CYLINDRICAL RC CONTAINMENT STRUCTURES UNDER SEISMIC LOADING

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ABSTRACT

The nuclear containment structure is one of the most important infrastructure systems ensuring the safety of a nuclear power plant. The structural behavior of a cylindrical containment structure made of reinforced concrete (RC) with large dimensions and numerous rebars is complex and difficult to predict. The complex behavior of the RC containment structure has been investigated in an international collaboration project between the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan and the University of Houston (UH), Houston, Texas. At NCREE two 1/13 scaled cylindrical RC containment specimens were tested under reversed cyclic loads. At UH, a finite element simulation of the two tested specimens was developed using a finite element analysis (FEA) program. In the program, a new shell element, the so-called CSMM-based shell element, was developed based on the Cyclic Softened Membrane Model and the formulation of an 8-node Serendipity curved shell element with a multi-layer approach. The UH simulated seismic behavior was close to the NCREE experimental results. This paper presents the theoretical development of the FEA program SCS and the comparisons of its predictions with the experimental structural behavior of the two RC containment specimens. This simulation model and the FEA program are excellent tools to develop effective performance-based design provisions.

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Cylindrical RC Containment Structures
Under Seismic Loading

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\textbf{ABSTRACT}

The nuclear containment structure is one of the most important infrastructure systems ensuring the safety of a nuclear power plant. The structural behavior of a cylindrical containment structure made of reinforced concrete (RC) with large dimensions and numerous rebars is complex and difficult to predict. The complex behavior of the RC containment structure has been investigated in an international collaboration project between the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan and the University of Houston (UH), Houston, Texas. At NCREE two 1/13 scaled cylindrical RC containment specimens were tested under reversed cyclic loads. At UH, a finite element simulation of the two tested specimens was developed using a finite element analysis (FEA) program. In the program, a new shell element, the so-called CSMM-based shell element, was developed based on the Cyclic Softened Membrane Model and the formulation of an 8-node Serendipity curved shell element with a multi-layer approach. The UH simulated seismic behavior was close to the NCREE experimental results. This paper presents the theoretical development of the FEA program SCS and the comparisons of its predictions with the experimental structural behavior of the two RC containment specimens. This simulation model and the FEA program are excellent tools to develop effective performance-based design provision.

\textbf{Introduction}

The safety of a nuclear power plant depends strongly on its containment structure. A nuclear containment structure is commonly a steel or reinforced concrete structure enclosing a nuclear reactor. This structure serves as a barrier to prevent various types of harmful radiation from contaminating the atmosphere during a rare nuclear meltdown accident [1]. The structural behavior of the RC nuclear containment structure with large cross sections, many layers of rebars, and complex stress conditions, is difficult to predict, especially when subjected to the earthquake loading. The seismic response of the RC nuclear containment structures is highly

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nonlinear caused by the highly inelastic behavior of materials including rebars and concrete under reversed cyclic actions. However, from the structural point of view, a whole RC nuclear containment structure can be visualized as assemblies of many RC elements so that the finite element analysis program combined with proper constitutive models for concrete and reinforcing bars can be a very powerful tool. The key to a rational analysis of the RC nuclear containment 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 material model can be incorporated into a finite element analysis program to predict the behavior of the whole structure under different kinds of loading.

To predict the response of the RC nuclear containment structure under severe loading, researchers need to use accurate material models and efficient numerical tools. In general, lumped-mass stick models and finite element models are two methods commonly used for the analysis modeling of the nuclear containment structure [1]. Many researchers have used finite element method to predict the behavior of RC nuclear containment structures. The main approach is to consider the RC nuclear containment as a shell-type structure and to use an appropriate shell element to simulate its behavior. The reinforced concrete shell element is often developed by combining a constitutive model of reinforced concrete material into finite element formulations of a general shell element with layer approaches. The studies show 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-type structures using the finite element method.

![Figure 1 Overview of Cyclic Softening Membrane Model for reinforced concrete](image-url)
The main problems faced by most of the researchers in the analysis of RC nuclear structures are that the finite element analysis often requires extensive 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 numerical problems when applied to the structure level, which requires a large number of elements. In recent years, the smeared-crack concept has been widely used in the analysis of RC structures. The concept allows the internally-cracked reinforced concrete composite to be treated as a simple, continuous material rather than a complicated, discontinuous composite [2]. 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 1980s, many researchers have conducted researches on the constitutive material of reinforced concrete based on the smeared-crack concept; Among these constitutive models, CSMM [3], as shown in Figure 1, is the most versatile and accurate and is capable of rationally predicting the cyclic shear behavior of reinforced concrete elements, including the stiffness, ultimate strength, descending branch, ductility, and energy dissipation capacity.

Over the past several decades, researchers at the University of Houston have made significant contributions on the finite element analysis of RC elements and members subjected to shear. Zhong [4] developed a nonlinear finite element computer program, the Simulation of Concrete Structures (SCS), using the OpenSees framework [5]. In the program, a two-dimensional reinforced concrete plane stress membrane element was developed based on the Cyclic Softened Membrane Model to simulate the behavior of reinforced concrete shear walls subjected to static, reversed cyclic and dynamic loading. Recently, Luu, Mo and Hsu [6] implemented a new shell element, the so-called CSMM-based shell element, into the SCS program. The element was developed based on the Cyclic Softened Membrane Model [3] and the formulation of an 8-node Serendipity curved shell element [7] with a layered approach [8]. The developed CSMM-based shell element successfully predicted the structural behavior of several types of three-dimensional RC structures, such as RC panels, a RC cylindrical tank, a three-dimensional RC shear wall and circular and rectangular RC hollow bridge piers.

The purpose of this paper is to validate the capacity of the developed CSMM-based shell element to simulate the cyclic response of nuclear containment structures using the test results of two 1/13-scaled RC containment specimens subjected to reversed cyclic loads.

**CSMM-Based Shell Elements**

The CSMM-based shell element was developed by utilizing the formulation of an 8-node Serendipity curved shell element [7]. 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 (Figure 2). The Serendipity shape function was applied to all DOFs. The element showed excellent performance when applied to the cases of moderate thick shell structures by using the standard full integration rule [9]. The idea of creating the element arose from the difficulty of solving the ill-conditioned equations that occurred in the three-dimensional solid element when
the dimension in the thickness direction was small. Therefore, it is also referred to as a
degenerated curved shell element [7]. The degenerated curved shell element with the layered
approach has been recognized as one of the most effective and reliable methods for analysis of
RC shell-type structures since the 1970s [9].

By using the degenerated curved shell element with the layered approach, the behavior of
RC shell structures can be captured directly from the cyclic stress-strain relationships of the
materials, and no phenomenological rule is needed. The element was derived from the equations
of three-dimensional continuum mechanics by reducing their dimensions in the thickness
direction and was based on the Reissner-Mindlin theory, which only requires C0 continuity in the
shape function for assuring complete inter-element deformation compatibility and can model the
behavior of reinforced concrete shells with significant transverse shear deformation. The local
material stiffness matrix of the shell element was derived based on the layered approach given by
Scordelis and Chan [8], in which the section of the shell element can be divided into several
layers throughout the thickness (Figure 3). The strains at each layer are assumed to be uniform
and interpolated by shape functions from the displacements at all nodes of the element. The
detailed presentation of the finite element formulation of the shell element is given in [6].

Simulation of RC Nuclear Containment Structures

The experimental program included the construction and testing of two 1/13-scaled
nuclear containment specimens. These specimens were designed to investigate the behavior of a
RC nuclear containment isolated from a nuclear power plant and subjected to the gravity and
earthquake loads. The specimens were designed based on the prototype of an Advanced Boiling
Water Reactor (ABWR) nuclear containment structure. The real-size containment has a height of
29.5 m, a radius of 15.5 m (center-line dimension) and a thick wall of 2.0 m. Each specimen
included three parts: the main containment, top block and bottom block. The bottom block
simulated the rigid foundation while the top block simulated the rigid floor system. These blocks were designed with steel plate boxes filled with concrete and a large amount of reinforcing steel. These blocks were designed conservatively to avoid significant deformation occurring in the blocks so that the nonlinearity occurred only in the containment walls during the tests. Rotations of the top and bottom blocks in the vertical plane were prevented during the test to ensure the containments deforming in a double-curvature manner during the tests. The dimensions of the test specimens are shown in Figure 4. The containments had a height of 2.25 m and a radius of 1.175 m (centerline dimension). The outer and inner diameters of the containments were 2.5 m and 2.2 m, respectively. The thickness of the containment was 0.15 m. The top and bottom blocks of the specimens had a cross section of 3.5 m x 3.5 m and a depth of 0.73 m.

![Figure 4 Dimensions of the RCCV specimens](image)

![Figure 5 Reinforcement detail of the RCCV specimens](image)
At the NCREE Laboratory in Taiwan, the test specimens were subjected to horizontal loading up to their maximum capacity with a set of specially built steel loading frames. The test setup was used to simulate gravity and the lateral and vertical earthquake loads. Figure 6 gives an overview of the test setup with various equipment components, including the horizontal actuators, vertical actuators, L-shape steel loading frame systems and the specimen. The specimens were loaded axially using four 1000-kN-capacity vertical hydraulic actuators. Pin connections were used at the end of the vertical actuators. The simulated lateral earthquake load was applied by eight 1000-kN-capacity horizontal actuators under displacement control. The horizontal actuators were bolted to a rigid concrete reaction wall and the L-shape loading frame so that the center of the loading axis passed through the specimen’s mid-height. The specimens were connected to a strong concrete floor using high-strength all-thread steel rods that went through the foundation of the specimens. The loading frame was allowed to move freely in the vertical plane. Additional steel frames bolted to the solid floor were placed on the north and south sides of the specimen to prevent the horizontal out-of-plane displacement. During the tests, the containment specimens were subjected to constant vertical axial loads and horizontal reversed-cyclic load until failure.

Comparison of Analytical and Test Results

Hysteretic Loops

Figure 7 shows the relationships of the horizontal actuator force and the corresponding drift ratio. The predictions conducted by Luu et al. [6] from the University of Houston is shown in this figure to compare with the experiment results. The maximum horizontal force applied on Specimen 1 was 5577 kN with a drift ratio of 0.53% and its strength decreased afterward. For Specimen 2 the maximum horizontal applied force was 5807 kN with a drift ratio of 0.92% and its strength decreased afterward.
Failure Modes

The two test specimens were almost identical; however, the failure modes of the two specimens were very different. Specimen 1 failed due to the sliding shear that happened at the top of the specimen, as shown in Figure 8(a).

(a) Sliding shear                                                                 (b) Web shear

**Figure 8. Photographical view of specimen failure modes at their peak strengths**

The peak load of Specimen 1 might have been higher if the sliding shear had not occurred. The sliding shear cracks started to occur on the top of the specimen at a drift of 0.5% and became larger when the load increased. Before the sliding shear failure, no critical damage of the concrete and reinforcement was observed in the specimen. Learning from the failure of Specimen 1, vertical steel bars (called dowel bars) were doubled in the top and bottom regions of
Specimen 2 to prevent the sliding shear failure. The method was successful because no sliding shear failure occurred in Specimen 2 and the sliding shear cracks on the top of the specimen were eliminated. As a result, Specimen 2 failed when the concrete crushed in the mid-height region due to the web shear failure as shown in Figure 8 (b). Specimen 2 reached a higher peak load and a greater deformation when compared to Specimen 1.

Conclusions

Two 1/13-scaled cylindrical RC containment specimens were tested at the National Center for Research on Earthquake Engineering (NCREE) to investigate the structural behavior of RC nuclear containment structures under reversed cyclic loading. The tests were undertaken as part of an international collaboration project between the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan and the University of Houston (UH), Houston, Texas. The nonlinear finite element analysis of the nuclear containment vessel specimens was conducted through the finite element program SCS using the developed CSMM-based shell element. The analytically predicted results compared very well with the experimental data. Overall, the primary backbone curves, the initial stiffness, the peak strength, the descending branch, the yielding distributions and the failure characteristics were accurately predicted. The analytical hysteresis loops also provided accurate measurements of the pinching effect and the energy dissipation capacity. Hence, the FEA program (SCS) with the developed CSMM-based shell element is a very powerful tool to investigate the seismic behavior of RC containment structures.

References