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Development of CSMM-based shell element for reinforced concrete structures

C.H. Luu, Y.L. Mo *, Thomas T.C. Hsu

Department of Civil and Environmental Engineering, University of Houston, 4800 Calhoun, Houston 77204, USA

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ABSTRACT

Reinforced concrete shell structures have been widely used in a variety of modern engineering applications. It is found from earthquake reconnaissance that reinforced concrete (RC) shell structures, such as nuclear containments, cooling towers, roof domes, shear walls, etc., are the key elements in resisting earthquake disturbances. This paper presents the development of a finite element analysis (FEA) program, SCS-3D, to predict the inelastic behavior of RC shell structures. In the program, a Cyclic Softened Membrane Model (CSMM)-based shell element is developed based on the degenerated shell theory with a layered approach and taking into account the CSMM developed at the University of Houston. To form the FEA program, the constitutive relation modules and the analysis procedure were implemented into a finite element program development framework, OpenSees developed at UC Berkeley. Several large-scale structural tests were employed to validate the developed FEA program, including RC panels subjected to a combination of shear and bending, three-dimensional RC shear wall and cylindrical RC tanks subjected to reversed cyclic loading.

1. Introduction

Due to the high strength-to-weight ratio and the efficient load-carrying capacity, the reinforced concrete (RC) shell structures have been widely used in a variety of modern engineering applications, such as pressure vessels, water tanks, cooling towers, arch dams roof domes and varieties of containers [1]. The reserved cyclic behavior of RC shell structures is very difficult to predict, especially when they are subjected to the earthquake loading. It is because the seismic response of the RC shell structures is highly nonlinear, which is caused by highly inelastic behavior of materials including rebars and concrete under-reversed cyclic actions. However, from the structural point of view, a whole RC shell structure can be visualized as an assembly of many RC elements. This concept makes it easier for the analysis of the complex structure, in which the finite element analysis combined with proper constitutive models for concrete and reinforcing bars could be a very powerful tool. The key to rational analysis of the RC structure is to completely understand the behavior of one element isolated from the structure. Once a rational model is developed to predict the behavior of one element, this rational model can then be incorporated into a finite element program to predict the behavior of the whole structure under different kinds of loading.

Since the 1970's, many researchers have proposed an analytical model to predict the behavior of RC shell structures using the finite element method. The main approach used by most researchers is to develop a reinforced concrete shell element by combining a rational constitutive model of reinforced concrete material into finite element formulations of a general shell element with layer approaches (Hand, Pecknold [2]; Cervera, Hinton [3]; Scordelis and Chan [4]; Hu and Schnobrich [5]; Polak and Vecchio [6]; Kim, Lee [7]; Zhang, Bradford [8]; Lee [9]; Xiang, Mo [10]; Gopinath, Iyer [11], Matešan, Radnić [12], Hrynyk and Vecchio [13], and Lu, Xie [14]). The main problem faced by most researchers in the analysis of RC shell structures using the finite element method was that it often required expensive computational time due to the complicated material models and the difficulties encountered in the stability and accuracy of the solutions. Some material models for reinforced concrete material such as fracture mechanics or detail crack localizations were successfully verified at the element level but faced a numerical problem when applied at the structure level, which requires a large number of elements. It is found from the above researches that a selection of appropriate material models, which provides adequate accuracy with reasonable computational time, plays an important role in the success of the analysis of the RC shell structures using the finite element method.

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* Corresponding author.
E-mail address: yilungmo@central.uh.edu (Y.L. Mo).

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Nomenclature

X, Y, Z	global coordinate of the shell element
X, Y, Z	local coordinate of the shell element
ξ, η, ζ	curvilinear coordinate of the shell element
V_{1i}, V_{2i}	nodal vectors tangential to the middle surface of the shell element
V_{3i}	nodal vector perpendicular to the middle surface of the shell element
1–2	the principal stress directions of the applied in-plane stresses
$x_{si} - y_{si}$	local coordinate of a steel layer in i$^{\text{th}}$ direction
θ_1	angle between the (x-y) coordinate system and (1–2) coordinate system
θ_{si}	angle between the (x-y) coordinate system and (x_{si}-y_{si}) coordinate system
t_i	the thickness at node i of the shell element
$N_i(\xi, \eta)$	the two-dimension shape function at node i
$\ell_{ki}, m_{ki}, n_{ki}$	the direction cosines of the nodal vector V_{ki}
u_{Xi}, u_{Yi}, u_{Zi}	displacements at node i with respect to the global coordinate
α_i, β_i	rotations at node i with respect to the global coordinate
$\sigma_X, \sigma_Y, \sigma_Z$	normal stresses in X-, Y-, and Z- directions
$\tau_{YZ}, \tau_{XZ}, \tau_{XY}$	shear stresses in X-, Y-, and Z- directions
$\sigma_x, \sigma_y, \sigma_z$	normal stresses in x-, y-, and z- directions
$\tau_{yz}, \tau_{xz}, \tau_{xy}$	shear stresses in x-, y-, and z- directions
$\varepsilon_x, \varepsilon_y, \varepsilon_z$	meared biaxial normal strains in x-, y-, and z- directions
$\gamma_{yz}, \gamma_{xz}, \gamma_{xy}$	smeared biaxial shear strains in x-, y-, and z- directions

σ_1^c, σ_2^c	normal stresses of concrete in 1- and 2- directions
$\varepsilon_1, \varepsilon_2$	smeared biaxial strains in 1- and 2- directions
$\bar{\varepsilon}_1, \bar{\varepsilon}_2$	smeared uniaxial strains in 1- and 2- directions
N_x, N_y, N_{xy}	membrane stress resultants
M_x, M_y, M_{xy}	bending moment stress resultants
Q_x, Q_y	transverse shear stress resultants
$[\mathrm{k}^e]$	element stiffness matrix
$[K]$	global stiffness matrix
$\{\mathrm{f}^e\}$	internal force vector
$[\mathrm{B}]$	strain-displacement matrix
$[\mathrm{J}]$	Jacobian matrix
$[\mathrm{D}]$	local material matrix
$[\bar{\mathrm{D}}_{in}]$	in-plane tangential material matrix
$[\bar{\mathrm{D}}_{out}]$	out-of-plane tangential material matrix
$[\bar{\mathrm{D}}_c]$	uniaxial tangential matrix of concrete
$[\bar{\mathrm{D}}_{si}]$	uniaxial tangential matrix of embedded rebars
$[V]$	Hsu/Zhu matrix
$\bar{E}_1^c$	concrete tangent uniaxial modulus in the 1-direction
$\bar{E}_2^c$	concrete tangent uniaxial modulus in the 2-direction
$\bar{E}_{si}$	steel tangent modulus of the steel layer in the i$^{\text{th}}$ direction
G_{12}^c	shear modulus of concrete in (1–2) coordinate
ρ_{si}	reinforcement ratio of the steel layer in the i$^{\text{th}}$ direction
$[T(\alpha)]$	transformation matrix $\begin{bmatrix} \cos^2\alpha & \sin^2\alpha & 2\sin\alpha\cos\alpha \\ \sin^2\alpha & \cos^2\alpha & -2\sin\alpha\cos\alpha \\ -\sin\alpha\cos\alpha & \sin\alpha\cos\alpha & \cos^2\alpha - \sin^2\alpha \end{bmatrix}$

In recent years, the “smeared-crack” concept has been widely used in the analysis of RC structures. This concept allows internally cracked reinforced concrete composite to be treated as a simple, continuous material rather than a complicated, discontinuous composite [15]. The advantage of this simplification is that mechanics-based analysis can be applied to predict the behavior of the RC shell structures regardless of cracking. To implement this simplification, the material constitutive models must be based on the smeared (averaged) stress and strain relationship of the internally cracked RC elements. Since the 1980’s, studies of the constitutive material of reinforced concrete based on the “smeared-crack” concept have been carried out by many researchers; however, an experimental study of shell elements could only be carried out by a few research groups [16,17]. Using the experimental results of panel tests, many constitutive models for RC have been proposed. The models are the Compression-Field Theory and Modified Compression Field Theory by Vecchio and Collins [18]; Disturbed Stress Field Theory by Vecchio [19]; Rotating-Angle Softened Truss Model (RA-STM) [20,21]; Fixed-Angle Softened Truss Model (FA-STM) [22], the Softened Membrane Model (SMM) [23] and the Cyclic Softened Membrane Model (CSMM) [24]. Among these constitutive models, the CSMM is the most versatile and accurate, as shown in Fig. 1. It is capable of rationally predicting the cyclic shear behavior of reinforced concrete membrane elements including the stiffness, ultimate strength, descending branch, ductility and energy dissipation capacity. The model is even extended to study the behavior of steel plate ultra high-performance concrete structures [25].

Following the success of the membrane element development [26], the present study accomplishes three main tasks: (1) to formulate the CSMM for the development of a shell element, called CSMM-based shell element, in the finite element program, (2) to implement the developed CSMM-based shell element into a finite element program SCS-3D, using OpenSees as a framework and (3) to validate the finite element program SCS-3D by comparing its predictions with the experimental results of several large-scale structural tests including RC panels subjected a combination of shear and bending, three-dimensional RC shear wall, and cylindrical RC tanks subjected to reversed cyclic loading.

2. Research significance

The development of a finite element program for reinforced concrete structures includes three components, namely modeling, formulation and implementation. In this paper, the Cyclic Softened Membrane Model (CSMM) [24] is adopted for the simulation of reinforced concrete shell-type structures. The major contributions of this study are the formulation and the implementation, which resulted in a finite element program called Simulation of Three Dimensional Concrete Structures (SCS-3D). The CSMM-based shell element implemented in the finite element program SCS-3D can predict accurately the hysteretic loops of three dimensional RC shell structures subjected to seismic loading.

3. Finite element formulation

The CSMM-based shell element is developed by utilizing the formulation of an 8-node Serendipity curved shell element [27] with a multi-layer approach [4] accompanying with the Cyclic Softened Membrane Model (CSMM) [24]. The Serendipity shell element has a total of eight nodes with five degrees of freedom (DOF) at each node, three translational DOFs, and two rotational DOFs. The idea of creating this element arose from the difficulty