Delamination and the structural response of RC thin shell in nuclear shield buildings with unanticipated construction openings

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ABSTRACT: This paper examines the structural response in a thin shell concrete dome with construction openings. The weight of the dome is carried in axial compression along the hoops and meridians of the dome. The openings interrupt the hoops and meridians and the dome's weight must be redistributed around the openings; resulting in zones of increased compression near the opening. In the affected areas there is a significant difference between the compression on the top surface of the dome, and that on the bottom surface. The dome was cast in two layers. This study examines the potential for fracture (and thus delamination) as a result shear stress at the interface of the two layers. The stresses are largest around the opening. The shear capacity of the interface is determined by previous empirical studies of composite beams. The shear stresses in the dome with openings are not large enough to cause delamination.

1 INTRODUCTION

1.1 *Introduction*

As Nuclear Power Plants age many require steam generator replacement. There is a nickel alloy in the steam generator tubes that is susceptible to stress cracking and although these cracks can be sealed the generator becomes uneconomical without 10%-15% of the tubes (Chernoff & Wade, 1996). The steam generator in a typical nuclear power plant is housed in the containment structure next to the reactor. The equipment hatch is not big enough to facilitate steam generator replacement, thus construction openings in the dome of the containment structure are required. Where both the walls and the dome of the structure have been post-tensioned such openings are generally made in the walls, and where only the walls are post-tensioned it is easier to put the openings in the dome. This paper examines the effects of such openings in the dome.

The prototype nuclear containment shield building is made up of a 0.6m (2ft) thick dome atop 0.91m (3ft) thick and 51.9m (170ft) high cylindrical walls, radius 20m (65.5ft), with a tension ring (15ft) high and 2.4m (8ft) thick in between. The dome of the building is cast in two layers; a lower 23cm (9in) layer that serves as the formwork for an upper 38cm (15in) layer.

The aim is to evaluate the stresses through the 0.6m depth of the dome roof of the shield building. . The finite element model of the dome is made from a series of layers of solid-elements. In the model the hoop and meridian stresses are not uniform through the depth at any point on the dome. The stresses vary linearly from the top surface of the dome to the underside of the dome. This variation is indicative of bending, and where this bending stress itself varies there will be a horizontal shear stress in the dome. This paper aims to establish the extent and the magnitude of these horizontal shear stresses in the dome with openings and in the dome without openings (if any).

Should the shear stresses at the interface between the two layers of the dome prove to be significant there is the potential for cracking leading to delamination.

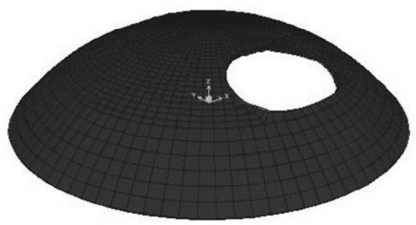
1.2 *Previous Research*

There is little published research on the structural response of nuclear containment structures to any unanticipated construction openings.

Mac Namara et al, 2007 examines a model (with the same geometry as that considered in this paper) made from shell elements and demonstrates the redistribution of the weight of the dome around construction openings leading to zones of increased meridian compression either side of the opening, and zones of increased hoop compression above and below the opening.

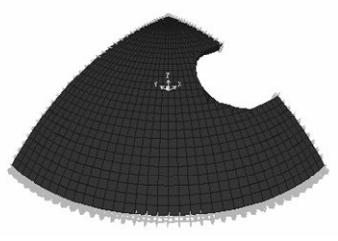
Bennett, 2005 studies construction openings (of a similar size to those considered here) made in the *walls* of a shield building for steam generator replacement. Bennett concluded that the impact of the opening on the stresses due to self weight was local, and though significant in comparison to the stresses in the structure without openings, insignificant in terms of material strength.

For the question of delamination, the available references are empirical studies of delamination at the interface of two layers of concrete in *beams* only. Patnaik, 2001 gives horizontal shear strengths for beam interfaces of between ~1700kN/m^2 and ~6200kN/m^2 (~250psi and ~900psi), and cites a series of previous studies that give similar results. The study concluded that the horizontal shear strength at the interface of the beams was independent of concrete strength and depth of beam to tie spacing ratio.



(a)

(b)



(c)

Figure 1. The finite element model; (a) the full dome, (b) the cross section, and (c) The quarter section.

1.3 *Description of the Model*

This paper examines a generic nuclear containment shield building as described in section 1.1.

The analysis of a model made from shell elements (Mac Namara et al, 2007) showed that the effect of the boundary conditions of the dome had only a local impact on the stresses and forces in the dome. That analysis also established that the openings in the dome had no significant effect on the stresses in the walls or the tension ring. For this reason and for computational simplicity the analysis in this paper was limited to the dome roof of the structure. The dome is modeled as a series of layers of solid-elements with fixed connections at the base. For further ease of computation and to allow for a finer mesh only one quarter of the dome is modeled. The boundary conditions along the x and y axes replicate the symmetry of the dome. The full dome and the final model are shown in Figure 1.

The model is analyzed under dead load only, the only load that acts on the shield building while the steam generator replacement is carried out (and the construction openings are in place).

2 RESULTS

2.1 *Axial and Bending Stresses in the Dome without Openings*

We first examine the distribution of stresses in the structure without openings. These stresses are compared both to the expected stresses under membrane theory (to verify the model) and to the stresses in the model with openings (to fully examine the impact of the openings on the structure).

Thin-shell concrete domes are assumed to carry all loads as axial forces in two orthogonal directions. Meridian forces and stresses act along the meridians of the dome (the meridians of a dome are like lines of longitude on a globe). Hoop forces and stresses act along a series of parallel hoops (the hoops of a dome are like lines of latitude on a globe)

In Membrane Theory, the meridian stress resultant;

$$N_{\varphi} = aq\left(\frac{1}{1+\cos\varphi}\right) \tag{1}$$

and the hoop stress resultant;

$$N_{\theta} = aq\left(\frac{1}{1+\cos\varphi} - \cos\varphi\right) \tag{2}$$

where a is the radius of curvature of the dome; 26.8m (88ft), q is the load on the dome (self weight), and φ is the angle between the radii of the dome at the crown and at the point in question (Billington, 1982).

Figures 2 and 3 show the membrane theory values for hoop and meridian stresses respectively and compare those to the *average* value for stresses at the same point returned by the finite element model. The hoop and meridian stresses are in compression throughout and are, as expected, the same at the crown, 320kN/m^2 (46psi) of compression. Hoop stress decreases from the crown to the base where it is approximately 48.3kN/m^2 (7psi). The meridian stress increases from the crown to the base where it is approximately 390kN/m^2 (56psi). The stresses in the finite element model agree closely with those predicted by membrane theory with small deviations close to the base of the dome. These deviations are easily explained by the different boundary conditions assumed by membrane theory and by the model.

The boundary condition assumed by membrane theory at the base of the dome is that of a roller perpendicular to the tangent of the dome at that point. The dome is constrained the direction of the tangent at the base, it is free to move in the direction perpendicular to the tangent, and free to rotate. The finite element model assumes a fixed connection at the base of the dome (Billington, 1982).

Figures 2 and 3 also compare the hoop and meridian stresses found for the dome in the shell-element model in Mac Namara et al, 2007 to those of the solid-element model. The only significant difference is that the shell model analysis has hoop tension close to the base that is not evident in the solid-element model. This is also due to a difference in boundary conditions. Where the shell-element model has the ring and wall attached to the dome, the solid-element model has fixed boundary conditions. A separate analysis of a shell model with fixed boundary conditions confirms that we do not expect to see hoop tension at the base of a fixed dome, made of either shell or solid-elements (Mac Namara, 2007).

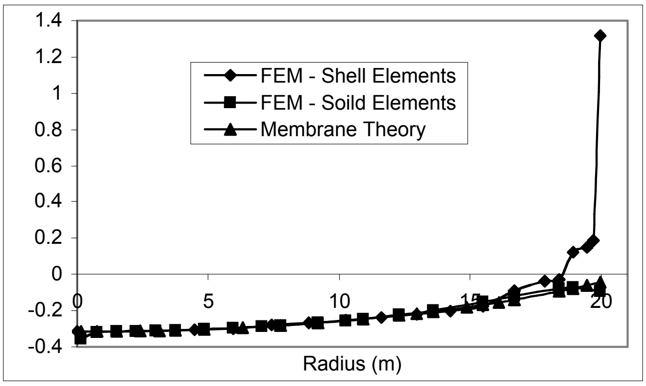


Figure 2. Hoop stresses for the solid-element and shell-element models compared with membrane theory.

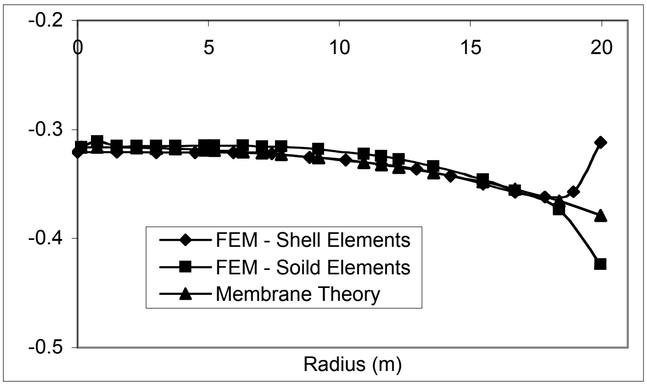


Figure 3. Meridian stresses for the solid-element and shell-element model models compared with membrane theory.

The stresses for the solid-element model in Figures 2 and 3 are the *average* stresses through the depth of the dome. The model does indicate variation of hoop and meridian stresses through the depth of the dome. For the most part these variations are small, indicating little bending. In most of the dome the portion of total stress that is a bending stress is on the order of 10%. This indicates that although the model is made up of solid-elements, it is exhibiting shell behavior and is an appropriate approach to examine the stresses in the structure

There is more significant bending associated with the meridian stress at the base of the dome. This part of the dome is expected to deviate from membrane theory of shell behavior (much of the self weight is carried by out of plane shear). This deviation is also a result of the difference in boundary conditions discussed above.

2.2 *Axial Stresses in the Dome with Openings*

Figures 4 and 5 show the hoop and meridian stresses in the dome with openings compared to the dome without openings. The stresses in the dome with openings are plotted for two axes, Axis 90 is the axis of symmetry through the dome that bisects the openings and Axis 0 is the axis of symmetry through the dome perpendicular to Axis 90. Note that Figures 4 and 5 plot the *average* stresses through the depth of the dome at any point.

As expected the hoop stresses along axis 90, the axis that bisects the opening, show zones of increased hoop compression with respect to the dome without openings between the crown and the opening. The stress is 480kN/m^2 (70psi) in the dome with openings compared to 311kN/m^2 (45psi) in the dome without). There is another zone of increased hoop compression between the opening and the base. The stress is 360kN/m^2 (52psi) in the dome with openings compared to 191kN/m^2 (27 psi)in the dome without.

The meridian stresses along axis 90 show the expected decrease in meridian compression both above and below the opening and 0kN/m^2 immediately above the opening (where there is no material below to support self weight) and 0kN/m^2 immediately below the opening (where there is no material above to cause meridian stress).

Generally the stresses in the solid-element mode compare well with shell-element model in Mac Namara et al, 2007. The shell-element mode does display a small hoop tension stress immediately above and below the opening that is not present in the results for this solid-element model. However, the solid-element model shows considerable bending stress at these points.

the solid-element model has fixed boundary conditions. A separate analysis of a shell model with fixed boundary conditions confirms that we do not expect to see hoop tension at the base of a fixed dome, made of either shell or solid-elements (Mac Namara, 2007).

Figures 4 and 5 show that on Axis 0 (the axis furthest from the openings) the hoop and meridian compression in the dome with openings is close to that of the dome without openings. In the top half of the dome the hoop ***and*** meridian stresses, in the dome with openings, are within 40% of those in the dome without, this difference falls to 10% and less in the lower half of the dome. This behavior is the same as that of the shell model, and illustrates the local and limited nature of the influence of the openings on the stresses in the dome.

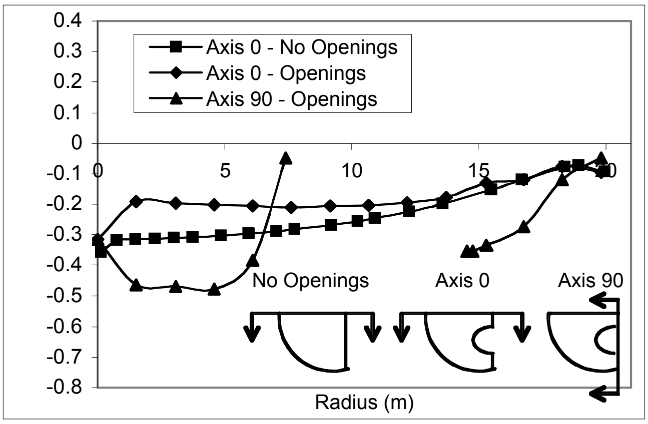


Figure 4. Hoop stresses for the solid-element models with and without openings.

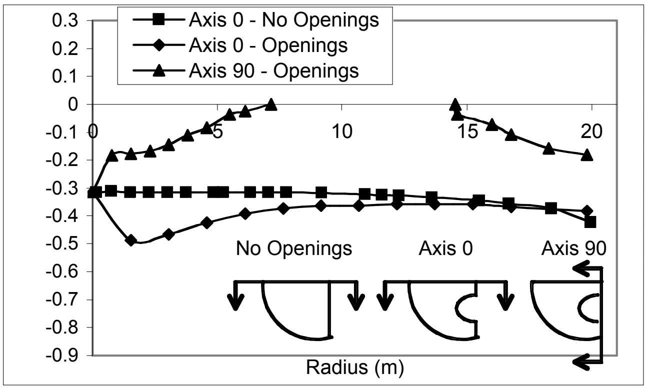


Figure 5. Meridian Stresses for the solid-element models with and without openings.

The values for hoop and meridian stress across the dome (and not just along the axes shown in Figures 4 and 5) show the redistribution of hoop and meridian compression around the openings. The hoop and meridian compression that would have been taken by the missing material is redistributed around the opening. Thus, there is increased hoop compression between the opening and the crown and between the opening and the base, and increased meridian compression on the either side of the openings. There is a corresponding decrease in hoop compression on either side of the openings, and a decrease in meridian compression between the opening and the crown and between the opening and the base.

The maximum hoop stress at any point through the depth of the model with openings is 703kN/m^2 (102psi) of compression and is found at the bottom corner of the opening. The maximum meridian stress is 1110kN/m^2 (161psi) and is found in the region of increased compressive meridian stress alongside the opening.

These maximum stresses are between 2 and 3 times larger than the maximum stresses in the dome without openings. However magnitude of the stresses is insignificant when compared to material strength (~20,000kN/m^2, ~3000psi). This is not surprising considering the large factor safety such a structure would have under dead load alone.

2.3 *Bending Stresses in the Dome with Openings*

There is more variation of hoop stresses (i.e. more bending) in the dome with openings as compared to the dome without, even along axis 0 away from the openings. Bending constitutes up to ~30% of total hoop stress along axis 0 as opposed to ~10% in the dome without openings. Along this axis there is less hoop bending near the crown and the base than in the rest of the dome. The pattern and magnitude of bending is same along axis 90, except immediately above and below the opening where the variation of hoop stress through the depth is even more significant. Bending constitutes ~60% of the total hoop stress immediately above the opening and ~40% immediately below.

The impact of the openings on the variation of meridian stress is less significant than the impact on hoop stress. Along axis 0, bending accounts for ~10% of the total meridian stress, the same as in the dome without openings. Along axis 90 the variation of meridian stress through the depth is significant in comparison with average stress through the depth. However, as the total meridian stresses along this axis are very small (due to the opening – see Figure 5) the magnitude of this bending is insignificant.

Near the base, along both axes, there is bending on the order of 40-80% of total stress, this is not however an impact of the opening and is present in the dome with openings and is a function of the boundary conditions of the dome.

2.4 *Shear Stresses in the Dome with Openings*

The bending evident in the solid-element model of the dome with openings is accompanied by shear stresses. The shear stresses are largest where the magnitude of the bending changes most rapidly. The maximum shear stresses in the model are immediately adjacent to the opening.

In general the shear stresses associated with the hoop stress (the S13 stresses, where the one direction is the hoop direction and the three direction is the local vertical axis for the element) are larger than those shear stresses associated with the meridian stresses (the S23 shear stresses where, the two direction is along the meridians of the dome, and the three direction is the local vertical axis for the element).

The maximum S13 shear stresses are found in an area where the hoop stresses are increased relative to the dome without openings; immediately above the opening. Incidentally, this is not the location of maximum hoop stress which is below the opening. The maximum S13 shear stress is 86kN/m^2 (12.5 psi) and is found at the top corner of the opening.

The maximum S23 shear stresses are also found where the associated (meridian) stresses are largest. Although the S13 stresses are generally the larger, the maximum S23 shear stress is 95kN/m^2 (13.8 psi), and is found at the side of the opening.

The shear stresses in the rest of the dome, away from the opening and away from the base of the dome, are even smaller, with maximums of ~ 20kN/m^2 (3psi).

All of the shear stresses in the dome with openings are trivial and they are not significant enough to represent any threat of delamination.

3 CONCLUSIONS

3.1 *Conclusions*

Text The solid-element dome without openings displays little bending and insignificant shear stresses and the average stresses through the depth of the dome are consistent both with the stresses in the shell-element model model and with membrane theory. Thus, the use of such a model made of solid-elements to examine shear stresses and the potential for delamination in a dome with openings is valid.

The pattern and magnitude of average hoop and meridian stresses through the depth of the solid-element model of the dome with openings also compares well with the hoop and meridian stresses in the shell-element model model. The analysis of the solid-element dome with openings shows considerably more bending than the dome without openings (by a factor of 6). The analysis also shows significantly more shear stress in the dome with openings. These shear stresses are largest along the edges of the opening; however the magnitude of the shear stresses is very low and will not cause delamination (even locally).

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