INSTABILITY BEHAVIOR OF STIFFENED DOME LINERS UNDER CONSTRUCTION CONDITION

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SUMMARY

The purpose of a steel liner on the inside of the Containment is to ensure a leak-tight vessel. In addition, the liner functions as internal formwork during the construction of the concrete shell. The radius to thickness ratio of present day containment liners range from 1400 to 2500 and as such the design of a suitable stiffening or supporting system to preclude buckling becomes a major consideration.

Classical buckling solutions for thin shells are several times larger than experimental results due to initial imperfections, initial stresses and the influence of boundary conditions. As a result, it is extremely difficult to predict the buckling strength of the dome shell. The purpose of this paper is to present techniques related to stability analysis, design concepts and behavior of dome liners. Various stiffening systems are examined from economy, schedule and constructability point of view.

The various failure modes can be classified as either buckling due to local instability or to an overall instability of the shell. Local instability may occur due to buckling of liner panel between a pair of rings and stringers or torsional and lateral buckling of the stiffeners. Methods are developed for proportioning stiffening system to preclude local buckling.

Overall stability is a function of concrete pour height and thickness, loading distribution, time elapse between successive placements, rate of concrete placement, arrangement of stiffeners and other external supports. A computer program based on system energy minimization is used to study the overall instability of stiffened domes. Modelling techniques, effect of temperature and lack of bond, and their influence on results are discussed.

Deviation of the dome from its intended surface due to inherent limitations in fabrication techniques significantly reduce the buckling strength. Actual buckling pressure, $P_a$, is a function of the classical buckling pressure $P_{cr}$ and the geometric parameters of the shell. A correlation factor defined as ratio of $P_{cr}/P_a$, is established for common geometric parameter of containment dome liners, based on extensive search of available literature.

Results for a self-standing stiffened hemispherical dome are presented in the form of mode shapes and buckling loads. Based on the results, a pouring scheme is recommended for an economical stiffening system.

Recommendations are made to select the stiffening system and predict the buckling loads for preliminary analysis and design of the dome liner. Existing methods and code provisions related to tolerance, design criteria etc. are examined and recommendations made from practical considerations.
1.0 INTRODUCTION

A steel liner plate is attached to the entire inner surface of a single-barrier reinforced or prestressed concrete containment for the purpose of providing a leak-tight vessel. In addition, the liner serves as an interior formwork during construction of the concrete shell. Due to a large radius to thickness ratio of present day containment liners (1400 to 2500), buckling considerations assume a major role in liner design.

Several schemes are considered to support the liner during concrete placement. One method often used is to support the liner by an internal truss and purlin system as shown in Figure 1. The loads are transferred through the truss to a rotating platform or polar crane bracket. This method has the following disadvantages: time-cost factor for erection and removal of the truss system, interference of containment internal work, fitting truss components to imperfect liner shape, and the cost of the steel used.

For reinforced concrete containments, the large amount of reinforcing steel in the dome is sometimes utilized to partially support the dome liner by tying to the reinforcement. The disadvantage of such a system is the interference problem of field welded hangers to the heavily congested reinforcement in the dome.

Another method is a self-standing dome stiffened with structural steel sections to resist buckling under construction conditions without any external support. The advantage of this method is that internal containment work is not interrupted and the amount of steel used is considerably less than that used in a truss support system.

The objective of this paper is to present analysis, design and related details of the self-standing dome liner for the construction condition.

2.0 SYSTEM DESCRIPTION AND CONSTRUCTION

2.1 DOME LINER PLATE

The recommended minimum thickness of the dome liner plate is 3/8 inch. However, fabricators would prefer a 1/2 inch thick plate which helps in reducing imperfections and meeting tolerances. Therefore, the design thickness must be optimized between extra cost of fabrication required for the thinner plate, and the extra cost of higher prestressing levels or more reinforcement to counteract forces induced by thicker plates during the design basis accident condition.

2.2 STIFFENER ARRANGEMENT

Various stiffener arrangements are used depending on the dome shape, radius and thickness of dome, construction and erection methods, and the requirements of non-service load conditions. A typical stiffener arrangement is shown in Figure 2 for hemispherical dome. The structural Tee sections provide overall rigidity and the less stiff plate sections divide the liner into smaller sections to preclude plate buckling. The arrangement basically consists of meridional and circumferential stiffeners up to a
minimum of 50° to 60° from the spring line beyond which a square grid pattern may be used.

Since continuous stiffeners are also utilized for transferring the shear during the design basis accident condition, the size of the stiffeners must be based on available test results (Ref. 1) or tests must be performed.

2.3 CONCRETE PLACEMENT SEQUENCE
A typical concrete placement sequence for a hemispherical dome is shown in Figure 3, with external formwork required for the lower portion (45°-50°) of the dome. The pour length for each placement is measured along the arc of the dome. The pour length for any particular dome is a function of the overall buckling capacity of the dome and the amount of stiffeners used. The recommended pour length is 5 to 7 feet, with a minimum of three days between successive pours. The upper portion of the dome is placed in two horizontal layers. The thickness of the first layer is a function of the critical buckling load of the spherical cap, constructibility and delamination considerations during prestressing. The first layer must include the lower layers of dome reinforcement. When this layer develops strength, it will act in combination with the liner as formwork for the second layer. A seven day interval between these placements is recommended. A concrete placement rate of 1-1/2 to 2 feet per hour is suggested.

In reinforced concrete containments, it may often be necessary to pour nonaxisymmetrically in order to reduce the exposed surface and thus help in eliminating cold joints. The designer must be cautioned for such conditions since the applied concrete pressure increases due to a higher rate of placement and the critical buckling load decreases on account of the nonsymmetrical loading condition.

3.0 ACCEPTANCE CRITERIA

3.1 STRESS CRITERIA
The compressive and tensile stresses for either membrane or combined membrane and bending are limited to 2/3 fy where fy is the yield stress of the material, as per ASME Section III Division 2 Code (Table CC3720-1 of Ref. 2).

3.2 BUCKLING CRITERIA
The Division 2 Code (Ref. 2) does not provide any specific buckling criteria for liners under construction condition. The following buckling criteria are recommended for dome liners:

1) Overall Buckling:
   a) Unstiffened dome under biaxial compression: Minimum Factor of Safety (F.S.) = 4.0
   b) Two-way stiffened dome under biaxial compression: Minimum F.S. = 2.0
2) Local Buckling:
   a) Local Buckling of liner plate and stiffeners: Minimum F.S. = 2.0

In addition to the Factor of Safety, a Correlation Factor, as discussed in Section 4.3, is applied to the classical buckling load to account for the discrepancies between experiments and theory.

In using the above criteria, the designer must apply sound judgment for each specific case because of the following uncertainties:

1) Large numbers of randomly distributed liner imperfections
2) Uncertain boundary constraints
3) Initial stresses in the liner

3.3 TOLERANCE CRITERIA
The Division 2 Code (Ref. 2) provides the following dome liner tolerance criteria: "The inner surface of the liner head shall not deviate from the specified shape by more than 1-1/4% of the inside diameter of the liner shell."

This provision for liner yields large deviations from the true surface which is unacceptable for erection. The Task Group on Liner Tolerances of the Division 2 Code Committee, has recommended a 6-inch deviation from the theoretical location (Ref. 3).

4.0 BUCKLING ANALYSIS
Thin shells are susceptible to buckling because of their low bending stiffness. Therefore, stiffeners are provided to increase the bending stiffness of the liner and to prevent local instability. The stiffeners are sized and spaced such that overall stability will determine the concrete placement sequence and pour length.

4.1 LOCAL PLATE AND STIFFENER BUCKLING
The design of the stiffener spacing, d, to preclude local plate buckling is based on Buchert (Ref. 4)

\[
\frac{P_{cr} \cdot R}{2t} = \frac{1}{160} \left(\frac{0.6d}{R}\right)^2 + \frac{4}{3} \left(\frac{d}{R}\right)^2 \left[ -\frac{1}{\left(\frac{6d}{R}\right)^2} \right]
\]  

Where:  
\( R \) = radius of the dome  
\( t \) = thickness of the liner

\( P_{cr} \) = external pressure which includes the factor of safety

The stability of the stiffeners themselves is determined by classical theory as given in Timoshenko (Ref. 5).

4.2 OVERALL STABILITY
Considerable work has been done in the past on unstiffened domes (Ref. 6). However, for stiffened domes, the only practical solution has been developed by Buchert (Ref. 7).  

Nonaxisymmetric loading and imperfection conditions have been discussed in Reference 8.
4.2.1 BUCHART'S APPROACH

For perfect stiffened spherical shells, Buchart's closed form solution for the design critical pressure, $P_{cr}$ is given by:

$$P_{cr} = \frac{0.19E}{R^2} \cdot \frac{1}{t_m} \cdot \frac{1}{t_b}^{3/2} \quad (2)$$

Where: 
- $E$ = modulus of elasticity
- $R$ = radius of shell
- $t_m$ = equivalent membrane thickness
- $t_b$ = equivalent bending thickness

This formulation has the following limitations:
1) Only square mesh stiffeners are considered.
2) Partial and nonaxisymmetric pressure cases are not included.
3) Is based on tests of spherical caps with comparatively smaller $R/t$ ratios than are expected in containment dome liners.

Based on these limitations this approach is used only for the conceptual design of the stiffener system.

4.2.2 COMPUTER ANALYSIS

The final overall buckling analysis is performed using computer program ROSORA (Ref. 9, 10). This program is used to determine the minimum buckling load for any particular loading configuration which may occur during construction.

The computer program is a general shells of revolution program accommodating branched and stiffened shells of various geometries, wall types and thicknesses. Loading is in terms of pressure and/or line loads both thermal and mechanical.

Figure 4 shows the analytical model for the dome liner. The cross-section is modeled in segments approximating the placement sequence for ease of load input. The hoop rings are included as they appear on the actual structure. The meridional stiffeners are input as an equivalent stiffener based on smeared cross-section. In addition as different segments of the liner are analyzed, the concrete in place is also modeled with the attained strength and thickness. Material properties of liner and stiffeners are input. The model is loaded with a unit uniform pressure representing concrete. Other mechanical loads such as dead loads are included as constant loads. The only varying load in the analysis is the pressure load.

The program calculates the critical eigenvalues for a range of circumferential wave numbers as specified. The circumferential wave number represents the buckling mode shape in the circumferential direction. Any number of eigenvalues per wave number may be obtained. The critical buckling mode in the meridional direction is printed out and plotted corresponding to the minimum eigenvalue obtained.
The stability analysis consists of obtaining a critical eigenvalue for each concrete placement in the sequence. Effects of lack of bond between the liner and existing concrete are included in the analysis.

4.3 CORRELATION FACTOR

The results obtained from the computer analysis are based on a perfect shell with no deviation from true surface. Experimental results have shown that thin shells will buckle at loads much smaller than predicted by classical theory. In addition, scatter of the test results is often quite large (Ref. 11, 12).

The stability of the shell will depend on the dome slenderness ratio and the overall geometry, spherical dome or cap, as described by a geometrical parameter, γ. The effect on the buckling load by the geometrical parameter is defined by a Correlation Factor (C.F.). This factor Pcr/Pcl, the ratio of the classical buckling load to the actual buckling load, can be expected. Various formulas relating to correlation factors are given in the literature (Ref. 11 through 16). The recommended Correlation Factor used in the overall stability analysis is given by Baker (Ref. 13) which is based on a statistical study of experimental data (Ref. 11, 14).

\[
C.F. = \frac{P_{cr}}{P_{cl}} = 0.14 + 3.2/\gamma^2
\]  

Where: 
\[\gamma = \text{geometrical parameter} = \left[12 \left(1-\mu^2\right)\right]^{1/4} \left[R/t\right]^{1/2} \cdot 2 \sin \frac{\theta}{2}\]

Where: \(\mu = \text{Poisson's Ratio}\)

\(\theta = \text{Half the included angle of the spherical shell}\)

Equation 3 is plotted in Figure 5.

5.0 RESULTS OF OVERALL BUCKLING ANALYSIS

For the hemispherical dome shown in Figure 4, pour lengths of approximately 10 feet and 7 feet were examined with the results summarized in Tables I and II. The buckling load indicated is the eigenvalue divided by a Correlation Factor of 8 as determined for this dome. Corresponding Factor of Safety is also included. A comparison indicates a 100% increase in lowest Factor of Safety by reducing the pour length by 3 feet. The analysis also showed that the critical concrete placement for this dome was in the area of pours 3 and 4 for 7-foot pour lengths.

Figures 6 and 8 show the critical mode shapes for pours 2 through 5, 10, and 11. The buckling modes show that the maximum displacement occurs near the top of each placement. These areas should be given special consideration for proper stiffener arrangement. Figure 7 shows the normalized displacements corresponding to the critical eigenvalue of pour 3 in Table II.

Since the computer program assumes elastic conditions, the stresses in the concrete and steel liner are checked for elastic limits. It is found that neither the concrete nor the steel have exceeded the allowable stresses. This ensures that elastic buckling has not occurred.
The circumferential wave number corresponding to meridional stiffener spacing is checked. If this eigenvalue is critical, it indicates that the meridional stiffeners, as spaced, have little or no effect on the overall stability of the dome.

A lack of bond analysis was performed for the critical pour assuming lack of bond between the liner and concrete from the top of the pour to the last embedded stiffener. The result is a drop in the buckling load and corresponding safety factor by approximately 10% for a 6-inch lack of bond.

6.0 CONCLUSION

Of all the available schemes for dome liner support, the self-standing dome is found suitable for construction conditions. Though more analytical effort is involved for this scheme, considerable savings are achieved in material cost and construction time. In addition, the construction of the concrete dome supported by a self-standing liner is not on the critical path of the containment schedule. Available design formulations cannot be applied to stiffened domes because of limitations on partial and un asymmetrical loading and discrete stiffeners. Therefore, computer solutions are required to perform detailed analysis. Higher correlation factors are justified for large fabrication tolerance requirements and nonavailability of experimental results for large R/t ratios. It is suggested that data from prototype containments be obtained and utilized for better prediction of buckling behavior.

ACKNOWLEDGEMENT

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REFERENCES


(3) AGENDA FOR THE JOINT ACI-ASME COMMITTEE MEETING, March 18, 1977, San Diego, California.


### TABLE I
BUCKLING ANALYSIS RESULTS FOR 10-FOOT POUR LENGTH

<table>
<thead>
<tr>
<th>Load Number</th>
<th>Pour Length</th>
<th>Eigenvalue</th>
<th>Safety Factor</th>
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<tbody>
<tr>
<td>1</td>
<td>0 to 10.3'</td>
<td>116.0</td>
<td>1.99</td>
</tr>
<tr>
<td>2</td>
<td>10.3' to 20.6'</td>
<td>115.0</td>
<td>1.96</td>
</tr>
<tr>
<td>3</td>
<td>20.6' to 30.9'</td>
<td>116.0</td>
<td>1.94</td>
</tr>
<tr>
<td>4</td>
<td>30.9' to 41.2'</td>
<td>119.0</td>
<td>2.08</td>
</tr>
<tr>
<td>5</td>
<td>41.2' to 51.2'</td>
<td>127.0</td>
<td>2.81</td>
</tr>
<tr>
<td>6</td>
<td>51.2' to 61.2'</td>
<td>129.0</td>
<td>3.34</td>
</tr>
<tr>
<td>7</td>
<td>61.2' to 117.8'</td>
<td>59.0</td>
<td>1.76</td>
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### TABLE II
BUCKLING ANALYSIS RESULTS FOR 7-FOOT POUR LENGTH

<table>
<thead>
<tr>
<th>Load Number</th>
<th>Pour Length</th>
<th>Eigenvalue</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 to 7.0'</td>
<td>239.0</td>
<td>4.13</td>
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<tr>
<td>2</td>
<td>7.0' to 14.2'</td>
<td>216.0</td>
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<td>3</td>
<td>14.2' to 21.4'</td>
<td>208.0</td>
<td>3.56</td>
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<td>4</td>
<td>21.4' to 28.6'</td>
<td>207.0</td>
<td>3.65</td>
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<td>5</td>
<td>28.6' to 35.8'</td>
<td>211.0</td>
<td>3.87</td>
</tr>
<tr>
<td>6</td>
<td>35.8' to 43.0'</td>
<td>217.0</td>
<td>4.20</td>
</tr>
<tr>
<td>7</td>
<td>43.0' to 50.0'</td>
<td>230.0</td>
<td>5.17</td>
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<td>8</td>
<td>50.0' to 57.0'</td>
<td>237.0</td>
<td>6.01</td>
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<tr>
<td>9</td>
<td>57.0' to 64.0'</td>
<td>234.0</td>
<td>6.53</td>
</tr>
<tr>
<td>10*</td>
<td>64.0' to 117.8'</td>
<td>57.0</td>
<td>5.24</td>
</tr>
<tr>
<td>11+</td>
<td>64.0' to 117.8'</td>
<td>732.0</td>
<td>26.00</td>
</tr>
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* 1 ft thickness of cap
+ Remaining 2 ft thickness of cap
FIGURE 5  CORRELATION FACTOR VS GEOMETRIC PARAMETER

FIGURE 6  BUCKLING MODE SHAPES FOR LOWER POARS

FIGURE 7  CRITICAL NORMALIZED DISPLACEMENTS FOR LOAD NO. 3

FIGURE 8  BUCKLING MODE SHAPE FOR UPPER POARS