DEVELOPMENT OF CSMM-BASED SHELL ELEMENT FOR REINFORCED CONCRETE STRUCTURES

Presented
by
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Outline

1. Introduction
2. Formulation
3. Implementation
4. Validations
5. Nuclear Containment Vessels
6. Conclusions
1. Introduction

Reinforced Concrete Shell-Type Structures
1. Introduction

Opera House, Sydney, Australia (1973)  
(www.wikipedia.org)

TWA Flight Center at JFK Airport, NYC (1962)  
(www.wikipedia.org)

Modern RC shell structures in a nuclear power plant  
(www.wikipedia.org)
1. Introduction

Finite element (FE) methods have been used successfully for the structural analysis of reinforced concrete shell structures over the decades.

**Research Significance**

For an efficient FE analysis, it is necessary to have rational and effective numerical models for predicting accurately the structural behavior of large-scale RC shell structures.
1. Introduction

Research on RC Shell Structures using FEM

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>E. Hinton &amp; D.R.J. Owen M. Cervera &amp; E. Hinton</td>
<td>University College, Swansea, UK</td>
</tr>
<tr>
<td>1987</td>
<td>A.C. Scordelis &amp; E.C. Chan</td>
<td>University of California, Berkeley, USA</td>
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<td>1991</td>
<td>Adebar &amp; Collins M.A. Polak &amp; F.J. Vecchio</td>
<td>University of Toronto, Canada</td>
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<tr>
<td>1997</td>
<td>P. Irawan &amp; K. Maekawa</td>
<td>University of Tokyo, Japan</td>
</tr>
<tr>
<td>2002</td>
<td>T.H. Kim, K.M. Lee, H.M. Sin</td>
<td>Sungkyunkwan University, Korea</td>
</tr>
<tr>
<td>2006</td>
<td>Y.X. Zhang, M.A. Braford, R.I. Gilbert</td>
<td>University of New South Wales, Sydney, Australia</td>
</tr>
<tr>
<td>2012</td>
<td>H.J. Xiang, Y.L. Mo, T.T.C. Hsu</td>
<td>University of Houston, USA</td>
</tr>
</tbody>
</table>
1. Introduction

Select Element

Solid Element

Shell Elements

Flat Shell Element

Degenerated Curved Shell Element

Layer Approach

Develop Constitutive Models for RC

Biaxial Failure Curve
(Kupfer, Hilsdorf, Rusch 1960)

Compression Field Theory for Cracked Concrete
(Vecchio & Collins, 1986)

Constitutive Model for Mild Steel

Concrete

Steel
1. Introduction

Constitutive Models Developed at UH

(1) Rotating-Angle Softened Truss Model (RA-STM)
(2) Fixed-Angle Softened Truss Model (FA-STM)
(3) Softened Membrane Model (SMM)
(4) Cyclic Softened Membrane Model (CSMM)
(5) Cyclic Softened Membrane Model for Prestressed Concrete (CSMM-PC)
(6) Cyclic Softened Membrane Model for Prestressed Steel Fiber Concrete (CSMM-PSFC)
(7) Cyclic Softened Membrane Model for ECC (CSMM-ECC)
1. Introduction

Overview of Cyclic Softening Membrane Model (CSMM)

Uniaxial

Steel

Concrete

Softening Coefficient

Biaxial

Hsu/Zhu Ratio

Shear

Steel stress

Steel strain

Normal Steel

Stress in CSM

Concrete stress

Concrete strain

Normal Concrete

Softening Coefficient

Uniaxial

Cyclic Softening Membrane Model (CSMM)

Biaxial

Uniaxial

Steel

Concrete

Softening Coefficient

Biaxial Strains ~ Uniaxial Strains

\[ \epsilon_{11}, \epsilon_{22}, \epsilon_{12} \rightarrow \bar{\epsilon}_{11}, \bar{\epsilon}_{22}, \bar{\epsilon}_{12} \]

\[ v_{12} = 0.2 + 850 \epsilon_{sf} \quad \epsilon_{sf} \leq 0.002 \]

\[ v_{12} = 1.0 \quad \epsilon_{sf} > 0.002 \]

\[ v_{21} = 0.0 \]

\[ \sigma_{11} = \frac{(\sigma_{11}^C - \sigma_{22}^C)}{2(\epsilon_{11} - \epsilon_{22})} \]

\[ \zeta = \left(\frac{5.8}{f_{tc}^{\prime}(MPa)}\right) \left(\frac{1}{1 + 400 \epsilon_C}\right) \left(1 - \frac{f_{tc}^{\prime}}{24}\right) \leq 0.9 \]
1. Introduction

Research on Finite Element Analysis (FE) at UH

OpenSees

An object-oriented software framework (C++) for simulation applications in earthquake engineering using finite element methods.

Key features of OpenSees include the interchangeability and the ability to integrate existing libraries and new components into the framework without changing the existing code.

OpenSees is open-source software. OpenSees is a research tool.

FE Program for Simulation of Concrete Structure (SCS)
1. Introduction

Applications of SCS Program

RC Frame and Shear Wall (Zhong, 2005)

PC Girder (Laskar, 2009)

RC Shear Wall (Zhong, 2005)

PC Bridge Column (Laskar, 2009)
Research Objectives

• Develop a new shell element (named CSMMShellS8) based on the Cyclic Softened Membrane Model to formulate the degenerated shell theory with layered approach.

• Create a new finite element program (SCS-3D) with the developed shell element using OpenSees as a framework to predict the nonlinear behavior of RC structures.

• Validate the developed finite element program SCS-3D with several large-scale tests of RC shell structures subjected to reserved cyclic loadings.

• This research is undertaken as an international collaborative project between the National Center for Research on Earthquake Engineering (NCREE) and the University of Houston to investigate the inelastic behavior of RC nuclear containment vessels and two-story unsymmetrical RC building structures. The tests were performed at NCREE, and the design of the specimens and the study of the experimental results were performed at UH.
Model-Based Approach (MBS) is the basic methodology of this research.
2. Formulation

Element Selection

The degenerated curved shell element with layered approach has been recognized as the most promising element for analysis of RC curved shell structures since the 1970s. The element is derived from the equations of 3D continuum mechanics by reducing their dimensions in the thickness direction (Ahmad et al., 1970; Hughes, 1981; Hilton & Owen, 1984; Hu & Schnobrich, 1991; Cook, 2002)

20-Node Solid Element
8-Node Degenerated Curved Shell Element
5 DOFs per node

$X$-$Y$-$Z$ : Global coordinate system
$\xi$-$\eta$-$\zeta$ : Curvilinear coordinate system (xi, eta, zeta)
$V_{1i}$-$V_{2i}$-$V_{3i}$ : Nodal coordinate system
$x$-$y$-$z$ : Local coordinate system
2. Formulation

Fundamental Assumptions

1- A straight fiber that was perpendicular to the middle surface before deformation needs to remain straight but does not need to be perpendicular to the deformed middle surface (Mindlin theory)

\[ \gamma_{xz} \neq 0 \quad \gamma_{yz} \neq 0 \]

2- Stresses normal to the mid-surface are negligible

\[ \sigma_z = 0 \]

3- Each shell layer remains in the plane stress state and the out-of-plane shear behavior are decoupled from the in-plane stresses and strains
2. Formulation

Element Stiffness Matrix

\[
[k^e] = \int [B]^T [D][B] \, dV
\]

[B]: matrix representing the shape functions

[\Rightarrow Element Formulation]

[D]: constitutive material matrix

[\Rightarrow Constitutive Material Formulation (CSMM)]
2. Formulation

Element Geometry

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \sum N_i(\xi, \eta) \begin{bmatrix}
X_i \\
Y_i \\
Z_i
\end{bmatrix} + \sum N_i(\xi, \eta) \zeta t_i \begin{bmatrix}
\frac{I_{3i}}{2} \\
m_{3i} \\
n_{3i}
\end{bmatrix}
\]  
(Eq. 3.3)

The Displacement Field

\[
\begin{bmatrix}
u_X \\
u_Y \\
u_Z
\end{bmatrix} = \sum_{i=1}^{n \text{ node}} N_i(\xi, \eta) \begin{bmatrix}
u_{X_i} \\
u_{Y_i} \\
u_{Z_i}
\end{bmatrix} + \frac{1}{2} \zeta t_i \begin{bmatrix}
-\frac{V_{2i}}{V_{2i}}, \frac{V_{1i}}{V_{1i}}
\end{bmatrix} \begin{bmatrix}
\alpha_i \\
\beta_i
\end{bmatrix}
\]  
(Eq. 3.5)

\[
\left\{ \partial u \right\}_{\xi, \eta, \zeta} = \left[ \partial N(\xi, \eta, \zeta) \right] \{U_e\}
\]  
(Eq. 3.11)

\[
\left\{ \partial u \right\}_{X,Y,Z} = \left[ J_0 \right]^{-1} \left\{ \partial u \right\}_{\xi, \eta, \zeta} = \left[ J_0 \right]^{-1} \left[ \partial N(\xi, \eta, \zeta) \right] \{U_e\}
\]  
(Eq. 3.9)

To calculate strains

\[
\{U_e\} \text{ is the displacement vector of the shell element}
\]

\[
\{U_e\} = \{u_{X1}, u_{Y1}, u_{Z1}, \alpha_1, \beta_1, \ldots, u_{Xn}, u_{Yn}, u_{Zn}, \alpha_n, \beta_n\}^T
\]

\[
N_i(\xi, \eta) \text{ is 2D shape function at node i}
\]

\[
\left[ J_0 \right]^{-1} \text{ is Jacobian matrix (Eq. 3.23)}
\]
2. Formulation

The Strain-Displacement Relationship

\[
\varepsilon_x = \frac{\partial u_x}{\partial X} ; \quad \varepsilon_y = \frac{\partial u_y}{\partial Y} ; \quad \varepsilon_z = \frac{\partial u_z}{\partial Z} ; \quad \gamma_{xz} = \frac{\partial u_x}{\partial Z} + \frac{\partial u_z}{\partial X} ; \quad \gamma_{yz} = \frac{\partial u_y}{\partial Z} + \frac{\partial u_z}{\partial Y} ; \quad \gamma_{xy} = \frac{\partial u_x}{\partial Y} + \frac{\partial u_y}{\partial X} ;
\]

\[
\{ \varepsilon |_{X,Y,Z} \} = [H] \{ \partial u |_{X,Y,Z} \} \quad \text{(Eq. 3.7)}
\]

Combining Eqs (3.7 & 3.9) gives

\[
\{ \varepsilon \} = \left( [H][J_0]^{-1} \left[ \frac{\partial N (\xi, \eta, \zeta)}{\partial (\xi, \eta, \zeta)} \right] \right) \{ U_e \} = [B] \{ U_e \} \quad \text{(Eq. 3.12)}
\]

\[
[B] = [H][J_0]^{-1} \left[ \frac{\partial N (\xi, \eta, \zeta)}{\partial (\xi, \eta, \zeta)} \right] \text{ is strain-displacement relation matrix}
\]

Element Stiffness Matrix & Element Internal Force Vector

\[
[k^e] = \int_{V} \left[ B \right]^T \left[ D \right]_{X,Y,Z} \left[ B \right] \, dV \quad \& \quad [f^e] = \int_{V} \left[ B \right]^T \left[ \sigma \right]_{X,Y,Z} \, dV
\]

\[
dV = dx \, dy \, dz = \det[J] \, d\xi \, d\eta \, d\zeta \quad \text{is the element volume}
\]

\[
[D]_{X,Y,Z} \text{ is the global constitutive material matrix}
\]
2. Formulation

Constitutive Material Model

In the global coordinate:
\[ \{\sigma\}_{X,Y,Z} = [D]_{X,Y,Z} \{\varepsilon\}_{X,Y,Z} \]

In the local coordinate:
\[ \{\sigma\}_{x,y,z} = [D]_{x,y,z} \{\varepsilon\}_{x,y,z} \]

\[
[D]_{X,Y,Z} = [T_{\varepsilon}]^{T} [D]_{x,y,z} [T_{\varepsilon}]
\]

\[
[T_{\varepsilon}] = \begin{bmatrix}
\ell_1^2 & m_1^2 & n_1^2 & l_1m_1 & m_1n_1 & n_1l_1 \\
\ell_2^2 & m_2^2 & n_2^2 & l_2m_2 & m_2n_2 & n_2l_2 \\
\ell_3^2 & m_3^2 & n_3^2 & l_3m_3 & m_3n_3 & n_3l_3 \\
2l_1l_2 & 2m_1m_2 & 2n_1n_2 & l_1m_1 + l_2m_1 & m_1n_1 + m_2n_1 & n_1l_1 + n_2l_1 \\
2l_1l_3 & 2m_1m_3 & 2n_1n_3 & l_1m_1 + l_3m_1 & m_1n_1 + m_3n_1 & n_1l_1 + n_3l_1 \\
2l_2l_3 & 2m_2m_3 & 2n_2n_3 & l_2m_2 + l_3m_2 & m_2n_2 + m_3n_2 & n_2l_2 + n_3l_2 \\
\end{bmatrix}
\]

\[
X \ Y \ Z
\]
\[
x \ l_1 \ m_1 \ n_1 \\
y \ l_2 \ m_2 \ n_2 \\
z \ l_3 \ m_3 \ n_3 \\
\]

Implementation of CSMM

In-plane:
\[ \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} D_{\text{in}} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \]

Out-of-plane:
\[ \begin{bmatrix} \tau_{xz} \\ \tau_{yz} \end{bmatrix} = \begin{bmatrix} D_{\text{out}} \end{bmatrix} \begin{bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{bmatrix} \]
2. Formulation

Formulation of CSMM for Shell Element

Coordinate Systems for CSMM

Concrete Layer

Steel Layer

1-2: Orientation of Principal Stress

$\rho_i f_i$

$x_{si}$-$y_{si}$: Orientation of Steel Bar
2. Formulation

Formulation of CSMM for Shell Element (Cont. )

Compatibility Equations
\[
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix} = \begin{bmatrix}
T_e (\theta_1)
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{si} \\
0
\end{bmatrix} = \begin{bmatrix}
T_e (\theta_{si} - \theta_1)
\end{bmatrix}
\begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix}
\]

Concrete Layer  Steel Layer

Biaxial Strains ~ Uniaxial Strains
\[ \varepsilon_1, \varepsilon_2, \varepsilon_{si} \rightarrow \overline{\varepsilon}_1, \overline{\varepsilon}_2, \overline{\varepsilon}_{si} \]

Constitutive Laws of Uniaxial Materials
\[ \overline{\varepsilon}_1, \overline{\varepsilon}_2, \gamma_{12} \rightarrow \sigma_1^c, \overline{E}_1^c, \sigma_1^c, \overline{E}_1^c, \tau_{12}^c \]
\[ \varepsilon_{si} \rightarrow f_{si}, \overline{f}_{si} \]

Equilibrium Equations
\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = \begin{bmatrix}
T_e (\theta_1)
\end{bmatrix}^T
\begin{bmatrix}
\sigma_1^c \\
\sigma_2^c \\
\tau_{12}^c
\end{bmatrix} = \sum \begin{bmatrix}
T_e (\theta_{si})
\end{bmatrix}^T
\begin{bmatrix}
f_{si} \\
0 \\
0
\end{bmatrix}
\]

Concrete Layer  Steel Layer

\[
\begin{bmatrix}
D_{in}
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 1-V_{12}V_{21} & V_{12} \\
V_{12} & 1-V_{12}V_{21} & 1-2V_{12}V_{21}
\end{bmatrix}
\]

\[ c = \cos(\alpha) \quad s = \sin(\alpha) \]

\[ v_{12} = 0.2 + 850 \varepsilon_{sf} \quad \varepsilon_{sf} \leq 0.002 \]
\[ v_{12} = 1.0 \quad \varepsilon_{sf} > 0.002 \]
\[ v_{21} = 0.0 \]

(Mansour and Hsu, 2005)
(Mo, Zhong, and Hsu 2008)
2. Formulation

Formulation of CSMM for Shell Element (Cont.)

In-plane:

Concrete Layer

\[
\begin{bmatrix}
\bar{E}_1^c & \frac{\partial \sigma_1^c}{\partial \epsilon_2} & 0 \\
\frac{\partial \sigma_1^c}{\partial \epsilon_2} & \bar{E}_2^c & 0 \\
0 & 0 & G_{12}^c
\end{bmatrix}
\]

\( \bar{E}_1^c \); \( \bar{E}_2^c \) are the uniaxial tangent moduli of concrete in the principal stress directions.

\( \frac{\partial \sigma_1^c}{\partial \epsilon_2}; \frac{\partial \sigma_1^c}{\partial \epsilon_2} \) can be obtained by the uniaxial constitutive relationships and taking into account the stress/strain state of concrete.

Steel Layer

\[
\begin{bmatrix}
\rho_{si} \bar{E}_{si} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

\( \bar{E}_{si} \) is the uniaxial tangent modulus of embedded in-plane reinforcement

Out-of-plane:

Concrete Layer

\[
\begin{bmatrix}
\bar{D}_{out} \end{bmatrix} = K_s \begin{bmatrix}
G_{xz} & 0 \\
0 & G_{yz}
\end{bmatrix}
\]

\( K_s \) shear correction factor, taken as 5/6 (Maekawa et al. 2003)

\( G_{xz} = G_{xz} = G_0 = E_0 / 2(1 + \nu) \)

\( E_0 \) Elastic modulus of concrete, \( 3875 \sqrt{f_c'}(\text{MPa}) \) (Hsu & Mo, 2010)

\( \nu \) Poisson ratio of concrete, taken as 0.2
3. Implementation

Analysis Procedure

KrylovNewton Method (Carlson & Miller 1998)

Solution Algorithm (OpenSees)

\[
\begin{align*}
\sum R_i R_i^T &< TOL \\
\sum R_0 R_0^T &< TOL
\end{align*}
\]

For force

\[
\sum (\Delta U_i)^2 < TOL \quad \sum (\Delta U_0)^2 < TOL
\]

For displacement

\( \Delta U_i \) is the nodal displacement increment

\( R_i \) is the unbalanced nodal force

\( TOL \) is the specified tolerance

Convergence Criterion (OpenSees)
3. Implementation

Development of Finite Element Program SCS-3D

Element and Material Classes of SCS-3D Program

<table>
<thead>
<tr>
<th>Module</th>
<th>Type</th>
<th>Remark</th>
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</thead>
<tbody>
<tr>
<td>ConcreteZ01</td>
<td>UniaxialMaterial</td>
<td>Uniaxial constitutive model for concrete (Zhong, 2005)</td>
</tr>
<tr>
<td>SteelZ01</td>
<td>UniaxialMaterial</td>
<td>Uniaxial constitutive model for steel (Zhong, 2005)</td>
</tr>
<tr>
<td>CSMMLayer</td>
<td>NDMaterial</td>
<td>3D material model for each layer of CSMM-based shell element</td>
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<tr>
<td>CSMMSHELLS8</td>
<td>Element</td>
<td>8-node CSMM-based shell element</td>
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</table>

Implementation of element and material classes of SCS-3D program in OpenSees framework

OpenSees

OpenSees -- Open System For Earthquake Engineering Simulation
Pacific Earthquake Engineering Research Center -- 2.4.3 (rev 5634)
(c) Copyright 1999-2011 The Regents of the University of California
All Rights Reserved
(Copyright and Disclaimer @ http://www.berkeley.edu/OpenSees/copyright.html)

CSMM-based Curved Shell Element
3. Implementation

Development of User Interface for Pre- and Post-Processing using Eyeshot Framework (Cont.)
Accurate solution would be achieved even with fewer number of elements or large mesh size of elements.
4. Validations
4. Validations

Element Level

RC panels under in-plane loadings
RC panels under in-plane and out-of-plane loadings

Structure Level

RC Cylindrical Tank
RC 3D Shear Wall
RC Hollow Bridge Piers
4. Validations

RC Panels Tested by Pang (1991)

Dimensions of the specimens

Loading Scheme

Cross section mesh

Material Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>$f'c$ (MPa)</th>
<th>$f_c$ (MPa)</th>
<th>$\rho_y$ (%)</th>
<th>$f_t$ (MPa)</th>
<th>$\rho_t$ (%)</th>
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<tbody>
<tr>
<td>A2</td>
<td>41</td>
<td>463</td>
<td>1.19</td>
<td>463</td>
<td>1.19</td>
</tr>
<tr>
<td>A3</td>
<td>42</td>
<td>447</td>
<td>1.79</td>
<td>447</td>
<td>1.79</td>
</tr>
<tr>
<td>A4</td>
<td>42</td>
<td>470</td>
<td>2.98</td>
<td>470</td>
<td>2.98</td>
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</tbody>
</table>

Finite element model

Comparisons of experimental and analytical results
4. Validations

RC Panels Tested by Mansour (2001)

Dimensions of the specimens

Material Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>$f_y'$ (MPa)</th>
<th>$f_y$ (MPa)</th>
<th>$\rho_y$ (%)</th>
<th>$f_t$ (MPa)</th>
<th>$\rho_t$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA3</td>
<td>46</td>
<td>425.4</td>
<td>1.7</td>
<td>425.4</td>
<td>1.7</td>
</tr>
<tr>
<td>CE3</td>
<td>48</td>
<td>453.4</td>
<td>1.9</td>
<td>453.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Finite element model

Cross section mesh

Comparisons of experimental and analytical results
4. Validations

RC Panels Tested by Polak (1992)

Dimensions of the specimens

Loading scheme

Experimental results

Loading and Material Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>f'c (MPa)</th>
<th>Reinforcement in x-direction</th>
<th>Reinforcement in y-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f′y (MPa)</td>
<td>ρ′x (%)</td>
<td>f′y (MPa)</td>
</tr>
<tr>
<td>SM1</td>
<td>47</td>
<td>425</td>
<td>1.25</td>
</tr>
<tr>
<td>SM2</td>
<td>62</td>
<td>425</td>
<td>1.25</td>
</tr>
<tr>
<td>SM3</td>
<td>56</td>
<td>425</td>
<td>1.25</td>
</tr>
<tr>
<td>SM4</td>
<td>64</td>
<td>425</td>
<td>1.25</td>
</tr>
</tbody>
</table>
4. Validations

RC Panels Tested by Polak (1992) (Cont.)

Finite element model (Panel SM1)

Finite element model (Panel SM3)

Finite element model (Panel SM2 and SM4)

Cross section mesh
4. Validations

RC Panels Tested by Polak (1992) (Cont.)

Comparisons of experimental and analytical results
4. Validations

RC Cylindrical Tank (Maekawa et al., 2003)

Test Setup (Plan view)

Test Setup (Elevation view)

Dimension and reinforcement detailing of the specimen

Dimension and material properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$f'_c$ (MPa)</th>
<th>D (mm)</th>
<th>H (mm)</th>
<th>t (mm)</th>
<th>Vertical Reinforcement</th>
<th>Horizontal Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.0</td>
<td>3600</td>
<td>2000</td>
<td>100</td>
<td>384.0</td>
<td>410.0</td>
</tr>
</tbody>
</table>

Note: $f'_c$ = Compressive strength of concrete; $D$ = Diameter of the tank; $t$ = Thickness $f_y$ = Yielding strength of steel; $H$ = Effective height of the tank; $\rho_v$ = Percentage of the vertical steel; $\rho_h$ = Percentage of horizontal steel.
4. Validations

RC Cylindrical Tank (Maekawa et al., 2003) (Cont.)

Finite element model

Cross section mesh

Comparison of experimental and analytical results

Deformed shape and strain of horizontal steel bars at the peak load
4. Validations

3D RC Shear Wall (Palermo and Vecchio, 2002)

### Dimension of the specimen

![Dimension of the specimen](image)

### Reinforcement detailing of the specimen

![Reinforcement detailing of the specimen](image)

### Test Setup (Elevation view)

![Test Setup (Elevation view)](image)

### Dimension and material properties

<table>
<thead>
<tr>
<th>Wall Zone</th>
<th>$f'_c$ (MPa)</th>
<th>P (kN)</th>
<th>$P_{f/A_g}$</th>
<th>L (mm)</th>
<th>$f_y$ (MPa)</th>
<th>$\rho_l$ (%)</th>
<th>$f_y$ (MPa)</th>
<th>$\rho_t$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web</td>
<td></td>
<td>940</td>
<td>0.054</td>
<td>2020</td>
<td>605.0</td>
<td>0.8</td>
<td>605.0</td>
<td>0.73</td>
</tr>
<tr>
<td>Inner Flange</td>
<td>21.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Flange</td>
<td>0.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note:  
$ f'_c = $ Compressive strength of concrete;  
$ A_g = $ Area of cross section;  
$ f_y = $ Yielding strength of steel;  
$ L = $ Effective height of the wall;  
$ \rho_l = $ Percentage of the longitudinal steel;  
$ \rho_t = $ Percentage of transverse steel.
4. Validations

3D RC Shear Wall (Palermo and Vecchio, 2002) (Cont.)

Finite element model

Cross section mesh

Comparison of experimental and analytical results

Deformed shape and strain of compressive principal strain of concrete at the peak load
4. Validations

RC Hollow Bridge Piers (Yeh & Mo, 1999; 2001)

Material Properties

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>$f'_c$ (MPa)</th>
<th>$P$ (kN)</th>
<th>$P/A_y$</th>
<th>$L$ (mm)</th>
<th>$f_y$ (MPa)</th>
<th>$\rho_y$ (%)</th>
<th>$f_s$ (MPa)</th>
<th>$\rho_s$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1</td>
<td>34.0</td>
<td>4000</td>
<td>0.082</td>
<td>6500</td>
<td>460.0</td>
<td>1.7</td>
<td>343.0</td>
<td>1.1</td>
</tr>
<tr>
<td>PI1</td>
<td>34.0</td>
<td>4000</td>
<td>0.082</td>
<td>4500</td>
<td>460.0</td>
<td>1.7</td>
<td>510.0</td>
<td>0.45</td>
</tr>
<tr>
<td>PI2</td>
<td>32.0</td>
<td>3600</td>
<td>0.078</td>
<td>3500</td>
<td>418.2</td>
<td>2.15</td>
<td>410.0</td>
<td>0.26</td>
</tr>
<tr>
<td>PS1-C</td>
<td>31.7</td>
<td>3600</td>
<td>0.101</td>
<td>5500</td>
<td>418.2</td>
<td>2.15</td>
<td>410.0</td>
<td>0.9</td>
</tr>
<tr>
<td>PI1-C</td>
<td>33.8</td>
<td>3600</td>
<td>0.094</td>
<td>5500</td>
<td>418.2</td>
<td>2.15</td>
<td>410.0</td>
<td>0.3</td>
</tr>
<tr>
<td>PI2-C</td>
<td>30.9</td>
<td>3600</td>
<td>0.103</td>
<td>3500</td>
<td>418.2</td>
<td>2.15</td>
<td>410.0</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Note: $f'_c$ = Compressive strength of concrete; $A_y$ = Area of cross section; $f_y$ = Yielding strength of steel; $L$ = Effective height of the column; $\rho_y$ = Percentage of the longitudinal steel; $\rho_s$ = Percentage of transverse steel.
4. Validations

RC Hollow Bridge Piers (Yeh & Mo, 1999; 2001) (Cont.)

Finite element model for the specimens PS1, PI1, PI2

Finite element model for the specimens PS1-C, PI1-C, PI2-C

Cross section mesh
4. Validations

Summary of equations for the confined concrete model:

\[
\sigma_c = D \zeta \frac{f_{cc}'}{\kappa} \left[ 2 \left( \frac{\bar{\epsilon}}{\zeta \epsilon_{01}} \right) - \left( \frac{\bar{\epsilon}}{\zeta \epsilon_{01}} \right)^2 \right], \quad 0 \leq |\bar{\epsilon}| \leq |\zeta \epsilon_{01}|,
\]

\[
\sigma_c = D \zeta \frac{f_{cc}'}{\kappa} \bar{\epsilon}, \quad |\zeta \epsilon_{01}| \leq |\bar{\epsilon}| \leq |\zeta \epsilon_{02}|,
\]

\[
\sigma_c = D \zeta \frac{f_{cc}'}{\kappa} \left[ 1 - Z(\bar{\epsilon} - \epsilon_{02}) \right] \geq 0.3D \zeta \frac{f_{cc}'}{\kappa}, \quad |\bar{\epsilon}| > |\zeta \epsilon_{02}|,
\]

\[
\frac{\sigma}{f_{cc}'} = K_f e_c',
\]

\[
K_f = 1.0 + \frac{A_{co}}{140 P_{acc}} \left[ 1 - \frac{nc^2}{5.5 A_{co}} \left( 1 - \frac{s}{2B} \right) \right] \sqrt{\rho_f f_{yh}},
\]

\[
P_{acc} = 0.85f_{cc}'(A_{co} - A_s),
\]

\[
\epsilon_{s1} = 80 \times 10^{-6} \cdot K_f e_c',
\]

\[
\epsilon_{s2} = 0.0022 \left[ 1 + \frac{248}{c} \left( 1 - 5 \left( \frac{s}{B} \right)^2 \right) \rho_f f_{yh} \frac{e_c'}{f_{cc}'} \right],
\]

\[
\epsilon_{s5} = 0.225 \rho_s \sqrt{\frac{B}{s}} + \epsilon_{02},
\]

\[
Z = \frac{0.15}{\epsilon_{s5} - \epsilon_{02}}.
\]
4. Validations

RC Hollow Bridge Piers (Yeh & Mo, 1999; 2001) (Cont.)
Comparison between analytical results using confined and confined concrete models

Specimen PS1-C

Cross-section of the specimen
Input compressive stress-strain relationships
Comparison of analytical results with test result

Specimen P12-C

Cross-section of the specimen
Input compressive stress-strain relationships
Comparison of analytical results with test result
4. Validations

RC Hollow Bridge Piers (Yeh & Mo, 1999; 2001) (Cont.)

Comparisons of analytical and experimental results using confined model

Test Analysis
5. Nuclear Containment Vessels

Prototype of Lungmen containment vessel

Dimensions of RCCV specimens

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>( f_c ) (MPa)</th>
<th>D (mm)</th>
<th>H (mm)</th>
<th>t (mm)</th>
<th>Vertical Reinforcement</th>
<th>Horizontal Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCCV #1</td>
<td>35</td>
<td>2350</td>
<td>2250</td>
<td>150</td>
<td>9.5 365 2</td>
<td>9.5 365 2</td>
</tr>
<tr>
<td>RCCV #2</td>
<td>37</td>
<td>2350</td>
<td>2250</td>
<td>150</td>
<td>9.5 365 2 (4)</td>
<td>9.5 365 2</td>
</tr>
</tbody>
</table>

Note: 
- \( f_c \) = Compressive strength of concrete; 
- \( D \) = Diameter; 
- \( H \) = Net height; 
- \( t \) = Thickness; 
- \( f_y \) = Yielding strength of steel; 
- \( d_s \) = Diameter of steel bar; 
- \( \rho \) = Steel ratio in the vertical direction; 
- \( \rho_h \) = Steel ratio in horizontal direction
5. Nuclear Containment Vessels

Manufacturing of Specimens
5. Nuclear Containment Vessels

Strain Gauge Distributions

Specimen No. 1

Specimen No. 2

Plan view of strain gauge distribution
5. Nuclear Containment Vessels

Test setup

Horizontal actuators (Total: 8000 kN)

Loading protocol

Nuclear Containment Vessels

Horizontal actuators

Loading protocol

Testing plan view

Horizontal actuators

Loading frame

Data acquisition systems

Horizontal LVDT

Specimen

Loading direction
5. Nuclear Containment Vessels

Experimental Results

Critical Points on the load vs. displacement curves

<table>
<thead>
<tr>
<th>Points</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>First cracking of concrete</td>
</tr>
<tr>
<td>2a</td>
<td>First yield of vertical steel bars in the positive direction</td>
</tr>
<tr>
<td>2b</td>
<td>First yield of horizontal steel bars in the positive direction</td>
</tr>
<tr>
<td>3a</td>
<td>First yield of vertical steel bars in the negative direction</td>
</tr>
<tr>
<td>3b</td>
<td>First yield of horizontal steel bars in the negative direction</td>
</tr>
<tr>
<td>4</td>
<td>Peak load in the positive direction</td>
</tr>
<tr>
<td>5</td>
<td>Peak load in the negative direction</td>
</tr>
</tbody>
</table>

Experimental Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Loading Direction</th>
<th>$\Delta_y$ (mm)</th>
<th>$P_y$ (kN)</th>
<th>$\Delta_{max}$ (mm)</th>
<th>$P_{max}$ (kN)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(+)</td>
<td>7.84</td>
<td>3706</td>
<td>16.7</td>
<td>5580</td>
<td>2.13</td>
</tr>
<tr>
<td></td>
<td>(-)</td>
<td>7.86</td>
<td>3634</td>
<td>16.0</td>
<td>4794</td>
<td>2.04</td>
</tr>
<tr>
<td>2</td>
<td>(+)</td>
<td>7.04</td>
<td>3363</td>
<td>20.2</td>
<td>5805</td>
<td>2.87</td>
</tr>
<tr>
<td></td>
<td>(-)</td>
<td>7.38</td>
<td>3675</td>
<td>16.5</td>
<td>5487</td>
<td>2.23</td>
</tr>
</tbody>
</table>
5. Nuclear Containment Vessels

Failure Mode of Specimen No. 1

Sliding shear failure (Cycle 13 – Drift 0.3%)

Failure Mode of Specimen No. 2

Web shear failure (Cycle 14 – Drift 1.5%)
5. Nuclear Containment Vessels

Finite element models of RCCV specimens

Specimen No. 1

Specimen No. 2

<table>
<thead>
<tr>
<th>Element Type</th>
<th>$\rho_v$</th>
<th>$\rho_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSMMShellS8 Element (Type 1)</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>CSMMShellS8 Element (Type 2)</td>
<td>4 %</td>
<td>2 %</td>
</tr>
</tbody>
</table>
5. Nuclear Containment Vessels

Comparisons of analytical and experimental results

Critical Points on the load vs. displacement curves

<table>
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</tr>
</thead>
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<td></td>
</tr>
<tr>
<td>3a</td>
<td>First yield of vertical steel bars in the negative direction</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>First yield of horizontal steel bars in the negative direction</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Peak load in the positive direction</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Peak load in the negative direction</td>
<td></td>
</tr>
</tbody>
</table>

Experimental Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Loading Direction</th>
<th>$\Delta_y$ (mm)</th>
<th>$P_y$ (kN)</th>
<th>$\Delta_{max}$ (mm)</th>
<th>$P_{max}$ (kN)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(+)</td>
<td>7.84</td>
<td>3706</td>
<td>16.7</td>
<td>5580</td>
<td>2.13</td>
</tr>
<tr>
<td></td>
<td>(-)</td>
<td>7.86</td>
<td>3634</td>
<td>16.0</td>
<td>4794</td>
<td>2.04</td>
</tr>
<tr>
<td>2</td>
<td>(+)</td>
<td>7.04</td>
<td>3363</td>
<td>20.2</td>
<td>5805</td>
<td>2.87</td>
</tr>
<tr>
<td></td>
<td>(-)</td>
<td>7.38</td>
<td>3675</td>
<td>16.5</td>
<td>5487</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Analytical Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Loading Direction</th>
<th>$\Delta_y$ (mm)</th>
<th>$P_y$ (kN)</th>
<th>$\Delta_{max}$ (mm)</th>
<th>$P_{max}$ (kN)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>7.8</td>
<td>3829</td>
<td>16.7</td>
<td>5400</td>
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</tr>
<tr>
<td></td>
<td>(-)</td>
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<td>3764</td>
<td>16.9</td>
<td>5367</td>
<td>2.22</td>
</tr>
<tr>
<td>2</td>
<td>(+)</td>
<td>7.9</td>
<td>3897</td>
<td>18.3</td>
<td>5669</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>(-)</td>
<td>7.8</td>
<td>3873</td>
<td>18.1</td>
<td>5640</td>
<td>2.32</td>
</tr>
</tbody>
</table>
5. Nuclear Containment Vessels

Specimen No. 1

- Experimental crack pattern of Specimen No. 1 (Drift 0.5%)
- Contour of the angles between principal stress direction and local coordinate of Specimen No. 1 (Drift 0.5%)

Specimen No. 2

- Experimental crack pattern of Specimen No. 2 (Drift 0.5%)
- Contour of the angles between principal stress direction and local coordinate of Specimen No. 2 (Drift 0.5%)
5. Nuclear Containment Vessels

Contour of strains of the vertical steel bars in Specimen No. 1 at (First yield state)

- Loading direction
- Strain gauge distribution on vertical steel bars
- Experimental results
- Analytical results

Contour of strains of the horizontal steel bars in Specimen No. 1 at (First yield state)

- Loading direction
- Strain gauge distribution on horizontal steel bars
- Experimental results
- Analytical results
5. Nuclear Containment Vessels

Contour of strains of the vertical steel bars in Specimen No. 2 at (First yield state)

Loading direction

Experimental results

Analytical results

Strain gauge distribution on vertical steel bars

Contour of strains of the horizontal steel bars in Specimen No. 2 at (First yield state)

Loading direction

Experimental results

Analytical results

Strain gauge distribution on horizontal steel bars
5. Nuclear Containment Vessels

Contour of strains of the vertical steel bars in Specimen No. 1 at (Peak load state)

- Loading direction
- Strain gauge distribution on vertical steel bars
- Experimental results
- Analytical results

Contour of strains of the horizontal steel bars in Specimen No. 1 at (Peak load state)

- Loading direction
- Strain gauge distribution on horizontal steel bars
- Experimental results
- Analytical results
5. Nuclear Containment Vessels

Contour of strains of the vertical steel bars in Specimen No. 2 at (Peak load state)

Strain gauge distribution on vertical steel bars

Experimental results

Analytical results

Contour of strains of the horizontal steel bars in Specimen No. 2 at (Peak load state)

Strain gauge distribution on horizontal steel bars

Experimental results

Analytical results
5. Nuclear Containment Vessels

Study of Sliding Shear Failure Mechanism in Specimen No. 1

Horizontal load vs. displacement curve

\[ A_{sw} = \rho A = \rho \frac{\pi}{4} (D^2 - d^2) \]

\[ A_{sw} = 0.02 \frac{\pi}{4} (2500^2 - 2200^2) \]

\[ A_{sw} = 22150 \text{ (mm}^2\text{)} \]

\[ V_{sd} = 0.4 \times 22150 \times 360 = 3189 \text{ kN} \]

Calculation of sliding shear capacity

Stress-strain curve of vertical steel bar at point ST
(Stage: Point 5 on the load vs. displacement curve)

Stress-strain curve of vertical steel bar at point ST
(Stage: Point 6 on the load vs. displacement curve)
5. Nuclear Containment Vessels

Study of Web Shear Failure Mechanism in Specimen No. 2

Horizontal load vs. displacement curve

- Test
- Analysis

Web shear failure
(Cycle 14 – Drift 1.5%)

Stress-strain curve of concrete in principal direction at the top of the specimen (Peak load stage)

Stress-strain curve of concrete in principal direction at the middle of the specimen (Peak load stage)
7. Conclusions

• Using CSMM, a degenerated shell element with layered approach was developed. The developed shell element and the proposed analysis procedure were implemented into OpenSees to create a finite element analysis program SCS-3D, which can be used to predict the inelastic behavior of three-dimensional RC structures.

• Two 1/13-scale nuclear containment vessel specimens were designed and tested under revered cyclic loading. The first specimen failed by the sliding shear mode, and the second specimen failed by the web shear mode.

• The finite element program SCS-3D can predict the inelastic behavior of the RCCV specimens with good accuracy, including the cracking patterns, the first yielding points, the yielding distributions of the steel bars, the hysteretic loops of the load and displacement curve and failure modes.
Thanks for Your Attention.

Dept. of Civil and Environmental Engineering