Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division VI: Paper ID# 281

REPAIR OF DELAMINATED PRESTRESSED CONCRETE CYLINDERS USING POST-INSTALLED ANCHORS: PART I – RADIAL TENSION DEMAND AND FEM ANALYSIS

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ABSTRACT

For prestressed concrete cylindrical structures such as nuclear containments, tanks and silos, the curvature effect of the tendons introduces radial tensile stresses in the concrete shell which are generally neglected in the design of such structures. These structures are generally reinforced in the circumferential (hoop) and meridional (vertical) directions but not in the radial direction. This leaves these structures vulnerable to potential laminar cracking and delaminations during their life. In case of nuclear containments, such delaminations can also compromise the safety and leak tightness. Should delamination occur, the structure needs to be repaired by either replacing cracked concrete or by "pinning" the delaminated concrete layers together by post-installed anchors. The latter option of post-installed anchors is less invasive from construction stand point and generally suitable for repairing small or localized delaminations only. A comprehensive study is undertaken to explore various aspects and design consideration of post-installed anchors for prestressed concrete cylinders. The study is divided into two parts, (1) to develop the radial tension demand of the post-installed anchor and how to design and detail them and (2) the tightness requirement of delamination crack widths for effective use and installation post-installed anchors.

Part I of this study aims at the radial tension demand and design. The radial tension demand is first determined for an uncracked prestressed concrete cylinder using the proposed mechanical based model. Contribution from both membrane forces and unbalanced moments are subsequently added. Influence of existing delamination crack is studied using a detailed finite element analysis. Conclusion and recommendation are provided based on this detailed investigation.

INTRODUCTION

Radial tensile stresses are generally neglected in the design of prestressed concrete cylindrical structures such as nuclear containments, tanks and silos, thus leaves these structures vulnerable to potential laminar cracking and delaminations during their life. Should delamination occur, the structure may be repaired by "pinning" the delaminated concrete layers together by post-installed anchors, which is especially suitable for repairing small or localized delaminations. Obviously, the anchors would need to be designed for the expected radial tension across the crack and may be even the in-plane shear, depending upon the crack width. But there are no guidelines available on crack width that can be bridged, spacing or design force of such radial reinforcement.

A comprehensive study is undertaken to explore various aspects and design consideration of post-installed anchors for prestressed concrete cylinders. The study is divided into two parts, (1) to develop the radial tension demand of the post-installed anchor and how to design and detail them and (2) the tightness requirement of delamination crack widths for effective use and installation post-installed anchors. It is apparent that post-installed anchors would not be very effective for large crack widths of delaminations.

Part I of this study aims at the radial tension demand and design. The radial tension demand is first determined for an uncracked prestressed concrete cylinder using the proposed mechanical based model. Contribution from both membrane forces and unbalanced moments are subsequently added.

Influence of existing delamination crack is studied using a detailed finite element analysis with the crack and post-installed anchor explicitly included. An illustrative example is presented to demonstrate the process of determining radial tension demand of post-installed anchors and crack widening effect. Conclusion and recommendation are provided based on this detailed investigation.

RADIAL TENSION DEMAND FOR AN UNCRACKED PRESTRESSED CYLINDER

For uncracked cylindrical shells with curvature, radial stresses are generated due to the radial components of the fiber stresses. One major contribution to radial stress in prestressed containments, and other similar cylindrical structures such as silos, is the membrane compression in containment shell due to prestressing. Contributing also to radial stress in containments / silos are bending moments that originate due to partially post-tensioning, and / or other design loads such as seismic, wind or localized pressure.

For uniformly prestressed cylinders, radial tension and radial compression, respectively, occur in the outer region and the inner region of the shell, separated by circumferential prestressed cables. Such phenomenon has been studied by several researchers. A ‘smeared-out’ thin cylinder approach was proposed by Derby (1969) to approximately determine the stress pattern across the thickness of the shell for a multiple layer of prestressing. Moreadith and Pages (1983) reported a compression-tension interaction failure in Crystal River Unit 3 Dome delamination. Acharya and Menon (2003) evaluated radial stress distribution in the uniformly prestressed containment using two methods, ‘equilibrium of slice’ and ‘modified lame’, and show that results from the two methods are in conformity with each other. Finite element techniques have also been used by others (Stalnaker and Fugler, 1992; Rajagopalan, et. al., 2001).

Although radial stresses in uniformly prestressed containments / silos have been extensively studied, such results are not sufficient for the purpose of radial reinforcement design. Radial stress due to combination of membrane force and bending moment, during circumstances such as partial prestressing, may sometimes be more critical. This phenomenon has been discussed by some authors for prestressed silo design. However, few attempts have been made to formulate the consequences of radial stress variation. Safarian and Harris (1995) suggested that horizontal radial ties should be provided in order to resist radial stress in partially post-tensioned concrete silo walls. Gurfinkel (2000) proposed a simple formula to design the radial reinforcements in partially post-tensioned silos, in which the post-tensioning tendons are located at centerline of the cylindrical shell.

The three-dimensional (3D) finite element models are extensively used in modern day nuclear prestressed containment analysis / design to meet the expectation in the current nuclear regulation. In such models, concrete containment shells are modeled using 1-2 layers of shell elements or 4-6 layers of brick elements through the thickness of the containment shell. Post-tensioning tendons are taken into account either explicitly as truss elements or implicitly as pressures. The model allows for simulating various design scenarios and calculating design parameters such as membrane, shear forces and moments with adequate accuracy. However, such model is either lacking sufficient layers of elements to capture radial stress variation through the containment thickness (modeled with brick elements), or in case of shell elements, is incapable of producing the radial stress. In order to facilitate design of radial reinforcement using FEM, a very refined mesh through the shell thickness is required which makes the containment model impractical to run. Therefore, it is recommended that radial stress be calculated indirectly and outside the FEM analysis process. Wang and Munshi (2013a) proposed a comprehensive solution of radial stresses in both cylindrical and spherical prestressed concrete shells, which is adopted in this paper.

Consider a cylindrical shell subjected to a general combination of prestress and design loads as shown in Figure 1. Let it be assumed that at a given elevation, circumferential (hoop) membrane force N, circumferential bending moment M, external pressure $\mathrm{p_e}$, and internal pressure $\mathrm{p_i}$ are fully known functions with respect to cylindrical coordinate θ. The 2-D free body diagram of a slice with a small coordinate increment $d\theta$ is then illustrated in Figure 2.

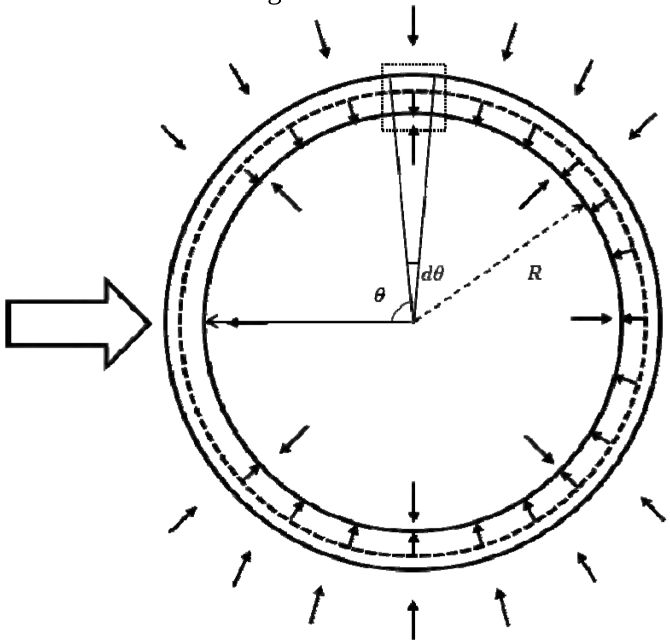

Figure 1. Cylindrical shell subjected to a general combination of prestresses and design loads

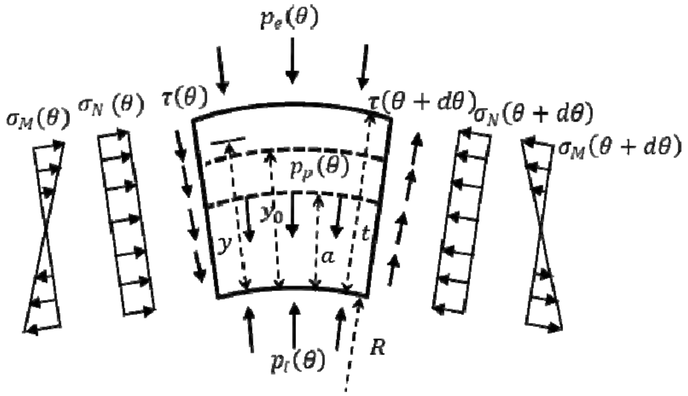

Figure 2. Free body diagram of a slice of shell with respect to $d\theta$

In Figure 1 and Figure 2, σ_N and σ_M are fiber stress in circumferential direction caused by membrane force N and bending moment M, respectively; Coordinate y denotes fiber distance measured from inner surface of the shell; p_p represents the radial pressure induced by curved post-tensioned tendons on concrete, located at $y = a$, in which a is the location of tendon centerline; R and t are cylinder shell inner radius and shell thickness, respectively; τ denotes the radial shear stress which is conventionally negligible in the design of nuclear prestressed concrete containment. Sign conventions are as illustrated in Figure 2.

With respect to a small $d\theta$, a mechanics solution of radial stress $\sigma_R(y_0, \theta)$ (positive for tension) at location $y = y_0$ may be developed by summing radial forces of a sub-slice measured from y_0 to t as (Wang and Munshi, 2013a):

$$\sigma_R(y_0,\theta) = \left| \begin{array}{ll} \sigma_{R0}(y_0,\theta) - \ p_e(\theta) & a^+ \leq y_0 \leq t \\ \sigma_{R0}(y_0,\theta) - (p_e(\theta) + p_p(\theta)) & 0 \leq y_0 \leq a^- \end{array} \right. \qquad (1)$$

Where $\sigma_{R0}(y_0,\theta)$ is given by [8]:

$$\sigma_{R0}(y_0,\theta) = N(\theta)\frac{(t-y_0)}{t(R+y_0)} + M(\theta)\frac{6y_0(t-y_0)}{t^3(R+y_0)} \qquad (2)$$

Eq. (1) in conjunction with Eq. (2) provides formulae method to calculate radial stresses in cylindrical shell of prestressed concrete containments. External pressure $p_e(\theta)$, and internal pressure $p_i(\theta)$ are known as design input. Circumferential (hoop) membrane force $N(\theta)$ and bending moment $M(\theta)$ could be obtained through analysis of the structure using any conventional method. The radial pressure induced by curved post-tensioned tendons on concrete, p_p is also a known constant if the containment is uniformly prestressed. In the case of a partially prestressed containment, $p_p(\theta)$ may be back calculated by summing radial forces of the whole slice in Figure 2, i.e. (Wang and Munshi, 2013a)

$$p_p(\theta) = \frac{N(\theta)}{R+a} - p_e(\theta) + p_i(\theta) \qquad (3)$$

Due to $p_p(\theta)$, radial stress $\sigma_R(y_0,\theta)$ (positive for tension) indicates a sudden drop at $y_0 = a$, as demonstrated in Eq. (4). Hence, radial tension within outer layer ($y_0 > a$) is generally more critical for the purpose of radial reinforcement design, than the one within inner layer ($y_0 < a$) (Wang and Munshi, 2013a)

$$\sigma_R(a^+,\theta) - \sigma_R(a^-,\theta) = p_p(\theta) \qquad (4)$$

For design of radial reinforcement in uncracked prestressed concrete cylindrical shells, the maximum radial tension is given by

$$\sigma_R^{\max} = \sigma_R(y_0 = a^+,\theta) = N(\theta)\frac{(t-a)}{t(R+a)} + M(\theta)\frac{6a(t-a)}{t^3(R+a)} - \ p_e(\theta) \qquad (5)$$

External pressure $p_e(\theta)$ is known as design input. Circumferential (hoop) membrane force $N(\theta)$ and bending moment $M(\theta)$ should be obtained via strength design load combinations, either using a practical finite element model or alternative analysis approaches with sufficient accuracy. The tensile demand of one post-installed anchor F may be calculated using the following strength equation:

$$F = A_c\sigma_R^{\max} \qquad (6)$$

In which A_c is the tributary concrete area corresponding to one post-installed anchor; $\sigma_R^{\max}$ denotes maximum radial tension within A_c, calculated using Eq. (5) at the location where delamination occurs.

EFFECT OF EXISTING CRACKS

The design tensile demand of the post-installed anchor established in Eq. (5) and Eq. (6) is based on a mechanical model of an uncracked prestressed concrete cylindrical shell. Should delamination occur, the cylindrical shell is divided as the outer layer and the inner layer separated by existing cracks. For repairing small or localized delamination, existing hairline cracks between the outer and inner layers are expected to be tight and able to transfer shear and compression. The tightness requirement and shear transfer capacity of delamination crack for effective use and installation post-installed anchors is studied in the Part II of this study (Wang and Munshi, 2013b).

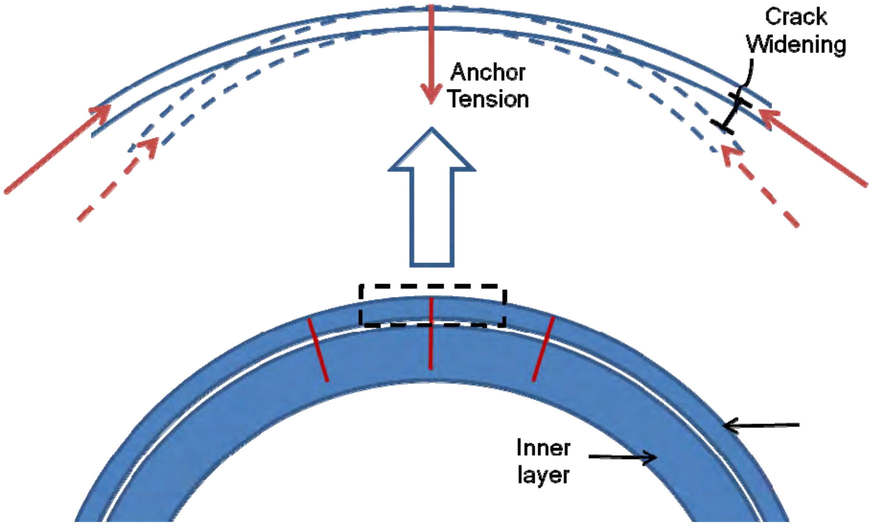

Figure 3. Crack Widening and Radial Force Reduction

The radial tension in a cylindrical prestressed concrete shell is mainly caused by the curvature effect of the tendons. In order to install post-installed anchors and repair the delamination, the structure should be properly detensioned to a "stress-free" condition so the existing hairline cracks are expected to be "closed".

After installation of post-installed anchors, the post-tensioning load should be applied and radial tension between inner and outer layers will be carried through radial anchors. It is expected that existing hairline cracks will be reopened at locations away from anchors and such widening effect could be calculated using the parametric finite element model proposed below. It is also worth mentioning that any residual crack width observed in the detensioned structure should be added to the calculated widening effect to obtain the total crack width, i.e.

$$w = w_r + w_p \qquad (7)$$

In which:

w : maximum crack width of delaminated structure after repair
w_r : observed residual crack width in the detensioned structure, ideally equals to 0
w_p : crack widening effect

See Figure 3 for illustration. Correspondingly, the design tensile demand of the post-installed anchor established in Eq. (5) and Eq. (6) is expected to be reduced. Such phenomena need to be taken into consideration for design of post-installed anchors. The magnitude of this crack widening depends on anchor / reinforcement spacing, stiffness of both anchor and outer layer of containment, and locations of the anchor as well as tendon conduits. A detailed parametric three dimensional (3D) finite element model illustrated in Figure 4 is used to study this phenomenon.

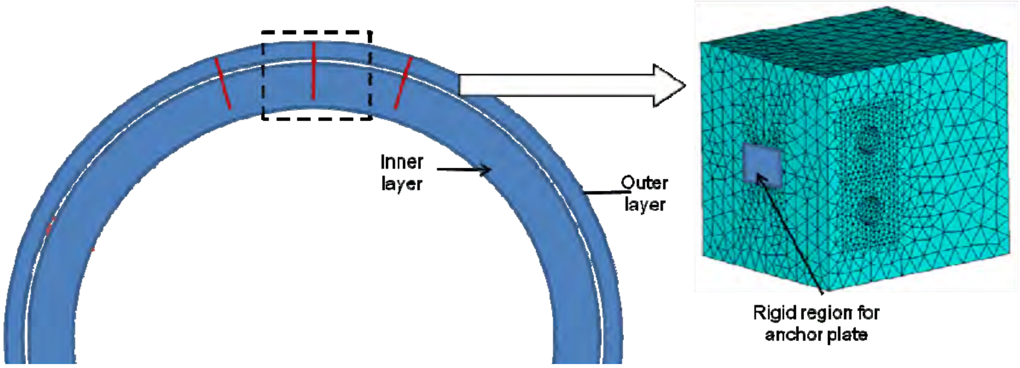

Figure 4. Finite Element Model for One Radial Anchor

The model is created using ANSYS Ver. 13, and represents a concrete segment tributary to one radial anchor. The anchor rod, the existing crack and penetrations of tendon conducts are explicitly included. The concrete portions of the model were modeled with element type SOLID186, which is a 3D 20-node structural solid (brick) element. This element type is well suited to model irregular meshes since it supports a pyramid shape. Using brick elements allows capturing a nonlinear stress distribution in the concrete. The radial anchor is modeled with element type BEAM188, which is a linear, quadratic, or cubic two-node beam element in 3-D. The hairline crack at the boundary between inner and outer layers of the cylindrical shell is modeled using double-node sets. Each double-node set is coupled in tangential direction, and connected by the nonlinear spring element COMBIN39. Coupling feature ensures shear force carried between two layers. A nonlinear force-deflection behavior has been assigned to nonlinear spring element COMBIN39, so that only compression but no tension is carried crossing the existing crack. Radial tension between inner and outer layers can only be carried through the radial anchor, which is modeled explicitly. The initial crack width should be set as zero to represent an idealized stress-free circumstance after the detensioning of the structure. A refined mesh is used for the surrounding regions of the anchor and tendon conduits' penetration. A detail view of meshing along the center plane of the model (where the anchor is located) is presented in Figure 5. Shared nodes between beam elements and solid elements provide bonding mechanism between anchor and concrete. To simulate the effect of the anchor head, a rigid region is also defined. Boundary conditions should be carefully established to represent reaction of rest of the structure, based upon geometry and loading characterization.

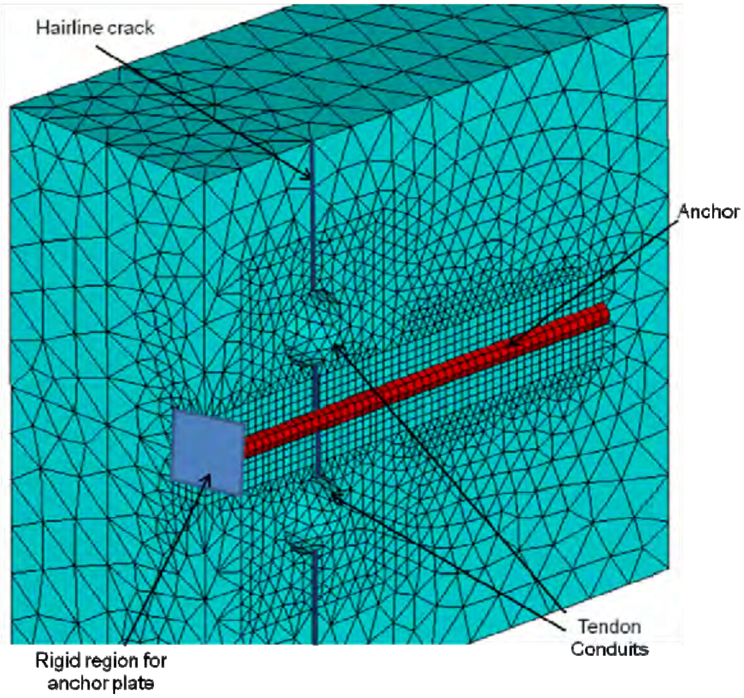

Figure 5. Mesh Detail along Center Plane

The model is created using ANSYS Parametric Design Language (APDL) such that material properties, concrete and anchor rod dimensions, locations of the anchor, crack and tendon conduits are defined as input parameters. Therefore, the model could be easily revised and applied into various design cases.

ILLUSTRATIVE EXAMPLE

In this section, a practical example of a delaminated cylindrical prestressed concrete shell subject to uniform prestress is presented to demonstrate the process of determining radial tension demand of post-installed anchors and crack widening effect. Assume a cylindrical prestressed shell, design parameters are set to be $\mathrm{t} = 3.5$ ft, $\mathrm{R} = 70$ ft, and $\mathrm{a} = 32$ in with assumed design pressure of $\mathrm{p_p} = 100$ psi. Concerning prestressing load only as an example, it follows that $\mathrm{N(\theta) = p_p(R + 0.5t) = 86.1\ kip/in}$, and $\mathrm{M(\theta) = 0}$. The maximum radial tension in uncracked prestressed concrete cylindrical shell is given by Eq. (5) as

$$\sigma_R^{\max} = N(\theta)\frac{(t-a)}{t(R+a)} = 24.1\ \text{psi} \qquad (8)$$

Assuming the anchor pattern with spacing of 36in × 36in, the tributary concrete area corresponding to one post-installed anchor $\mathrm{A_c} = 36 \times 36 = 1296\ \mathrm{in}^2$, and it follows from Eq. (6) that the tensile demand of one post-installed anchor,

$$F = A_c\sigma_R^{\max} = 31.2\ \text{kip} \qquad (9)$$

The effect of the delamination crack is studied using the detail 3D finite element model demonstrated in Figure 4 and Figure 5. As an example, two tendon ducts penetrations with diameter of 5” are included in the model. For illustration purpose, let it also be assumed the delamination crack is located at the centerline of tendon ducts. Prestressing is applied at boundaries as well as locations of tendons as pressure. Symmetrical boundary conditions are applied at top, bottom and both sides of the model to simulate reactions from the rest of the structure. The contour of radial displacement is shown in Figure 6. As expected, a displacement “jump” is observed across the hairline crack, which indicates widening of the existing hairline crack. By measuring the deflection difference in “coincident” nodes, it is found that the maximum crack widening occurs at far side away from the anchor, with the value of $w_p = 0.006$ in. Assuming an idealized circumstance that $w_r = 0$, it follows from Eq. (7) that the maximum crack width after repair $w = 0.006$ in. This value is within the threshold by which a “hairline crack” may be defined, with considerable margin. The hairline crack threshold is further investigated in the Part II of this study [9].

The maximum anchor axial tension is obtained as 28 kip. The difference between the FEM analysis result and the one from Eq. (8) may be explained by observed crack widening and corresponding constraint demand relief, as well as Poisson’s effect. Conservatively, it is suggested that this reduction effect be neglected for radial anchorage design purpose.

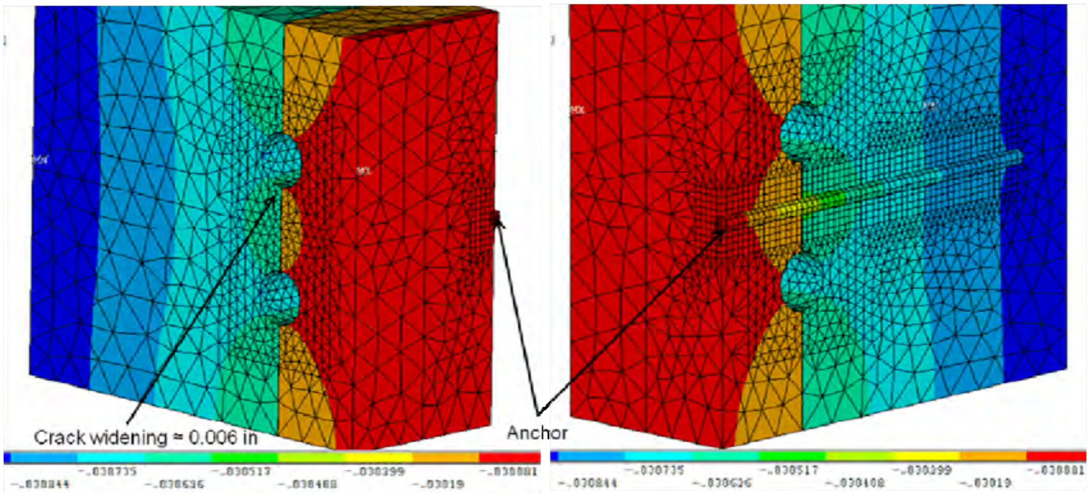

Figure 6. Contour of Radial Displacement

CONCLUSION

Radial tensile stresses are generally neglected in the design of prestressed concrete cylindrical structures such as nuclear containments, tanks and silos. This leaves these structures vulnerable to potential laminar cracking and delaminations during their life. Small or localized delaminations could be repaired by “pinning” the delaminated concrete layers together by post-installed anchors.

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