int_{-h/2}^{h/2}(1,z)\boldsymbol{\sigma}_m dz = 0.5h\sum_{i=1}^{n} w_i(1,z_i)\boldsymbol{\sigma}_{mi} = 0.5h\sum_{i=1}^{n} w_i(1,z_i)\mathbf{D}_0(\boldsymbol{\varepsilon}_{zi})\boldsymbol{\varepsilon}_{zi} \tag{14}$$

(*b*) *Out-of-plane shear forces*

The relationships used for calculating the transverse shear stress are $\tau_{xz} = G_{xz}\gamma_{xz}$ and $\tau_{yz} = G_{yz}\gamma_{yz}$. It is assumed that the contribution of shear resistance by shear reinforcement is not explicitly considered and the relationship between transverse shear forces (Q_x, Q_y) and shear strains (γ_{xz}, γ_{yz}) is linear, i.e., $G_{xz} = G_{yz} = G_0$. The out-of-plane shear modulus G_0 is assumed equal to the uncracked concrete shear modulus given as $G_0 = E_0 / 2(1+\upsilon)$ where E_0 is the elastic modulus and υ is the Poisson's ratio (Maekawa *et al.* 2003). From Eq. (9), we have

$$\begin{pmatrix} Q_x \\ Q_y \end{pmatrix} = hK_s \begin{bmatrix} G_{xz} & 0 \\ 0 & G_{yz} \end{bmatrix} \begin{pmatrix} \gamma_{xz} \\ \gamma_{yz} \end{pmatrix} \equiv \mathbf{D}_s \begin{pmatrix} \gamma_{xz} \\ \gamma_{yz} \end{pmatrix} \tag{15}$$

where G_{xz} and G_{yz} are the shear moduli. Finally, the constitutive relationship and the 8×8 secant material matrix $\mathbf{D}$ for the SSM element are derived as

$$\begin{pmatrix} \mathbf{N} \\ \mathbf{M} \\ \mathbf{Q} \end{pmatrix} = \begin{bmatrix} \sum_{i=1}^{n} s_i \mathbf{D}_0(\boldsymbol{\varepsilon}_{zi}) & -\sum_{i=1}^{n} s_i z_i \mathbf{D}_0(\boldsymbol{\varepsilon}_{zi}) & 0 \\ \sum_{i=1}^{n} s_i z_i \mathbf{D}_0(\boldsymbol{\varepsilon}_{zi}) & -\sum_{i=1}^{n} s_i z_i^2 \mathbf{D}_0(\boldsymbol{\varepsilon}_{zi}) & 0 \\ 0 & 0 & \mathbf{D}_s \end{bmatrix} \begin{pmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \\ \boldsymbol{\gamma} \end{pmatrix} \equiv \mathbf{D} \begin{pmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \\ \boldsymbol{\gamma} \end{pmatrix} \tag{16}$$

where $s_i = t_i$ or $0.5hw_i$, $\mathbf{Q} = (Q_x, Q_y)^T$ and $\boldsymbol{\gamma} = (\gamma_{xz}, \gamma_{yz})^T$.

2.4.2 Tangent form

The tangent material constitutive matrix $\bar{\mathbf{D}}$ is defined as

$$\bar{\mathbf{D}} = \partial \begin{pmatrix} \mathbf{N} \\ \mathbf{M} \\ \mathbf{Q} \end{pmatrix} / \partial \begin{pmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \\ \boldsymbol{\gamma} \end{pmatrix} = \begin{bmatrix} \partial \mathbf{N}/\partial \boldsymbol{\varepsilon} & \partial \mathbf{N}/\partial \boldsymbol{\kappa} & \partial \mathbf{N}/\partial \boldsymbol{\gamma} \\ \partial \mathbf{M}/\partial \boldsymbol{\varepsilon} & \partial \mathbf{M}/\partial \boldsymbol{\kappa} & \partial \mathbf{M}/\partial \boldsymbol{\gamma} \\ \partial \mathbf{Q}/\partial \boldsymbol{\varepsilon} & \partial \mathbf{Q}/\partial \boldsymbol{\kappa} & \partial \mathbf{Q}/\partial \boldsymbol{\gamma} \end{bmatrix} \tag{17}$$

Because $\partial \boldsymbol{\varepsilon}_{zi} / \partial \boldsymbol{\varepsilon} = \mathbf{I}$ and $\partial \boldsymbol{\varepsilon}_{zi} / \partial \boldsymbol{\kappa} = -z_i \mathbf{I}$, the tangent material matrix is obtained easily by applying the chain of derivation principle to Eq.(17). The non-zero elements of matrix $\bar{\mathbf{D}}$ are obtained as follows:

$$\bar{\mathbf{D}} = \partial \begin{pmatrix} \mathbf{N} \\ \mathbf{M} \\ \mathbf{Q} \end{pmatrix} / \partial \begin{pmatrix} \boldsymbol{\varepsilon} \\ \boldsymbol{\kappa} \\ \boldsymbol{\gamma} \end{pmatrix} = \begin{bmatrix} \sum_{i=1}^{n} s_i \bar{\mathbf{D}}_0(\boldsymbol{\varepsilon}_{zi}) & -\sum_{i=1}^{n} s_i z_i \bar{\mathbf{D}}_0(\boldsymbol{\varepsilon}_{zi}) & 0 \\ \sum_{i=1}^{n} s_i z_i \bar{\mathbf{D}}_0(\boldsymbol{\varepsilon}_{zi}) & -\sum_{i=1}^{n} s_i z_i^2 \bar{\mathbf{D}}_0(\boldsymbol{\varepsilon}_{zi}) & 0 \\ 0 & 0 & \mathbf{D}_s \end{bmatrix} \tag{18}$$

where $\bar{\mathbf{D}}_0(\boldsymbol{\varepsilon}_{zi}) = \partial\left(\mathbf{D}_0(\boldsymbol{\varepsilon}_{zi})\boldsymbol{\varepsilon}_{zi}\right) / \partial \boldsymbol{\varepsilon}_{zi}$ is the in-plane tangent constitutive matrix of the *i*-th layer. The details of the derivation of the in-plane tangent material constitutive matrix $\bar{\mathbf{D}}_0 = \hat{\bar{\mathbf{D}}}_0 \cdot \boldsymbol{\Lambda}$ for membrane elements can be found in (Zhong 2005) and

$$\hat{\bar{\mathbf{D}}}_0 = \mathbf{T}(-\theta_1) \cdot \bar{\mathbf{D}}_c \cdot \mathbf{V} \cdot \mathbf{T}(\theta_1) + \sum_i \mathbf{T}(-\theta_{si}) \cdot \bar{\mathbf{D}}_{si} \cdot \mathbf{T}(\theta_{si} - \theta_1) \cdot \mathbf{V} \cdot \mathbf{T}(\theta_1) \tag{19}$$

where

$$\bar{\mathbf{D}}_c = \begin{bmatrix} \bar{E}_1^c & \partial \sigma_1^c / \partial \bar{\varepsilon}_2 & 0 \\ \partial \sigma_2^c / \partial \bar{\varepsilon}_1 & \bar{E}_2^c & 0 \\ 0 & 0 & G_{12}^c \end{bmatrix} \text{ and } \mathbf{D}_{si} = \begin{bmatrix} \rho_{si}\bar{E}_{si} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{20}$$

3. IMPLEMENTATION OF SSM INTO OPENSEES

The Open System for Earthquake Engineering Simulation (OpenSEES) is an object-oriented software framework for simulating the seismic response of structural and geotechnical systems using finite element method (McKenna *et al.* 2000; Scott *et al.* 2008). OpenSEES has been developed in the Pacific Earthquake Engineering Center (PEER). It is a communication mechanism for exchanging and building upon research accomplishments, and has the potential for a community code and computational platform for earthquake engineering because it is an open source.

Constitutive laws of reinforced concrete, developed through previous research at UH have been added into SCS. In order to implement the SSM into OpenSEES, a new module named "RCShell" for RC shell section has been created. A new shell element has also been developed with considering the drilling degree of freedom based on the theory developed by Cook *et al.* (2002). As shown in Fig. 2, the new material module and element have been integrated with the existing material modules in OpenSEES. SteelZ01 and ConcreteZ01 are the uniaxial material modules for concrete and rebar, respectively. The RCPlaneStress is a nD material module to represent the Softened Membrane Model. The uniaxial materials of steelZ01 and concreteZ01 are related with material RCPlaneStress to determine the material stiffness matrix of membrane reinforced concrete in RCPlaneStress. The nD material RCPlaneStress supplies the in-plane stiffness matrix of each layer in RCShell. Using the OpenSEES as the finite element framework, the nonlinear finite element program Simulation of Concrete Structures (SCS) was extended for the simulation of three dimensional reinforced concrete structures subjected to monotonic and reversed cyclic loading. A standard analysis procedure is presented in Fig. 3. The RCShell section gives a connection between a nD material (i.e., RCPlaneStress in CSMM) and a shell element.

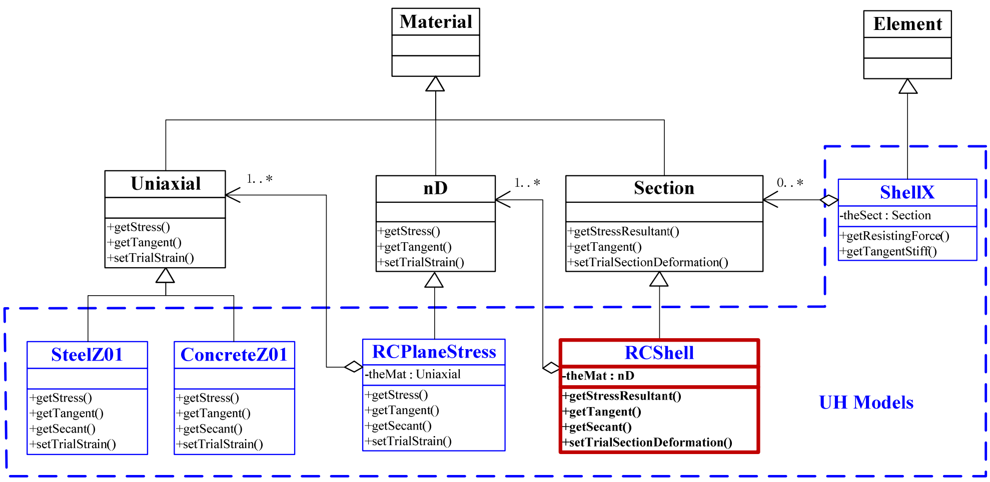

Figure 2. Implementation of SSM into OpenSEES

4. VALIDATION

4.1 Example 1: framed wall subjected to cyclic shear

Specimen FSW-13 tested by Gao (1999) was used to validate the SSM. The specimen is a 1/3-scale framed shear wall, subjected to a constant axial load at the top of each column and a reversed cyclic load at the top beam. The wall dimensions were 914.4 mm by 914.4 mm with a thickness of 76.2 mm. The cross-section of the boundary columns was 152.4 mm^2. The detail of reinforcement of the specimen is also shown in Table 1 and Fig. 4.

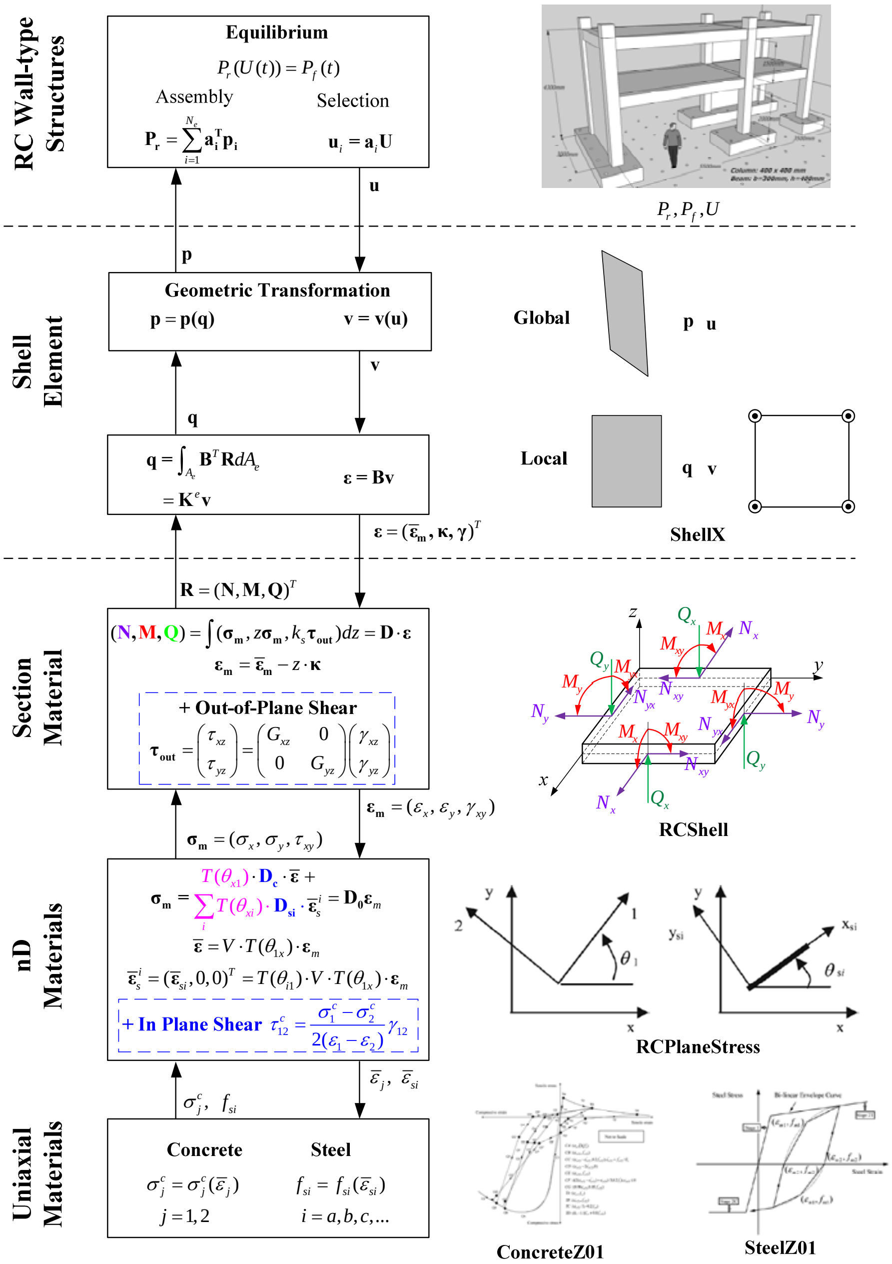

Figure 3. Modeling hierarchy for nonlinear RC structural analysis

Table 1. Dimension and properties of Specimen FSW-13 (Gao 1999)

f_c' (MPa)	Column & Beam			Wall Panel		Vertical Load	
	Hoop steel (mm)	Longl. steel	Longl. steel (%)	Panel steel (mm)	Panel steel (%)	N (kN)	Axial load ratio
56.91	#2@63.5	6#4	3.33	W2@152.4	0.23	89	0.07

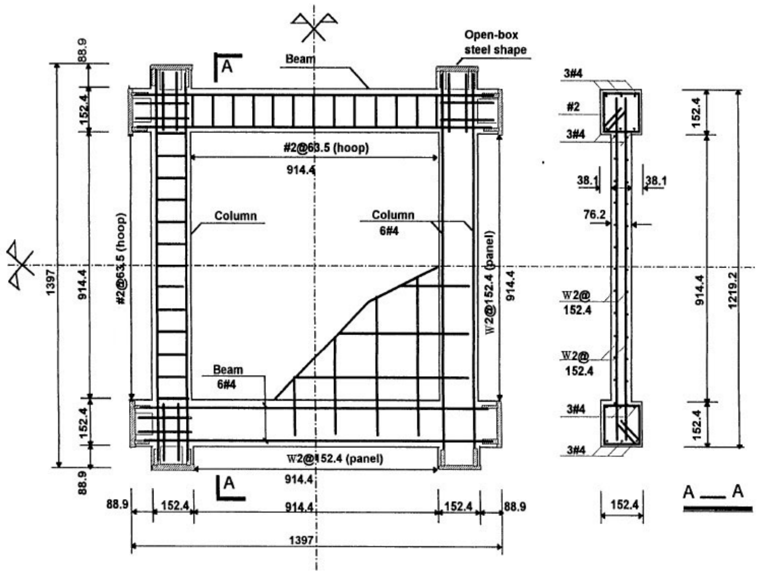

Figure 4. Dimensions and steel arrangement of specimen FSW-13 (Gao 1999)

The bottom left and right corners of the specimen were supported by a hinge and a roller, respectively. Finite element analyses were conducted on the specimen. The specimen was modeled by the finite element mesh, as shown in Fig. 5. The wall panel was defined by 25 ShellX elements. Each element was defined with a RCShell section that was developed based on the SSM. The section was discretized into five layers or five integration points. The material of each layer or point is a 2D material RCPlaneStress, which is composed of two uniaxial materials ConcreteZ01 and SteelZ01 (Zhong 2005). The nonlinear behavior of the element derives finally from the nonlinear stress-strain relation of the uniaxial materials. The boundary columns and beams are modeled as NonlinearBeamColumn elements, which are the existing element types in OpenSEES. Each of the beams and columns were divided into five elements. As shown in Fig. 5, the element was discretized into longitudinal steel, unconfined concrete and confined concrete fibers such that the section force-deformation relation is derived by integration of the stress-strain relation of the fibers. The stress and strain of the confined concrete was determined based on the modified Kent and Park model developed by Scott *et al.* (1982).

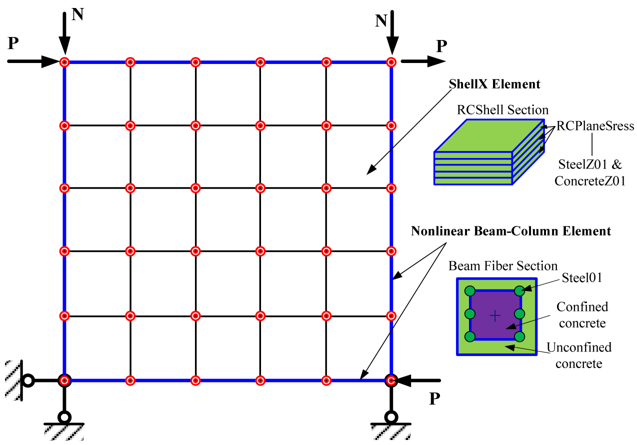

Figure 5. Finite element modeling of specimen FSW-13: load, mesh and materials

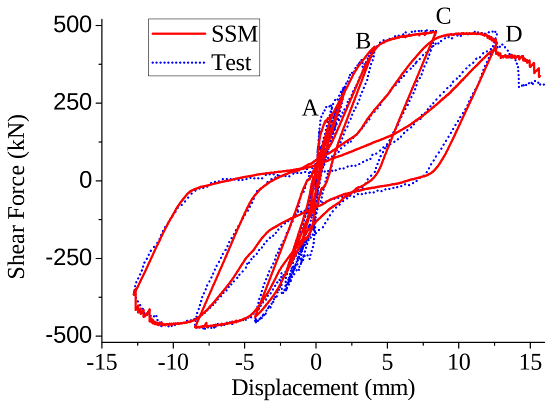

Figure 6. Shear force-drift displacement

The axial loads acting on the columns were applied as vertical nodal forces, which remain constant in the analysis. Reversed cyclic horizontal loads were then applied by a predetermined displacement control scheme. The nodal displacements and corresponding horizontal forces were recorded at each converged displacement step, and the stress and strain of each of the elements were also monitored. The analytical results of the shear force-drift relationships of the framed shear wall are illustrated by the solid hysteretic loops in Fig. 6. These dashed loops are compared to the dotted loops, representing the experimental results. It can be seen that excellent agreements were obtained for the primary backbone curves, including the initial stiffness, the yield point, the ultimate strength, and the failure state in the descending branch.

4.2 Example 2: RC wall subjected to monotonic pure torsion

Eight half-scaled RC walls, designed with the same thickness but different lengths and reinforcement ratios, were tested under monotonic torsion at Hong Kong Polytechnic University (Peng and Wong 2011). Although all walls were simulated using SSM, we only show the results of Specimen SW10-3 because the results of others are similar. Specimen SW10-3 was modeled with 5×6 shell elements. The bottom of the wall is fixed and the top is modeled by a rigid beam element to simulate the top slab used in the test. As shown in Fig. 7, the cracking torque predicted by SSM agrees well with that of test, but the maximum torque is larger than the experimental result by about 23.5%. Since the torsional (out-of-plane shear) effect on concrete softening is not considered in the model, the maximum torque predicted is higher than the experimental result.

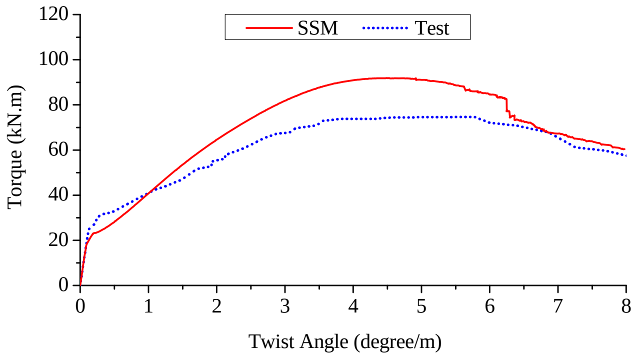

Figure 7. Comparison of torque-twist curves

5. CONCLUSIONS AND FUTURE WORKS

The theory of SSM for RC shell section was developed and implemented into OpenSEES to simulate the three-dimensional behavior of RC wall type structures under multi-direction loads. A new shell element with six degree of freedoms per node was also developed. It is very easy to connect with beam element because the two type of elements can share the same node. Two experimental walls are simulated to validate the model. One is under in-plane shear and the other is subjected to torsion. The results show that the SSM can predict the in-plane shear behavior very well and can also predict the cracking torque. However, the model should be refined to get a better prediction in the torque and twist angle relationship by taking into account a high order shell theory and the torsional effect on concrete softening.

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