ANALYSIS OF G. E. MARK III CONTAINMENT SYSTEM DRYWELL STRUCTURE

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SUMMARY

The analysis of the drywell structure in the G. E. Mark III containment system is presented and the loadings and solution techniques are discussed in this paper.

The drywell structure is a reinforced concrete cylindrical shell. In the bottom region of the shell, there are many 28 inch diameter horizontal vents arranged in a regular pattern. The main function of the drywell is to channel steam released during a main steam line break through the horizontal vents for rapid condensation in the suppression pool and to reduce radiation levels in the containment to permit normal access.

The drywell is designed to sustain all operating loads, thermal loads, seismic loads and accident loads. Dynamic loads are applied to the structure statically with dynamic load factors obtained from separate analysis. Seismic loads are applied as equivalent static loads obtained from seismic analysis of lumped-mass model of the structure. The design requires the various combination of dead and live loads, accident pressure loads, thermal effects under operating and accident conditions, safe shutdown and operating basis earthquakes, steam relief valve blow down loads, poolswell loads, and jet force and pipe whip loads due to pipe rupture. The loading combinations are presented in a detailed tabulated form.

The analysis is carried out by finite element techniques by using the NASTRAN computer program. In the general analysis, the drywell is idealized by triangular and quadrilateral plate elements. Due to symmetry, only half of the structure is modeled. The vent region is modeled by quadrilateral sandwhich plate elements. To take into account the reduction of stiffness due to the presence of the vents a separate finite element analysis was performed. A typical segment of the plate with the vent at its middle is idealized into small finite elements. It is then subjected to prescribed displacements at its boundary in such that one overall strain component of the plate is unity and all other strain components are zero. The force necessary to hold the plate in this deformed configuration is used to calculate the stress and thus establish the reduced elasticity matrices of the plate with a hole at its middle. The reduced elasticity matrices are later used as material property input for the sandwich plates in the vent region.

The stress distributions around the vents and forces or moments at the vicinity of large openings were investigated by applying the results obtained from the global analysis as boundary conditions to separate finite element models.

A procedure used to analyze the drywell structure is described. The method saves considerable computer time as well as modeling time. Furthermore, the analytical results are in sufficient detail that it can be used directly for design.

1. Introduction

The analysis of drywell structure in the G.E. Mark III Containment system is presented and the loadings and solution techniques are discussed.

The drywell is idealized into an assemblage of triangular and quadrilateral plate elements. For the vent region at the bottom of drywell, reduced stiffness were derived by separate finite element analysis to take into account the effects of the vent openings. The vent region is then modeled by quadrilateral sandwich plates with equivalent stiffness. The NASTRAN computer program is employed to obtain the finite element solutions.

2. Description of the Drywell Structure

2.1 Drywell Configuration

The drywell is a cylindrical, reinforced concrete wall 5 feet thick having an inside diameter of 73 feet and approximately 90 feet tall. A series of uniformly spaced, horizontal vents penetrate the wall in three equally spaced rows over the lower 14 feet of the drywell. The drywell is capped with a 4 feet thick flat reinforced concrete slab having a 32 feet diameter central opening. Two parallel, longitudinal reinforced concrete walls, 4 feet thick and approximately 25 feet high, run across the top slab. These walls serve as the longitudinal walls of the upper pool and structural stiffeners for the top slab. Three transverse walls of 2 feet 6 inches thick connecting the two longitudinal walls were used to form the complete upper containment pool.

2.2 Drywell Function

The main function of the drywell is to channel steam released during a main steam line break through the horizontal vents for rapid condensation in the suppression pool and to reduce radiation levels in the containment to permit normal access. The drywell also provides support to the upper pool, the working steel platforms, the sub-compartments and also serves as the anchor point for pipe lines penetrating the drywell wall.

3. Analytical Procedure

3.1 General

The analysis is carried out by finite element techniques by using the NASTRAN computer program. In the general analysis, the drywell is idealized by plate elements. Due to symmetry, only half of the structure is modeled as shown in Fig. 1. The use of flat plate elements to analyze cylindrical shell structures, although introducing some approximation, is well established as discussed by Zienkiewicz [1]. In the vent region, difficulty arises as how to adequately model the vent openings. In the conventional finite element analysis of structures with holes, large number of small elements are required for appropriate idealization of material around the holes. Such an analysis would be impractical because of the large number of vents in the vent region and the equations which must be solved would become excessive. However, since the vents are uniformly spaced and arranged in a regular pattern, and that the vents are small in size compared to the other dimensions of the drywell, an elastic finite element analysis may be used to derive the elasticity matrices based on the stress to overall strain relationship of a typical square plate panel with a hole at its center. Two elasticity matrices are derived, one for the plane stress condition and the other for the bending condition. The elasticity matrices are then treated as those of a solid plate of reduced stiffness caused by the hole. Thus, the vent region can be divided into plate elements and the lines of divisions may be chosen regardless of the actual location of the vents. The derivation of these elasticity matrices is straight forward and the procedure is first proposed by A. Ghali [2]. The vent region is lined with steel face plates at both faces of the concrete wall to achieve full composite action. With the reduced stiffness of the vent region established, the vent region is simply idealized by sandwich plates. The global finite element analysis of the drywell as a whole will give the average strains in these plates. The actual stress distribution may be obtained by separate finite element analysis of the typical plate panel using the results of the global finite element analysis as boundary conditions.

3.2 Derivation of Elasticity Matrices at Vent Region

For the purpose of deriving the elasticity matrices for the plate elements at the vent region, a typical panel is isolated for analysis as shown in Fig. 2. Because of symmetry, only one quarter of the plate panel is modeled by triangular plate elements as shown in Fig. 3. Although it is known that only one eighth of the panel is needed for the cases of in-plane shear and twisting moments, the quarter panel model will be used throughout in order to derive the two elasticity matrices by a single finite element model. Since we are only interested in the reduction of stiffness due to the vent opening, homogeneous, isotropic material may be used for this quarter panel model. Later on in the analysis of the drywell, adjustments are made to reflect that the vent region is actually sandwich plates.

The stress-strain relationship may be written as:

$$\{\sigma\} = [D]\{\varepsilon\} \qquad (1)$$

When the plate is subjected to in-plane forces only,

$$\{\sigma\} = \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} \quad \text{and} \quad \{\varepsilon\} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} \qquad (2)$$

Where σ_x and σ_y are stresses in the two orthogonal directions x and y and σ_{xy} is the in-plane shear stress.

For homogeneous, isotropic material, the elasticity matrix is a symmetrical matrix as follows:

$$[D] = \begin{bmatrix} D_{11} & \text{Symmetrical} & \\ D_{21} & D_{22} & \\ D_{31} & D_{32} & D_{33} \end{bmatrix} = \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \qquad (3)$$

Where E is the Young's modulus and ν is the Poisson's ratio.

When the plate is subjected to transverse loads producing bending, the matrices $\{\sigma\}$ and $\{\varepsilon\}$ in eq. (1) have the following meanings:

$$\{\sigma\} = \begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} \quad \text{and} \quad \{\varepsilon\} = \begin{Bmatrix} -\dfrac{\partial^2 \omega}{\partial x^2} \\ -\dfrac{\partial^2 \omega}{\partial y^2} \\ 2\dfrac{\partial^2 \omega}{\partial x \partial y} \end{Bmatrix} \qquad (4)$$

And the elasticity matrix for the assumed homogeneous, isotropic material becomes

$$[D] = \begin{bmatrix} D_{11} & \text{Symmetrical} & \\ D_{21} & D_{22} & \\ D_{31} & D_{32} & D_{33} \end{bmatrix} = \frac{Et^3}{12(1-\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \dfrac{1-\nu}{2} \end{bmatrix} \qquad (5)$$

The task is to derive the two elasticity matrices defined by eqs. (3) and (5) for the plate with a hole represented by the finite element model shown in Fig. 3.

For the in-plane force condition, the boundary displacements are applied to the model such that one of the three strains ε_x, ε_y or γ_{xy} is unity while the other two are zero. For the bending condition, one of the curvatures is made equal to unity while the other two are zero. By finite element analysis, sets of boundary forces necessary to maintain the imposed deformation configuration are obtained. These forces are then used to find overall stresses (or moments) which are the elements of the elasticity matrices defined by eq. (3) and eq. (5).

Since the elasticity matrices are symmetrical matrices, for each of the two matrices only three quantities need be derived (D_{11}, D_{21}, and D_{33}).

Define: μ = displacement in x-direction

ν = displacement in y-direction

ω = displacement in z-direction

θ_x = rotation about x-axis

θ_y = rotation about y-axis

The boundary displacements used to achieve the desired strains are first imposed on a solid plate with known material properties and having same dimensions as the typical plate panel to check the correctness of the imposed boundaries. For the in-plane force condition, the boundary displacements indicated in Fig. 4a is used. Displacement μ and ν not specified in the figure are free to occur unrestrained. This situation represents the stretching of the elements in the x-direction such that $\varepsilon_x = 1$ and $\varepsilon_y = \gamma_{xy} = 0$. The elements D_{11} and D_{21} are equal to the average stress on sides BC and AB, respectively. For the in-plant shear condition, the boundary displacement indicated in Fig. 4b is used. This situation represents distorting the plate by shearing forces along the edges such that $\varepsilon_x = \varepsilon_y = 0$ and $\gamma_{xy} = 1$. Thus, the element D_{33} is equal to the average shearing stress on sides AB or BC.

To derive D_{11} and D_{21} for the bending condition, the boundary conditions of Fig. 4c is used. The displacements imposed at the boundary nodes correspond to cylindrical bending of the plate such that: $\left\{-\frac{\partial^2 w}{\partial x^2}, -\frac{\partial^2 w}{\partial y^2}, 2\frac{\partial^2 w}{\partial x \partial y}\right\} = \frac{1}{\ell}\left\{1, 0, 0\right\}$

The elements D_{11} and D_{21} are equal to ℓ times the average moments normal to the sides BC and AB, respectively. The boundary displacements shown in Fig. 4d is used to derive D_{33} for the twisting moment condition. The imposed displacements corresponding to the situation of twisting the plate in such a way that:

$$\left\{-\partial^2 w/\partial x^2, -\partial^2 w/\partial y^2, 2\,\partial^2 w/\partial x \partial y\right\} = \frac{1}{\ell}\left\{0, 0, 1\right\}$$

The element D_{33} is equal to the twisting moment times the length ℓ on sides AB or BC.

Now the same boundary conditions were applied to the one quarter typical panel with a hole shown in Fig. 3. As described above, two elasticity matrices were obtained which includes the effects of the hole. By comparing the elements of the elasticity matrices with those of the corresponding solid plate elasticity matrices, two sets of equivalent Young's modulus E, Poisson's ratio ν and shear rigidity G may be obtained, one for plane stress and one for plate bending. The equivalent material properties are then used as material input for the sandwich plates at the vent region and the reduction of stiffness for these plates are handled automatically by the computer program.

3.3 Local Stresses

The stress distributions around the vents and forces or moments at the vicinity of large openings were investigated by applying the results obtained from the global analysis as boundary conditions to separate finite element models. One such model for the analysis of the personnel airlock is shown in Fig. 5.

4. Loads and Load Combinations

4.1 Loads Used in Design

The loads used in design of the drywell are defined as follows:

a. Dead Load (Symbol D)

Dead load including the weight of all structure and permanent equipment loads as applicable.

b. Live Load (Symbol L)

Live load including all moveable equipment not included in dead load, temporary loads during construction, maintenance or refueling, and crane live loads including allowance for impact.

c. Hydrostatic Pressure (Symbol G)

The hydrostatic pressure generated by the weight of water in the suppression pool or upper containment pool including wave action during earthquake condition.

d. Post Accident Flooded Condition (Symbol G')

The hydrostatic pressure during core recovery in the post LOCA condition.

e. Seismic Load (Symbol F_{eqo} and F_{eqs})

The seismic loads generated by the postulated OBE and SSE conditions. Three components earthquake is assumed.

f. Normal Operating Pressure (Symbol Z)

Pressure effects during normal plant operation or shutdown conditions based on the most critical transient or steady state condition.

g. Normal Operating Temperature Induced Loads (Symbol T_o)

The induced loads and moments due to thermal effects during normal plant operation or shutdown condition based on the most critical transient or steady state condition.

h. Safety Relief Valve Loads (Symbol P_{srv} and T_{srv})

The induced loads due to the pressure and thermal transient associated with operation of the safety relief valve system. There are six cases considered in the design as follows:

1. Any single valve blow down.
2. Any one of the low set point valve plus any other single valve around the circumference.
3. All six low set point valves.
4. Any four low set point valves plus any other single valves.
5. Blowdown of the eight automatic depressurization system (ADS) valves.
6. All nineteen valves blowdown to the pool simultaneously.

i. Loss of Coolant Accident (LOCA) Temperature and Pressure Loads (Symbol T_a and P_a)

The loads associated with a postulated high energy pipe break includes the pool swell loads. The bubble pressure, bulk swell and froth swell loads, drag pressure loads and other loads associated with pool swell are considered as abnormal pressure loads. The pool swell induced loads and associated accident pressures are combined taking into account of their time dependent behavior.

j. Interior Missiles (Symbol M)

The sources of potential interior missiles and the loads predicted are considered in design.

k. Penetration and Piping Related Loads (Symbols R_o, R_a, Y_r, Y_j and Y_m)

Where

R_o = Pipe reaction during normal operation or shutdown condition

R_a = Pipe reaction during accident condition including the thermal effects

Y_r = The equivalent static load on the structure generated by the reaction on the broken high energy pipe during the postulated break

Y_j = The jet impingement equivalent static load on structure generated by the postulated break

Y_m = The missile impact equivalent static loads

l. Test Pressure (Symbol P_t)

The pressure loads associated with the structural integrity test.

4.2 Loading Combinations

The combination of loads in determining the most critical design conditions are tabulated in Table 1 and Table 2.

5. Conclusions

The proposed method using equivalent stiffness for the vent region will permit the engineer to model the drywell in a simple, straight forward manner. And since modeling of the vents are no longer needed in the global finite element analysis, considerable savings of computer time can be resulted.

The analysis of the drywell is quite complex when thermal effects and concrete cracking is considered. However, there are many papers dealing with these subjects by various authors: G. Gurfinkel [3], T.D. Kohli and O. Gurbuz [4], De Pineres, O.G. [5], and therefore it is not discussed here.

References

[1] ZIENKIEWICZ, O.C., "The Finite Element Method in Engineering Science", McGraw-Hill, 1971.

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[3] GURFINKEL, G., "Thermal Effects in Walls of Nuclear Containments - Elastic and Inelastic Behavior", Presented at the First SMIRT Conference, Berlin, 1971.

[4] KOHLI, T.D., GURBUZ, O., "Optimum Design of Reinforced Concrete for Nuclear Containments, Including Thermal Effects", Presented at the Second ASCE Specialty Conference on Structural Design of Nuclear Plant Facilities, New Orleans, 1975.

[5] DE PINERES, O.G., "Analysis of Internal Pressure-Relieving R.C. Structures by the Proposed ACI (359) - ASME Code", Presented at the ASCE Specialty Conference on Structural Design of Nuclear Plant Facilities, Chicago, 1973.

TABLE I: LOADING COMBINATION FOR CONCRETE STRUCTURES

Load Combination	D	L	G	G'	Z	T_o	P_{srv}	T_{srv}	F_{eqo}	F_{eqs}	P_a	T_a	M	R_o	R_a	Y_r	Y_j	Y_m	P_t
Construction	1.4	1.7	1.4			1.3													
Testing	1.4	1.7	1.4		1.4	1.3													1.4
	1.4	1.7	1.4		1.4	1.3	1.7	1.3											
Normal Operation	1.4	1.7	1.4		1.4	1.3	1.7	1.3						1.3					
Normal Operation Plus (OBE) (Severe Environment)	1.4	1.7	1.4		1.4	1.3	1.7	1.3	1.9					1.3					
	1.2		1.4		1.2	1.3	1.4	1.3	1.9					1.3					
Safe Shutdown Earthquake (Extreme Environment)	1.0	1.0	1.0		1.0	1.0	1.0	1.0		1.0				1.0					
Accident Condition	1.0	1.0	1.0				1.25	1.0			1.5	1.0			1.0				
Abnormal Severe Environment	1.0	1.0	1.0				1.0	1.0	1.25		1.25	1.0			1.0	1.0	1.0	1.0	
Abnormal Extreme Environment	1.0	1.0	1.0				1.0	1.0		1.0	1.0	1.0			1.0	1.0	1.0	1.0	
Interior Missiles	1.0	1.0	1.0		1.0								1.0		1.0				
	1.0	1.0	1.0								1.0		1.0		1.0				
Post Accident Core Recovery	1.4	1.7		1.4		1.3			1.4					1.4					
	1.2			1.2		1.0			1.4					1.2					

TABLE II: LOADING COMBINATION FOR STEEL STRUCTURE

Load Combination	D	L	G	G'	Z	T_o	P_{srv}	T_{srv}	F_{eqo}	F_{eqs}	P_a	T_a	M	R_o	R_a	Y_r	Y_j	Y_m	P_t
Construction	1.0	1.0	1.0			1.0													
Testing	1.0	1.0	1.0			1.0													1.0
	1.0	1.0	1.0		1.0	1.0	1.0	1.0											
Normal Operation	1.0	1.0	1.0		1.0		1.0							1.0					
	1.0	1.0	1.0		1.0	1.0	1.0	1.0						1.0					
Normal Operation Plus (OBE) (Severe Environment)	1.0	1.0	1.0		1.0		1.0		1.0					1.0					
	1.0	1.0	1.0		1.0	1.0	1.0	1.0	1.0					1.0					
Safe Shutdown Earthquake (Extreme Environment)	1.0	1.0	1.0		1.0		1.0			1.0				1.0					
	1.0	1.0	1.0		1.0		1.0	1.0	1.0	1.0				1.0					
Abnormal Severe Environment	1.0	1.0	1.0				1.0		1.0		1.0				1.0				
	1.0	1.0	1.0				1.0	1.0	1.0		1.0	1.0			1.0	1.0	1.0	1.0	
Abnormal Extreme Environment	1.0	1.0	1.0				1.0			1.0	1.0				1.0				
	1.0	1.0	1.0				1.0	1.0		1.0	1.0	1.0			1.0	1.0	1.0	1.0	
Post Accident Core Recovery	1.0	1.0		1.0	1.0	1.0								1.0					
	1.0	1.0		1.0	1.0	1.0			1.0					1.0					

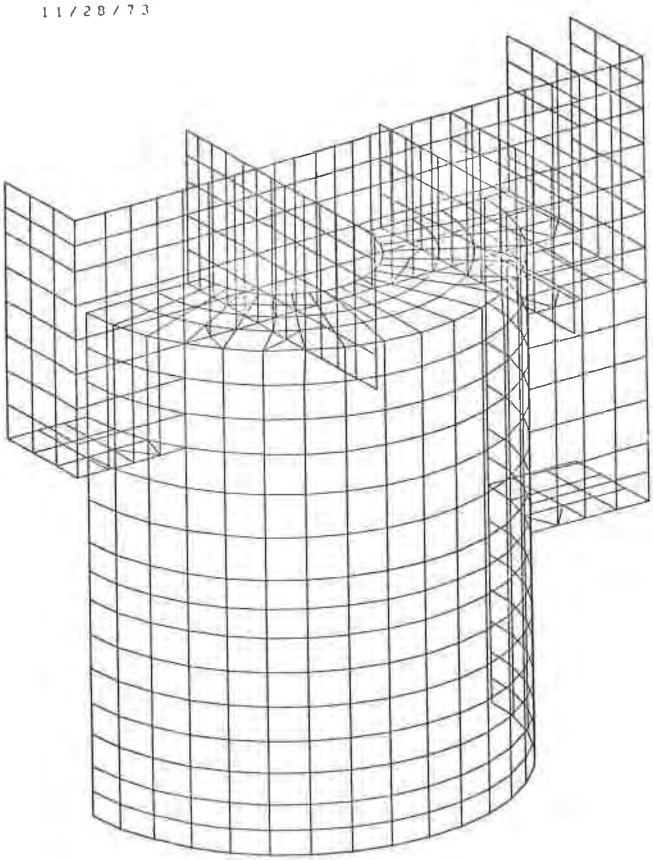


Figure 1. Drywell Finite Element Model

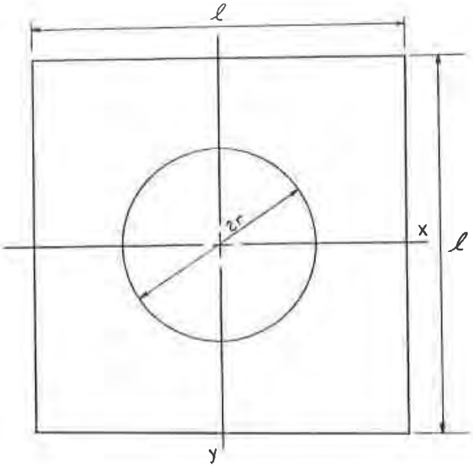


Figure 2. Typical Plate Panel with A Hole At Its Center

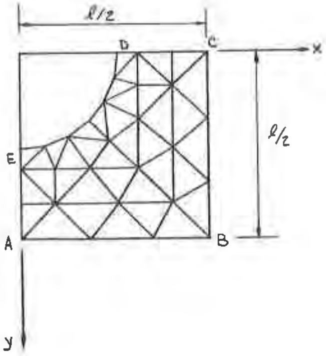
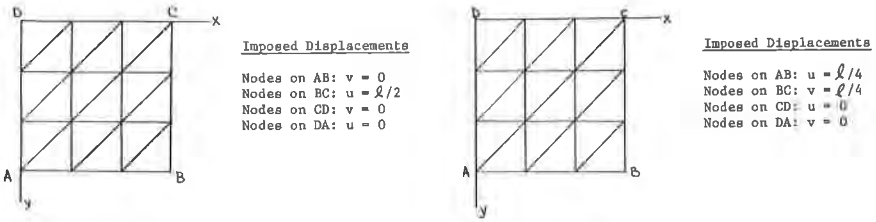
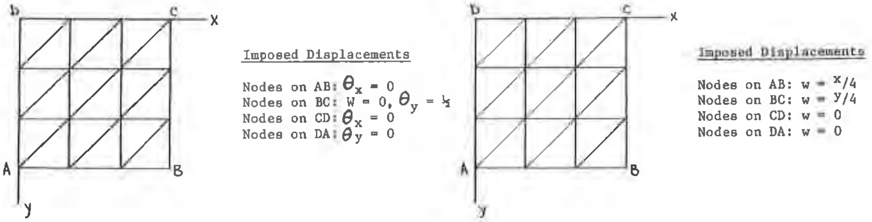


Figure 3. Finite Element Model of A Typical Plate Panel Quadrant Used For The Derivation of The Elasticity Matrices



(a) In-Plane Foace Condition (b) In-Plane Shear Condition



(c) Bending Moment Condition (d) Twisting Moment Condition

Figure 4. Finite Element Model and Boundary Conditions Used For The Derivation of The Elasticity Matrices

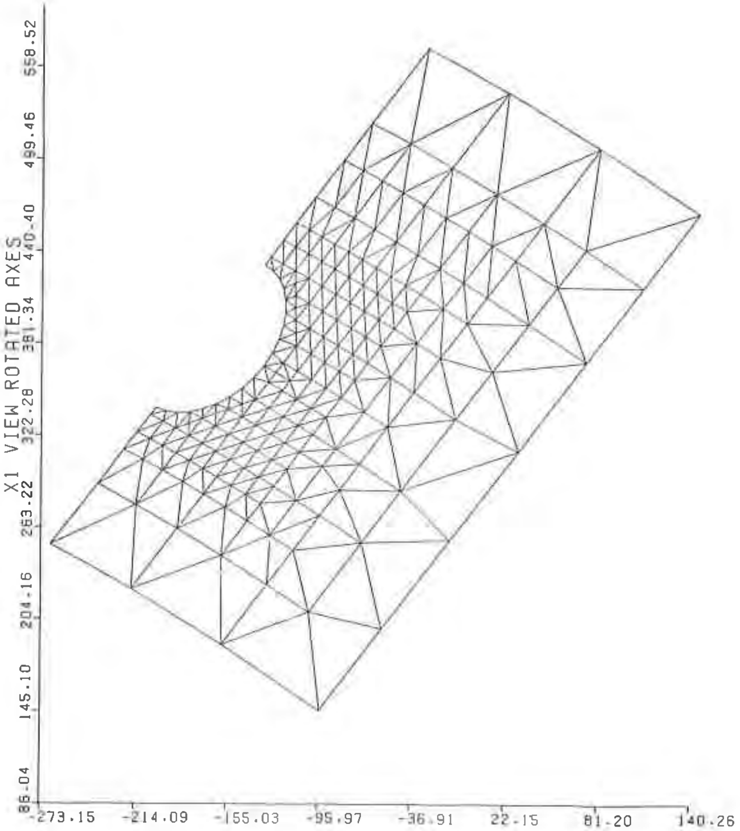


Figure 5. Finite Element Model For Local Stress Analysis Around The Personnel Air Lock