INFLUENCE OF PRESTRESSING ON RADIAL STRESSES IN NUCLEAR CONTAINMENT DOMES

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ABSTRACT

Considerable attention has been paid in evaluating the causes of delamination in two major prestressed concrete containment domes in USA and a recent incident in India. Conventionally, prestressed concrete domes are analyzed by idealizing them using surface elements, which do not have provisions for evaluating the normal force across the thickness direction. This has led to a research programme, which investigates the radial forces due to curved tendons in domes. The influence of post-tensioning on radial stresses in nuclear containment domes has been studied through 3-D finite element analysis, and the scope of this paper is limited to study of radial forces due to curvature and stress concentration effects alone using ADINA code. As a first stage a centerline idealization of the prestressing cables was made. The stress concentration caused by inclusion of duct holes as well as prestressing (prestressing forces inside a single duct, and each duct imparting stress concentration effect over the other) has been studied. The results show that for a prestressing cable placed anywhere within the thickness of the shell, the variation of normal radial stress changes from tension above the cable profile to compression below the cable profile, clearly indicating the existence of radial tension. The quantum of the radial tension is influenced by the parameters like radius, semi-central angle, rise of the shell and thickness. The magnitude of radial tension due to stress concentration effect around the prestressing ducts could normally exceed the tensile capacity of concrete. This necessitates the provision of reinforcements along the radial direction of the dome.

INTRODUCTION

Conventionally, prestressed concrete domes are analyzed by idealizing them using surface elements, which do not have provisions for evaluating the normal force across the thickness direction. The inadequacies in the modelling of Prestressed Concrete (PSC) shell structures are presented in [1]. Recently, considerable attention has been paid in evaluating the causes of delamination in two major prestressed concrete containment domes in USA and a recent incident in India [2-7]. Broadly, delamination of concrete can be categorized as

(i) Delamination due to deterioration in materiel property (corrosion) and
(ii) Delamination due to structural action namely due to radial tension.

Delamination due to deterioration in material property is not discussed in this paper. Delamination due to structural action (radial tension) in dome shells may be defined as the phenomenon in which the shell element develops in-plane cracks resulting in the separation of concrete into layers or laminae (parallel to mid-surface) along the shell thickness. Radial tension may also cause further distresses other than delamination. Delamination due to structural action is observed in PSC T-beams [8-9], Box Girder Webs [10], Cylindrical sections [11-13] and PSC Silos [14-15]. An overview of literature on evaluation of radial forces due to post-tensioning in curved PSC members is presented in Table 1. From the table it can be seen that only very little work has been reported in the literature regarding distribution and variation of radial stress through the thickness of internally prestressed domes especially with holes, necessitating a detailed study in this area.

The present research work is aimed to arrive at the adverse nature and profile of the radial stresses across the thickness direction of a dome due to prestressing action, which may lead to delamination. The parameters that may possibly influence the radial stress resultants in a PSC dome are studied in this work. FEM is used only as a tool in the best possible way. The FEM model could always be improved and that is not the aim of this work.

SCOPE OF THE WORK

In Indian PSC dome structures, prestressing cables are curved in profile [16]. There is a radial component of force due to prestressing throughout the length of the cable, which acts downward at the level of prestressing due to the curved profile. This radial component develops internal forces in terms of radial stress and transverse shear / radial shear across the thickness. The radial stresses across the thickness are generated due to the following phenomena.

(i) *Curvature effect* (Stressing of curved cables),
(ii) *Stress concentration effect* (Stress concentration around duct holes in shell section under membrane compression) and
(iii) *Force path deviation effect* (Deviation in force path in the thickness direction in the transition zone of openings area, due to changes in the shell thickness).

Table 1. Overview of literature on evaluation of radial forces due to post-tensioning in curved PSC members

Author(s)	Description	Delamination	Nature of work		Stress concentration		Comment
			Analytical	Experimental	Cable duct	Other	
McLeish [8]	T-Beams		✓	✓	✓		Design curves for three-duct sections
Tawfiq and Issa [9]	Florida Bulb-Tee Beams		✓	✓	✓	✓*	Influence of shape and material type of ducts on stress concentration
Landyth and Breen [10]	Curved box girder web	✓	✓	✓			Effect of duct arrangement on lateral forces from internal post-tensioning tendons
Derby [11]	Cylindrical Section		✓				"Smeared out" thin cylinder approach with prestress treated as "pseudo temperature"
Zarghamee et. al. [12-13]	Cylindrical Pipes	✓	✓	✓			Coating delamination
Stanaker and Fugler [14]	Silos	✓	✓			✓**	Radial ties of grade 40 steel as reinforcement
Safarian and Harris [15]	Silos		✓$^{+}$				Design of radial tie reinforcement using FIP's silo code
Ashar et. al. [4-7]	Steel-lined Containment	✓	✓				Radial rock anchors as reinforcement
Moreadith and Pages [3]	Steel-lined Containment	✓	✓				Investigation and repair of delaminated PSC dome

$^{+}$ = Design and guidelines ; * = Wedging Effect in Transition region ; ** = Improper splicing of ducts

There is also stress concentration effect due to embedded parts, ducts and openings, effect of thickening of shell, etc. These effects can not be studied using simple principles of structural mechanics or using thin shell theories. Hence more modern methods, using discrete and numerical approaches like FEM, have been resorted to. Proper assumption on d.o.f., boundary conditions and discretization may lead to acceptable results. The scope of the research work is restricted to investigation of radial stresses due to curvature effect and stress concentration effect alone using a linear static FEA code, ADINA [17].

PARAMETERS STUDIED

The scope can be best achieved by a three-dimensional analysis of such containment domes. However, the parameters and their ranges are large and the connected computational work becomes unmanageable. Hence, it is felt necessary to freeze certain parameters and their ranges depending on their relative effects on radial stress distribution. A basic understanding of the effects of different variables along with stress concentration effect is essential before arriving at a proper 3-D model. Accordingly a 2-D analysis was undertaken first. The effects of different boundary conditions and geometric parameters on the radial stress (F_{zz}) were studied and the details presented in [18]. It was evident that the radial stress varies inversely with radius and directly with rise, while change in thickness and semi-central angle do not affect its behaviour at the apex. A 3-D study was also undertaken for the analysis of singly curved shells with and without the effect of duct holes. The details are presented in [19-20].

The work presented in this paper is classified under different sub-sections as detailed

(i) Analysis without the effect of prestressing duct holes
  (a) *due to one-way prestressing scheme* : A PSC dome with a single cable running through the apex section is studied.
  (b) *due to two-way prestressing scheme* : A PSC dome with two prestressing cable running orthogonal to each other and crossing at the apex section is studied.
(ii) Analysis with the effect of prestressing duct holes

Stress concentration due to two prestressing ducts intersecting / touching each other in orthogonal directions is analysed. There is a combination of the stress concentration effect around the periphery of each duct, due to two separate prestressing ducts running in orthogonal directions. Prestressing is considered in one or both the ducts. A single duct case is not considered here. The ducts are always circular in shape.

FINITE ELEMENT MODELLING

Idealisation of Prestressing Action

PSC domes used for Indian NPP containment structures are of segmented hemispherical shape with a two-way prestressing scheme, which resembles a rectangular grid in plan.

Figure 1 shows the layout of prestressing cables running in one plane (YZ plane) in a two-way prestressing scheme. The cables are placed at discrete intervals.

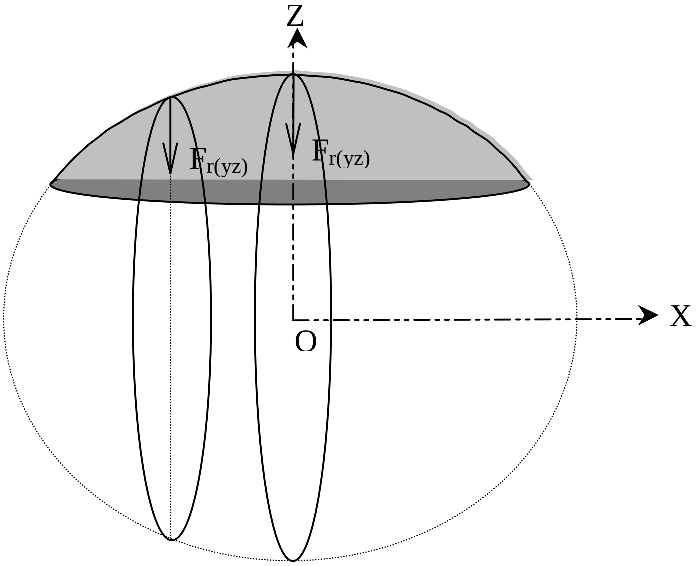

Fig. 1 3-D view of prestressing cable layout

The tension in the prestressing cable (T) is taken from a life size model as 2340 kN. This is arrived at based on applied tension in prestressing cables after deducting the immediate losses comprising of slip, friction and elastic shortening. If only a segment of sphere (shell) is considered, the hyperstatic moments are reduced to zero and the distribution of the reaction is uniform. Appropriate FE modelling has been done to simulate the radial pressure exerted by the cable in its own vertical plane. Equivalent nodal load method is adopted for the incorporation of the prestressing forces. The equivalent nodal loads are calculated such that it contains all the force components due to the arbitrary curvatures of a tendon draped in the shell.

The cable portion between two consecutive nodes is identified as a curved line instead of the usual straight-line approach. The nodal forces are calculated in three Cartesian coordinate axis directions depending on the node position. The various losses along the length of the cable and time dependent losses due to prestressing are not discretely considered. But, an average prestressing force after deducting for all the losses is considered to be acting uniformly over the entire length of the cable running inside the shell. The radial pressure exerted by a cable at any point (F_r), for a cable running parallel to XZ plane and parallel to YZ plane are given in equations 1 and 2.

$$F_{r(xz)} = \frac{-Tx}{\sqrt[2]{\left(r^2 - y^2\right)}\sqrt[2]{\left(x^2 + z^2\right)}}\,i - \frac{Tz}{\sqrt[2]{\left(r^2 - y^2\right)}\sqrt[2]{\left(x^2 + z^2\right)}}\,k \qquad (1)$$

$$F_{r(yz)} = \frac{-Ty}{\sqrt[2]{\left(r^2 - x^2\right)}\sqrt[2]{\left(y^2 + z^2\right)}}\,j - \frac{Tz}{\sqrt[2]{\left(r^2 - x^2\right)}\sqrt[2]{\left(y^2 + z^2\right)}}\,k \qquad (2)$$

In addition to the radial pressure exerted by the prestressing cable, there will be a slip force on the cables, which will cause the cables to slip from the curved surface of the shell. This slip force depends on curvature of the shell, the prestressing force, self-weight of the cable and orientation of the prestressing cable with respect to shell geometry. The two components that causes the slip force are self weight of the cable and prestressing force. The magnitude of the slip force due to self-weight of the prestressing cables is very negligible. The slip force due to prestressing depends on the orientation of the prestressing cables w.r.t. shell geometry. For Indian Nuclear Containment domes, this component can also be due to ignored since prestressing cables are more concentrated on the apex zone and the entire dome has got only a semi-central angle of 30°.

Material Modelling and Analysis

The scope of the work is limited to linear elastic analysis. Short-term static modulus of elasticity (E) corresponding to M45 grade of concrete (IS: 456-1978) and a Poisson’s ratio (υ) of 0.15 are used [21]. The unit weight of concrete is taken as 25 Kn/m^3. The problem is solved using ADNA with displacement formulations. Appropriate symmetric boundary conditions have been assigned to the nodes on the line of symmetry. A benchmark study is done on four different 3-D solid elements (TETRA4, TETRA10, HEXA8 and HEXA20), with varied aspect ratios to evaluate their suitability in modelling thin shell structures and to have an understanding on the meshing schemes to have acceptable convergence of results. Scordelis-Lo cylindrical roof problem was selected for the study [22]. Based on the results, HEXA20 elements were selected for meshing the geometry, which facilitates mapped meshing (rule based meshing). HEXA8 with IC is not selected because of its incompatible nature, although it is much better in represent bending when compared to a similar HEXA8 element without incompatible modes. For meshing the irregular curved geometry, TETRA10 elements are selected. Both TETRA10 and HEXA20 elements are second order elements, which provide higher accuracy than first-order elements for ``smooth'' problems that do not involve severe element distortions. The details are explained in [19].

RESULTS AND DISCUSSION

Three-Dimensional analysis of domes without effect of duct holes

An existing real life shell model is chosen for this study with the following dimensions: thickness (d) = 0.45m, centre line radius (r(CL))= 33.595m and semi-central angle (ϕ) = 30°. Both one-way and two-way prestressing schemes are taken up for study. One-way prestressing scheme is implemented as a concentric prestressing running through the apex of the dome. However, two-way prestressing scheme is applied with a slight eccentricity in the thickness direction. In two-way prestressing scheme, the two hypothetical prestressing ducts, which run orthogonally at the apex, are assumed to touch each other at the centre of the thickness. With line load idealisation, the cables have a slight eccentricity from the centre line of thickness to a level of $\pm d_h/2$, which come to ± 45 mm for a 90mm diameter duct hole. For both the cases, line load idealisation is adopted for modelling prestressing action. Fixed boundary conditions are adopted at the ends. Figure 2 shows the geometry of the dome along with the FE mesh and boundary conditions. Combined meshing technique is used for meshing. The geometry of the dome has been divided into regular geometry around the apex region to facilitate a rule based / mapped meshing using HEXA20 elements in the apex zone. Mapped meshing has been implemented in the regions, which facilitate such a technique. In other regions, free form meshing using TETRA10 elements were adopted to take care of the inter-element compatibility.

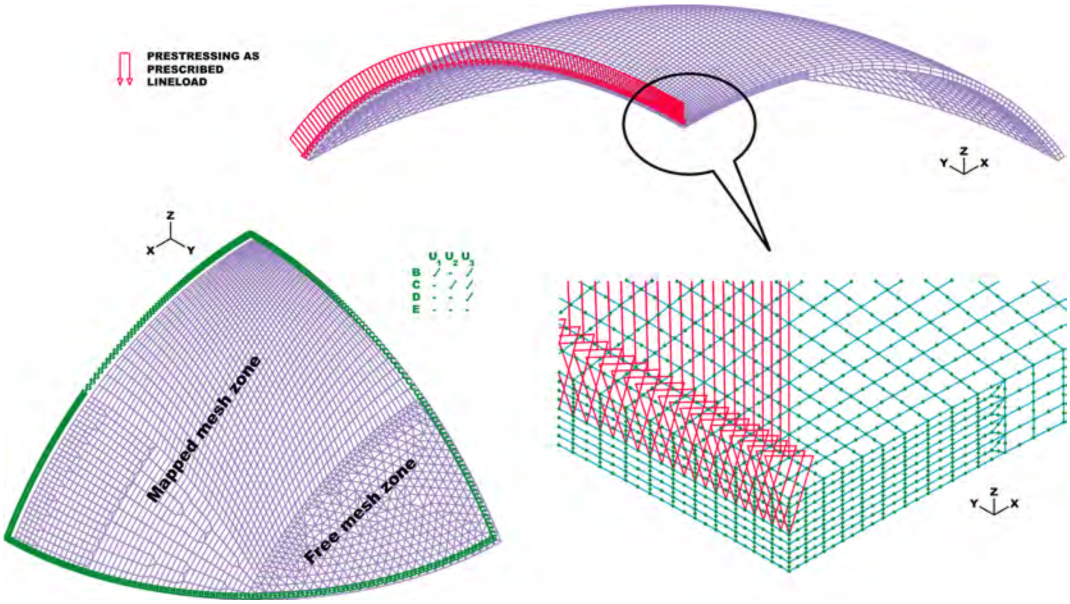

Fig. 2 One-way prestressing scheme of dome along with the geometry and FE mesh adopted

The results show that for a prestressing cable placed somewhere within the thickness of the shell, the variation of normal radial stress (F_{zz}) changes from tension above the cable profile to compression below the cable profile, clearly indicating the existence of radial tension and this is maximum at the apex section of the shell. The radial tensile stress that is zero at the outer surfaces of the shell, increases to a positive/negative maximum value at a point just above/below the line of prestressing, the increase being non-linear (Fig. 3). The transverse shear stresses (F_{xz} and F_{yz}) are maximum at the point of application of prestressing. Together with $F_{zz(max)}$ they may cause principal tensile stresses. But for a two-way prestressing scheme of dome, the distribution is the superposition of the F_{zz} stress gradients got due to a one-way prestressing scheme of a dome in two different planes (Fig. 4). Here too a combined meshing technique is adopted with HEXA20 and TETRA10 elements.

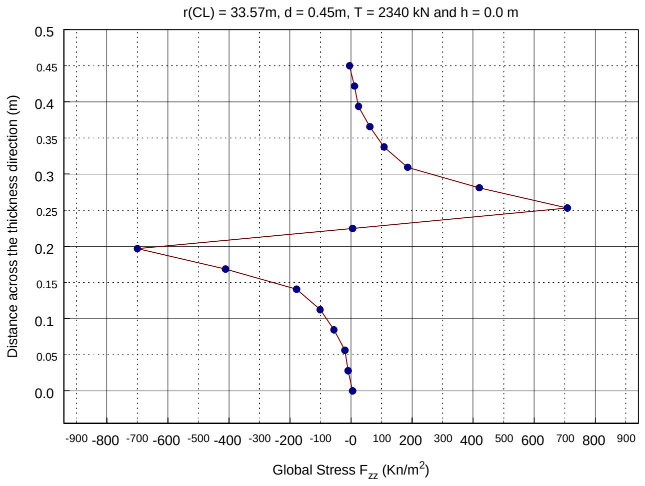

Fig. 3 Variation of F_{zz} for a dome under one-way prestressing scheme

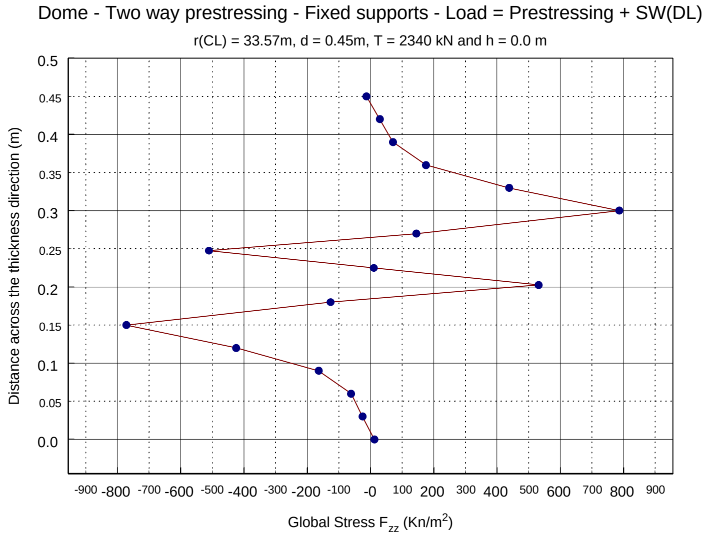

Fig. 4 F_{zz} stress gradient for a dome under two-way prestressing scheme

Three-Dimensional analysis of domes with effect of duct holes

The next case is the study of stress concentration around the apex region where the two prestressing duct holes run orthogonal to each other (Fig. 5). When two circular ducts touch each other, at the point of contact the thickness of the concrete material is zero (i.e. the two ducts touch each other only at a point). Hence, FE meshing around the intersection region will result in sliver and distorted elements, if no special care is taken to prevent them in meshing. A combined meshing scheme with mappped mesh around the apex region with HEXA20 elements and TETRA10 elements for free form zone is adopted (Fig. 6). All the three possible combinations of loading namely (i) prestressing only in the bottom prestressing duct, (ii) prestressing only in the top prestressing duct and (iii) prestressing in both bottom and top prestressing ducts are analysed for the case in which two ducts run orthogonal to each other.

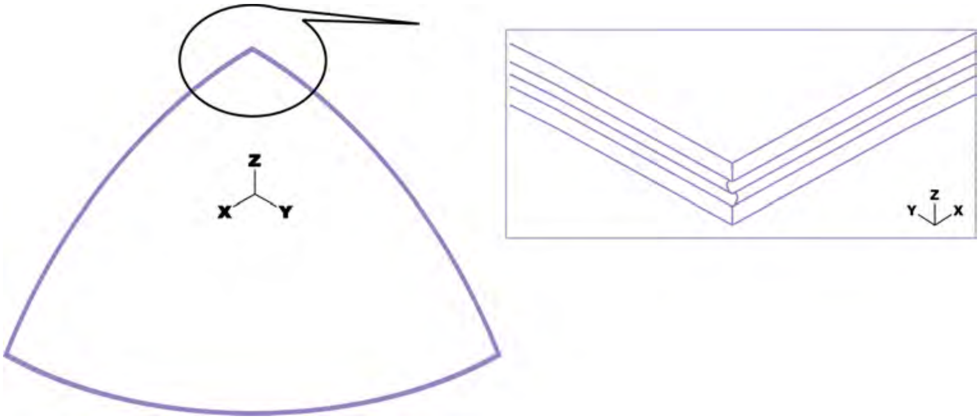

Fig. 5 Dome geometry showing the intersection of two prestressing ducts at the apex

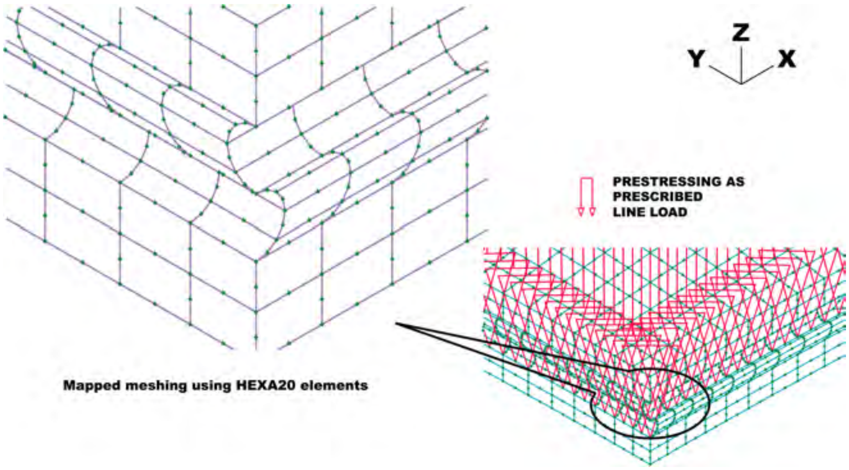

Fig. 6 FE mesh around the intersection of two prestressing ducts at the apex – Prestressing in both top and bottom prestressing ducts

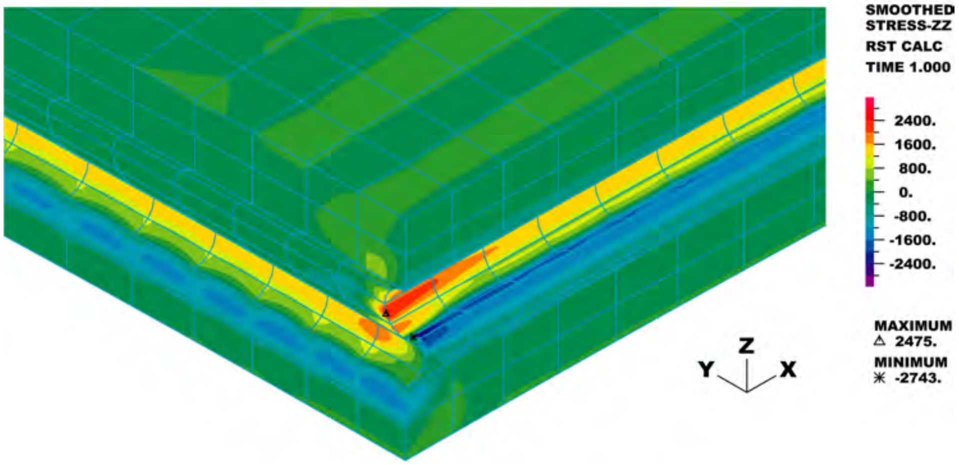

Fig. 7 F_{zz} stress contours around duct intersections at the apex of dome – Prestressing in both top and bottom ducts

CONCLUSIONS

The following are the salient conclusions drawn from the 3-D analysis conducted to investigate the effect of prestressing on the radial stresses in nuclear containment domes. The results are applicable for the parameters and their range considered and assumptions made in the 2-D and 3-D analysis:

(i) The assumptions made in thin shell theory do not provide for F_{zz}, which plays a predominant role in internally prestressed concrete shells. Hence, thin shell theory is not directly usable for the analysis of PSC shells with internal prestressing done along the curvature direction.

(ii) From the analysis it is clearly seen that for a prestressing cable placed somewhere within the thickness of the shell, the variation of normal radial stress changes from positive above the cable profile (tension) to negative below the cable profile (compression) (2-D and 3-D analysis).

(iii) Influence of BC's on radial stress (F_{zz}) is very minimum especially at the apex where the radial stress is maximum and can be considered negligible. Radial stress varies inversely with radius and directly with rise & eccentricity of prestressing while changes in thickness and semi-central angle do not affect the behaviour of F_{zz} at apex (2-D analysis).

(iv) F_{zz} stresses obtained due to curvature effect alone without considering stress concentration effect is very low to cause delamination failure, but the radial stresses due to stress concentration effects are significant. Hence, stress concentration effect should be taken care of in any analysis to study radial stresses in PSC shells (2-D and 3-D analysis).

An understanding on the existence and variation of radial stresses due to prestressing across thickness direction of singly curved and doubly curved shells has been achieved. The results show that radial stress plays a major role in PSC shell structures prestressed along the curved edge. Such PSC shells should be designed to take care of radial tension across the thickness direction of shell by the provision of adequate radial reinforcement. Details of the above research work are explained in [19]. The study of stress concentration (with special reference to radial forces) due to force path deviation, structural discontinuity caused by service openings, etc. will be an immediate area for further research. The existence of duct hole material could also be included.

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NOMENCLATURE

d = Thickness of the Shell
d_h = Diameter of hole
E = Short-term static modulus of elasticity of concrete
F_r = Radial pressure exerted due to prestressing at any point along the cable profile
F_{zz} = Normal stress along the radial direction / Radial stress
$F_{zz(max)}$ = Maximum radial stress (tension)
$F_{zz(min)}$ = Minimum radial stress (compression)
r(CL) = Radius of the shell (Centre Line radius)
T = Tension in the prestressing cable
(x,y,z) = Coordinates of any point
θ = Angular distance of any cross-section from the apex in degrees (Angle measured from the apex towards the support)
ϕ = Semi-central angle / Half angle of the shell
υ = Poission's ratio of the material

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