SMiRT-12 / K. Kussmaul (Editor)

H05/2

STUDY ON THE NON-LINEAR ANALYTICAL METHOD CONSIDERING LATERAL SHEAR FAILURE MECHANISM FOR RCCV UNDER INTERNAL PRESSURE

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ABSTRACT : A rectangular reinforced concrete containment vessel (RCCV) is being considered for use in a fast breeder reactor (FBR), because of advantages in arrangement of equipment and ease of construction. However, with the rectangular shape, considering the failure mode of the containment vessel due to internal pressure, there is some possibility of out-of-plane shear failure. Therefore, in this paper, an analytical method to express the phenomena of out-of-plane shear failure is proposed, and an example calculation is presented.

An analysis was carried out using the finite element method (FEM), which could consider both material nonlinearity and geometric nonlinearity. The structure was modeled using 4-node layered shell elements and joint elements which could consider nonlinearity for out-of-plane deformation.

Through this analysis, in-plane force and out-of-plane force for internal pressure were evaluated. The failure mode of the rectangular RCCV subjected to internal pressure was out-of-plane shear failure type. The failure phenomenon was simulated well by this proposed method.

1. INTRODUCTION

For nuclear power facilities, many studies of the pressure resistance at design pressure levels for a containment vessel have been done by experimental and numerical analysis. However, only a few of these studies have examined the ultimate strength under internal pressure. Furthermore, most of these studies have focussed on a cylindrical dome shaped containment vessel, in which stress distributions are different from those in a rectangular containment vessel. Regarding to out-of-plane stress, most of these studies leave the issue with a comparison of allowable unit stress because it scarcely becomes critical.

However, for a rectangular containment vessel, there is a possibility of excessive out-of-plane force appearing in the vicinity of the open hatches, or in places such as the joints of the floors and walls.

Thick slabs or walls subjected to out-of-plane force should be considered as a three dimensional stress condition. However, the RCCV was modeled using shell elements and joint elements for convenience in this study, and the analysis was carried out considering nonlinearity for in-plane and out-of-plane shear directions.

2. OBJECT OF THE ANALYSIS

The plan and section of the rectangular containment vessel, which was the object of this analysis, are shown in figure 1. The structure presumed for this study consists of a top slab, outer walls, the walls of the fuel transportation cell, and a cylindrical wall. The top slab, outer walls, and walls of the fuel transportation cell are assumed to be 1.5 meter thick, while the cylindrical wall is assumed to be 1.0 meter thick. The top slab has large open hatches for equipment. The outer walls also have openings for pipes of the primary coolant system and fuel transportation.

Under these conditions, the top slab could become critical for internal pressure. In this case, the failure mode of the top slab may be thought of as having two possible conditions:

(1) out-of-plane shear failure in the vicinity of the open hatches, or in places such as the joints of the floors and walls.

(2) combined flexure and tension failure mode between the open hatches.

3. ANALYTICAL MODEL

3.1. CONDITIONS OF THE ANALYSIS

(1) STRUCTURAL OUTLINE

The object of this analysis is an RC structure. The specified compressive strength of concrete (f'c) is 300 kgf/cm^2. Reinforcing steel of the floor and walls is placed perpendicularly in two directions. The reinforcement ratio for the total sectional area of the concrete is 1.02%. However, there are also ring bars in order to reinforce the open hatch areas. The total sectional area of the reinforcing steel is 95.7 cm^2.

(2) LOADING CONDITIONS

In the analysis, the structure was subjected to dead load and internal pressure. Internal pressure is expressed in terms of rising atmospheric pressures on the inside of the containment vessel at the time of an accident. Internal pressure was loaded on the top slab, outer walls, and walls of the fuel transportation cell. The open hatches and openings are assumed to remain completely airtight under internal pressure at the time of the accident.

Analysis was performed using load incremental method, starting with dead load, and then adding internal pressure. Internal pressure was loaded in the first step to 1.2 kgf/cm^2, then in increments of 0.2 kgf/cm^2 from 1.2 kgf/cm^2 to 1.6 kgf/cm^2, then in increments of 0.02 kgf/cm^2, until the failure.

(3) FINITE ELEMENT IDEALIZATION

The structure is divided into two parts, centered on the top slab's open hatch (position shown in fig. 1 A-A), which are assumed to be in a symmetrical condition. Figure 2 shows the finite element meshes. The bottom of the walls are assumed to be completely fixed.

In the model transformation for the concrete in the top slab and the walls, 4-node layered shell elements were used, as shown in figure 3 (a). The shell elements are divided sectionally into 9 layers. The reinforcements are placed at corresponding position inside the section as equivalent reinforcement layers. In order to consider nonlinearity for out-of-plane shear stress on the top slab, joint elements are inserted between the shell elements, as shown in figure 3 (b). The joint elements consist of translational springs in 3 directions (X, Y, Z), and rotational springs in 2 directions (X, Y).

(4) ANALYSIS PROGRAM AND CONSTITUTIVE LAWS OF MATERIALS

The analysis was performed using ABAQUS, a three dimensional general purpose nonlinear analysis program, which is capable of considering both material nonlinearity and geometric nonlinearity. The constitutive law of the concrete under in-plane stress condition, was added by a user defined subroutine with the concept described below.

Orthotropic model for equivalent uniaxial strain,which was proposed by Darwin, et. al.[1] ,is adopted for the stress-strain relationship. The uniaxial stress-strain curve of the concrete is shown in figure 4 (a). The ascending curve under compressive monotonous load follows a proposal of Fafitis, et. al.[2]. The strain softening region after reaching the compressive strength is expressed by a straight line proposed by Darwin, et. al.[1]. Tension-cut-off is assumed after tensile cracking. Failure criteria for concrete under biaxial stress condition follows a proposal of Kuper, et. al.[3], as shown in figure 4 (b). Bilinear stress-strain relationship is assumed for the reinforcements, as shown in figure 4 (c).

The joint element rigidly links concrete elements to each other. After a value of the allowable out-of-plane shear force is exceeded, the spring force in the out-of-plane direction (Z) is completely released. After this, the stiffness of the spring becomes zero, and the concrete elements come apart (figure 4 (d)). The allowable out-of-plane shear force for the spring is defined according to the following formula.

$$Q_A = L \cdot J \cdot Fs \quad \ldots\ldots\ldots (1)$$

Q_A : allowable out-of-plane shear force for a spring (kgf)
L : effective length for a spring (cm)
J : distance between the centers of tension and compression for the concrete section (cm)

Fs : allowable unit out-of-plane shear stress
for temporary loading of the concrete [4] (kgf/cm^2)

$$Fs = (5 + f'c/100) \times 1.5$$

f'c : specified compressive strength of concrete (kgf/cm^2)

The translational springs and rotational springs in the in-plane direction (X,Y) are assumed as a rigid linear model.

3.2. ANALYSIS RESULTS

An initial crack appeared at an internal pressure of 1.2 kgf/cm^2. It appeared the right side open hatch visinity on the top slab (top surface), as marked in figure 5.

The out-of-plane shear force was first reached the allowable value in the vicinity of the right side open hatch on the top slab, as shown in figure 7 at nodes 'c' and 'd'. The internal pressure at this time was 1.6 kgf/cm^2. The cracks appeared in only one limited area under a pressure of 1.6 kgf/cm^2 (figure 6). On the other hand, the maximum value of principle strains did not reach either the strain value at compressive strength of the concrete nor yield strain value of the reinforcement. Therefore, it is concluded that this structure maintains the integrity to a pressure of 1.6 kgf/cm^2.

Figure 7 shows the relationship between internal pressure (P) and the vertical displacement of the top slab (δ). The positions of nodes 'a' and 'b' show places where the displacement due to in-plane stress was remarkable. The positions of nodes 'c' and 'd' are places where out-of-plane shear failure occurred.

The relationship between out-of-plane shear force (Q) and internal pressure (P) is shown in figure 8. The out-of-plane shear force values are measured at the central point (Gaussian integration point) of the shell elements.

Figure 9 shows failure modes on the top slab. The area in which out-of-plane shear failure occurred was from the vicinity of the open hatches toward the wall, at an angle of 45 degree. Cracks caused by in-plane stress were distributed between the open hatches on the top slab.

Out-of-plane shear failure began at a pressure of 1.6 kgf/cm^2, and the analysis showed numerical instability at a pressure of 1.74 kgf/cm^2. Figure 10 shows deformation modes from 1.6 kgf/cm^2 to 1.74 kgf/cm^2. Developments of the deformations along the nodes due to the out-of-plane force are expressed in terms of extension of the joint elements.

4. CONCLUSION

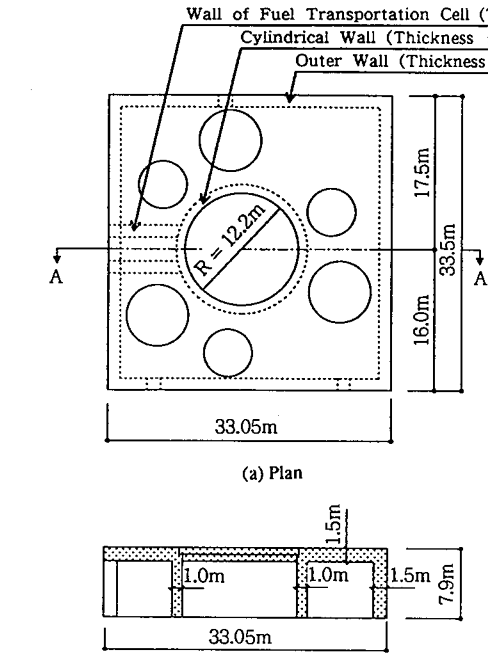
The behavior of a model structure up to the out-of-plane shear failure under internal pressure was simulated in this analysis. Using the proposed method, it is possible to predict the location at which out-of-plane shear failure is likely to occur.

However, this method does not consider the transfer of out-of-plane forces between cracked surfaces. In order to consider the transfer of out-of-plane stresses between cracked surfaces, it would be necessary to account of such factors as the vertical stress level applied to the cracked surface, the width of the cracks, the dowel action, and many other factors which would affect on the results.

Furthermore, as the criteria for out-of-plane shear failure are still being studied, the allowable unit out-of-plane shear stress for temporary loading given in the reference 4) was used for the analysis. Therefore it is considered that the analytical results is more or less conservative. It needs further experimental work on this problem in the future.

5. ACKNOWLEDGEMENTS

This study had been performed under the sponsorship of the nine Japanese electric power companies, Electric Power Development Company, and The Japan Atomic Power Company. The authors would like to express their sincere appreciation to all parties involved.



(a) Plan

(b) A-A Section

Fig.1 Example Structure

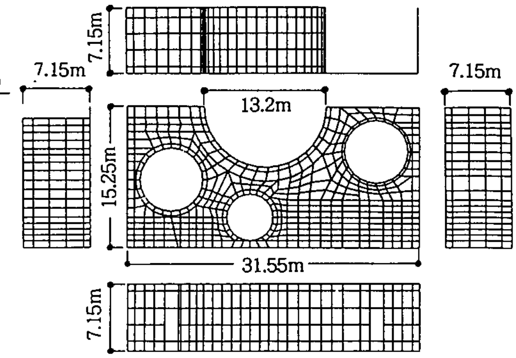
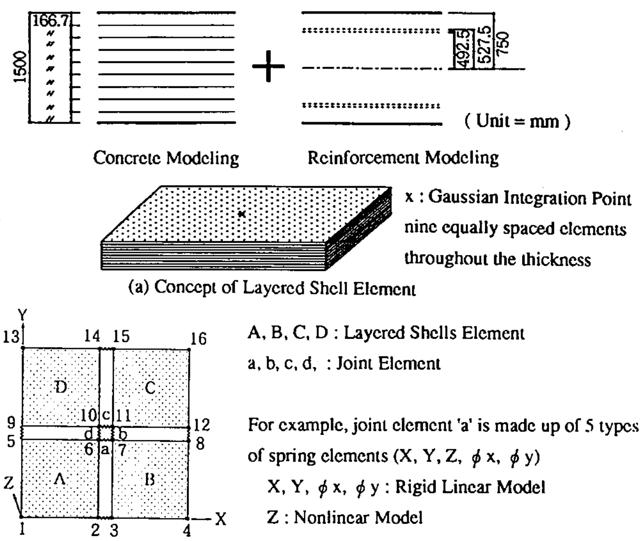


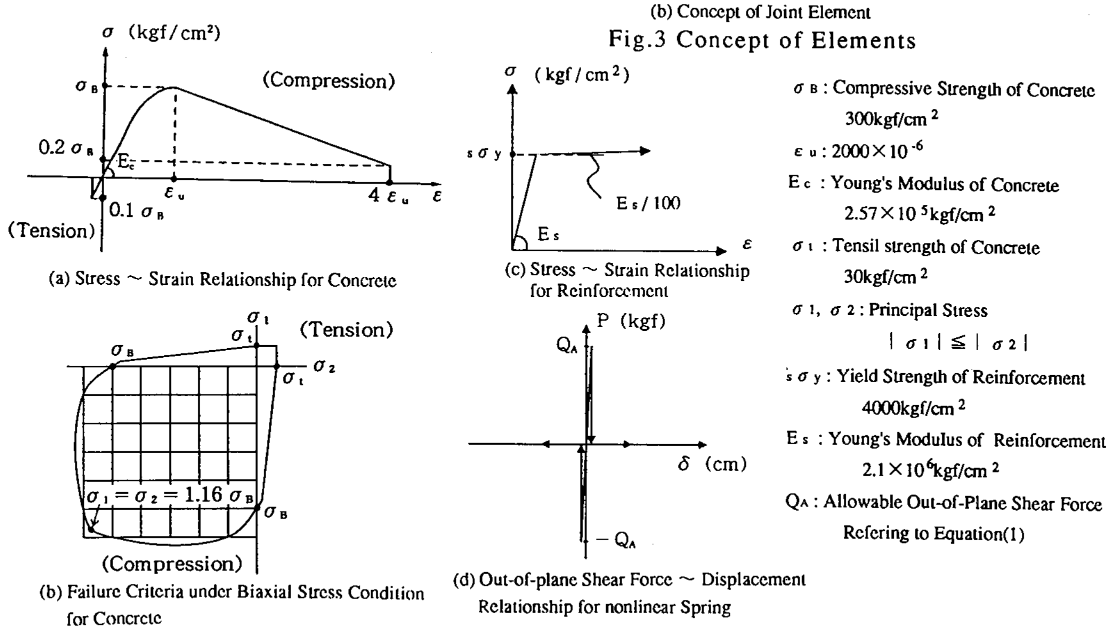
Fig.2 Finite Element Mesh



(a) Concept of Layered Shell Element

(b) Concept of Joint Element

Fig.3 Concept of Elements



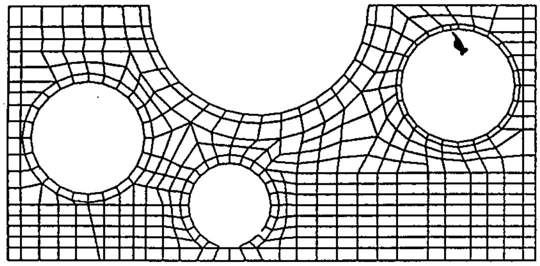
(a) Stress ~ Strain Relationship for Concrete

(b) Failure Criteria under Biaxial Stress Condition for Concrete

(c) Stress ~ Strain Relationship for Reinforcement

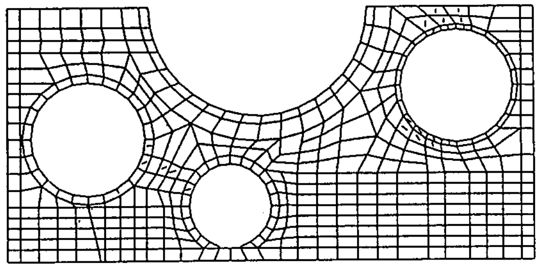
(d) Out-of-plane Shear Force ~ Displacement Relationship for nonlinear Spring

Fig.4 Constitutive Laws of Materials

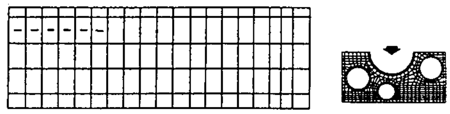


(a) Top Slab (Top Surface)

Fig.5 Initial Crack for In-plane Stress

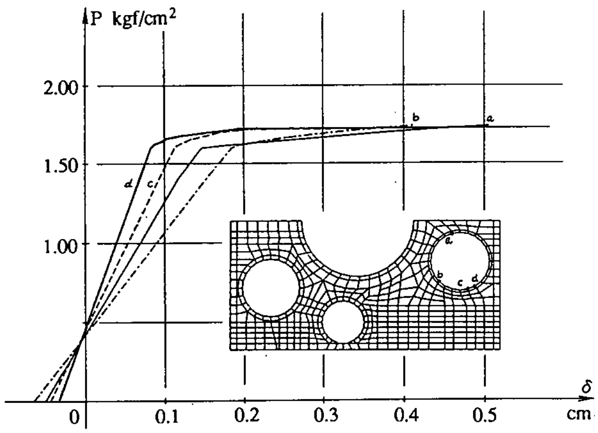


(a) Top Slab (Top Surface)



(b)Cylindrical Wall (Outer Surface)

Fig.6 Cracks for In-plane Stress



Deformation for in-plane stress was dominant at node 'a' and 'b'.
Out -of-plane shear failure occured at node 'c' and 'd'.

Fig.7 Internal Pressure ~ Displacement Relationship

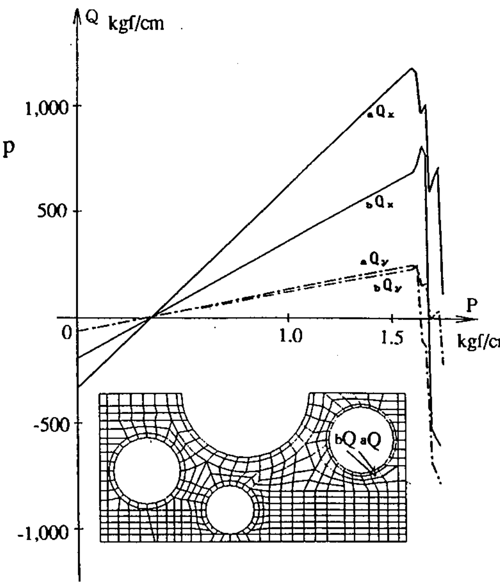
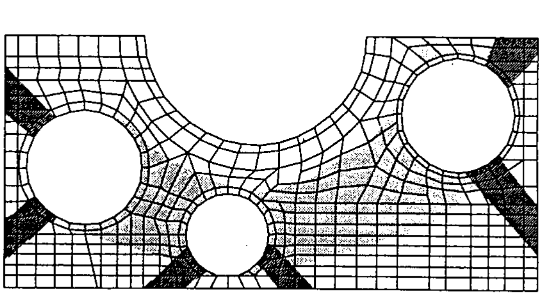


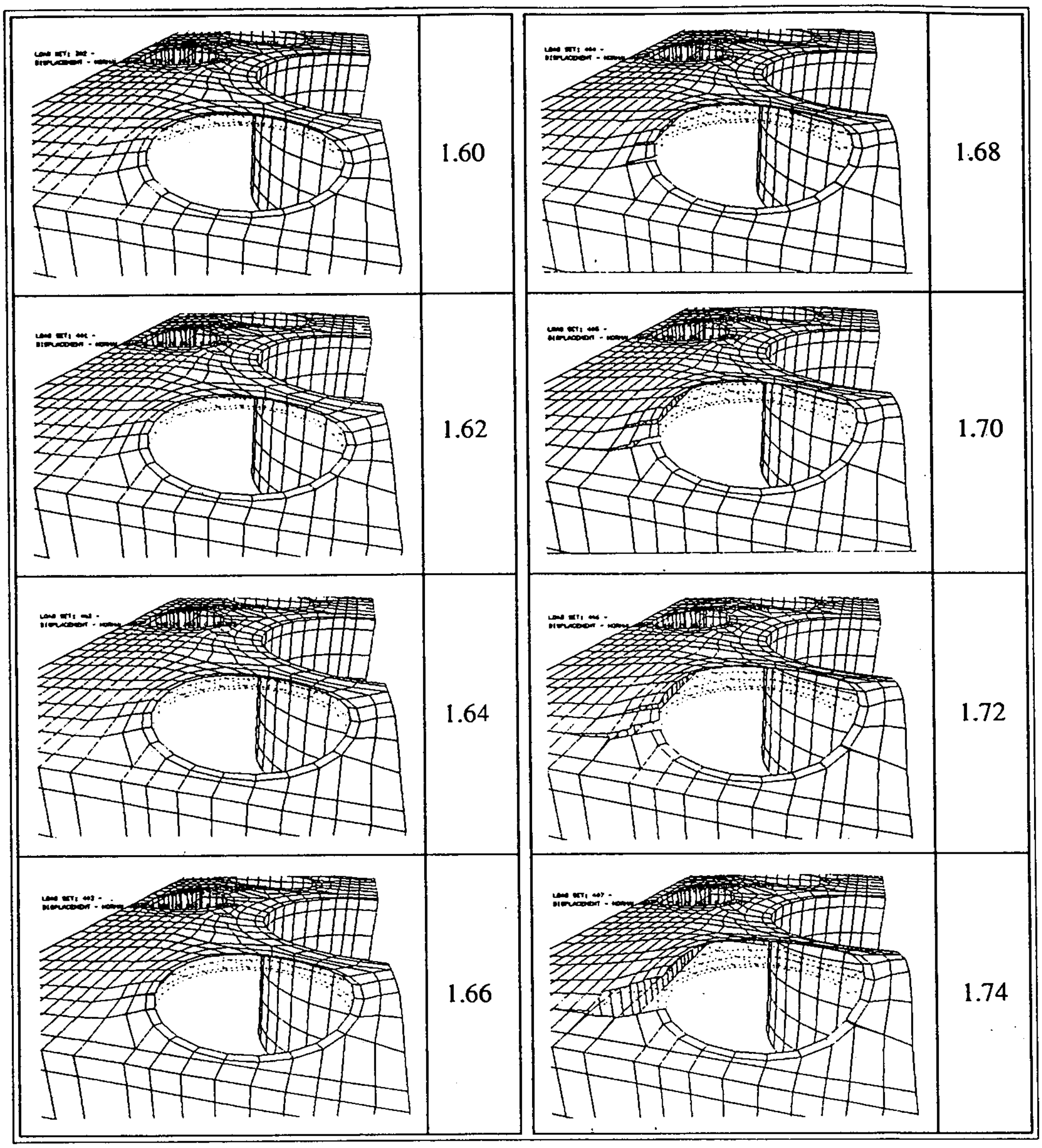
Fig.8 Out-of-plane Shear Force ~ Internal Pressure Relationship



: Area of Cracks for Bending Stress
: Area of Out-of-plane Shear Failure

Fig.9 Area of Cracks

(Unit : kgf/cm^2)



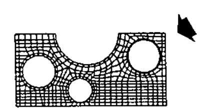


Fig.10 deformation of the model from 1.60 to 1.74 kgf/cm^2

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