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EVALUATION OF LOCAL DETENSION IN PRESTRESSED NUCLEAR CONTAINMENT USING DETAILED FINITE ELEMENT ANALYSIS

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ABSTRACT

Nuclear containments are critical components for safety of nuclear power plants. Failure of such structures can result in catastrophic safety consequences as a result of leakage of radiation. The containments are generally either steel, reinforced concrete or prestressed concrete depending upon the diameter and internal design pressure. Prestressed concrete containments have been used in large nuclear containments with significant design internal pressure. In these containments, externally applied force in the form of prestressed tendons is applied to counter the internal design pressure due to LOCA (loss of coolant accident) and other accident loads. The tendons once placed within the concrete, are stretched and locked off against the ends of the concrete. During the life circle of a prestressed concrete containment, localized tendon detensioning may occur as results of surveillance, tendon maintenance, or tendon failure. Should such an incident happen, it is not likely to affect the global behavior of the containment, but its local effect may need to be evaluated. This timely evaluation is discussed in this paper, however the ultimate disposition of the power plant would be subject to the rules of the applicable regulatory agency.

A simple but accurate approach is presented in the paper to evaluate the effect of an accident with several adjacent tendons detensioned. In lieu of modeling the whole containment, a localized 3D finite element model (FEM) is created to study this phenomenon by carefully choosing applied boundary conditions. The model is developed using parametric coding so that it can be easily revised and applied to various design cases. Results of FEM analysis are interpreted using established formula and then the evaluation is carried out. It is concluded that such explicit finite element evaluation is worthwhile in developing a higher degree of confidence with expected performance of the containment.

INTRODUCTION

Nuclear concrete containments are intended to provide a leak-tight boundary against accident pressure loading which essentially dictates the generally used cylindrical shape. The size of the containment and available free volume depends upon equipment layout and operational requirements. In general, conventionally reinforced concrete containments have been used for small containments with low to moderate internal design pressure, while large containments with relatively high internal design pressure require a prestressed concrete. Prestressing is required when containment pressure requirements become large, and the consequent design loads (causing high tension demand within the containment shell) cannot be handled by conventional reinforced concrete.

Design of concrete containments in the United States is now carried out under ASME Section III, Div 2 Code (2010) for Concrete Containments - Joint ACI/ASME Technical Committee on Concrete Pressure Components for Nuclear Service under the sponsorship of the American Concrete Institute and the American Society of Mechanical Engineers. The two Societies have agreed that requirements for concrete containments will be published as Section III, Division 2, of the ASME Boiler and Pressure Vessel Code. Prestressed concrete containments are cylindrical structures with a hemispherical or torospherical dome and a flat basemat slab with a tendon gallery running under the cylindrical wall (ASCE SP-58, 1980). As indicated above, prestressing is required when containment pressure requirements become large and the consequent design loads cannot be handled by conventional reinforced concrete. Early prestressed containments in the United States, such as those used at Palisades and Turkey Point were designed for 1.5 times the accident design pressure. They consisted of a cylinder, shallow dome with a ring girder and 6 vertical buttresses. The ring girder is provided to accommodate vertical and dome prestressing tendons end anchorages. The buttresses are used to accommodate hoop prestressing tendons end anchorages. The prestress level was subsequently reduced to 1.2 times the accident design pressure with 3 buttresses and about 1000 ton capacity tendons. ASCE SP-58 (1980), ACI 349 (2013), Munshi, et.al. (2013), Stevenson (1989), Kohli and Gurbuz (1976), BC-TOP-5A (1975), NUREG/CR-6906 (2006) and NUREG/CR-6810, give detailed discussion on various aspects of prestressed containment design and testing.

During the life cycle of a prestressed concrete containment, localized tendon detensioning may occur asa result of surveillance, tendon maintenance, or tendon failure. Should such an incident happen, it is unlikely to affect the global behavior of the containment, but its local effect may need to be evaluated. In particular for an unintended accident with several adjacent tendons detensioned, an on-time assessment should be performed within a short period in order to ensure that the containment is still capable of performing its safety function. Otherwise the power plant needs to be shut down. The three-dimensional (3D) finite element models are extensively used in modern day nuclear prestressed containment analysis to meet the expectation in the current nuclear regulation. Creating a 3D FE model of the whole containment, however, is time consuming and thus not suitable for the urgent assessment should an unintended accident with several adjacent tendons detensioned occurs. In this paper, a simple but accurate approach is presented to evaluate effect of an accident with several adjacent tendons detensioned. In lieu of modeling the whole containment, a localized 3D finite element model (FEM) is created to study this phenomenon by carefully choosing applied boundary conditions. The model is developed using parametric coding so that it could be easily revised and applied to various design cases.

An assumed accident case which may occur in a typical prestressed nuclear containment is demonstrated as an example in the paper to facilitate presentation and discussion of the proposed approach. Results of FEM analysis are interpreted using established formula and then the evaluation is carried out. Although the resultant data is limited to this fictitious case, the purpose is to illustrate an engineering practice which can be applied in real accident cases. It is concluded that such explicit finite element evaluation is worthwhile in developing a higher degree of confidence with expected performance of the containment.

EXAMPLE CASE DESCRIPTION

Consider a prestressed concrete containment illustrated in Figure 1, with design parameters presented in Table 1.

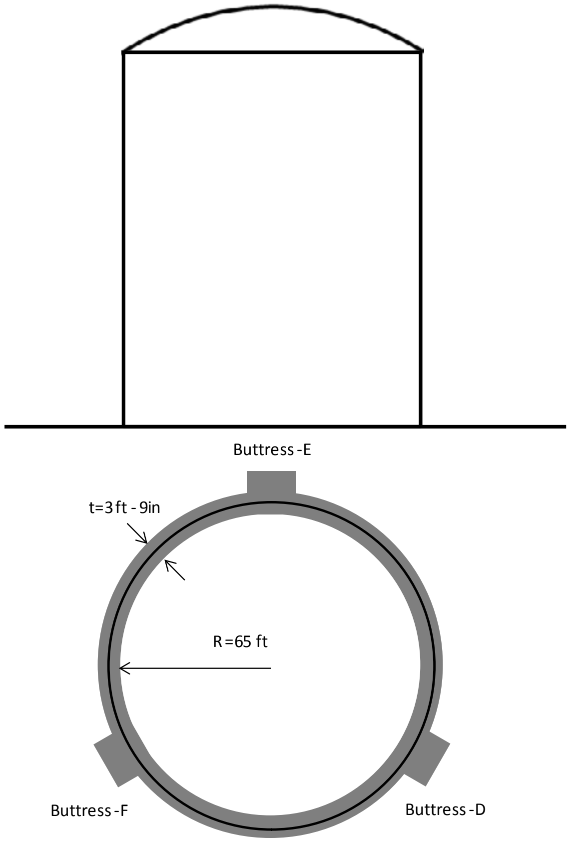

Figure 1: Illustrative example of a prestressed concrete containment

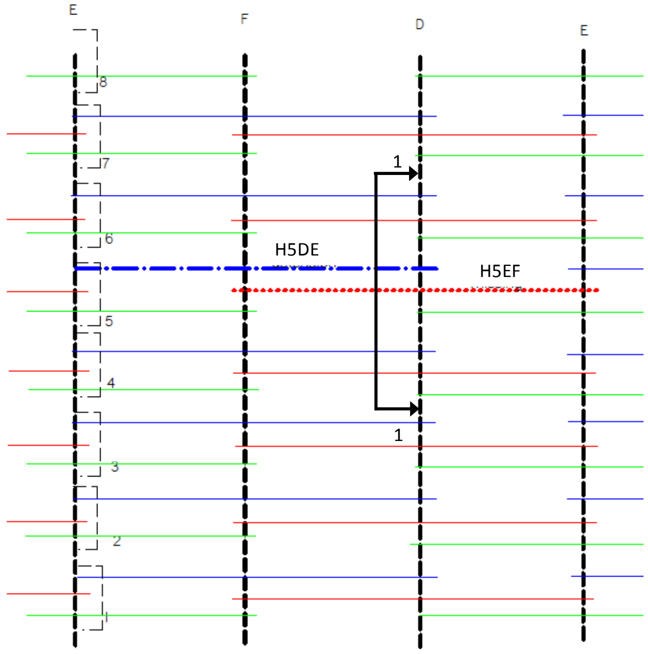

Figure 2: Elevation view of hoop tendons

Table 1: Design Parameters

Parameters	Values	Notes
R	65 ft	Cylinder radius
t	3 ft – 9 in	Shell thickness
T	1100 kip/tendon	Remaining hoop tendon force when accident occur
s	19.125 in	Hoop tendon spacing (average)
$F=T/s$	690 kip/ft	Remaining hoop prestress
p	54 psi	LOCA pressure

The elevation view of hoop tendons is shown in Figure 2, with buttresses D, E and F demonstrated as three dash lines D, E, and F respectively. As shown in Figure 2, each hoop tendon covers two “panels” and a group of three tendons comprise a 360 degree circle. Such a group is denoted by a number in Figure 2, as Group 1, Group 2, etc. In any “panel” covered by such a tendon group, there will be two tendons which impose radial pressure on the concrete segment.

By way of an example, let it be assumed that two adjacent tendons H5DE and H5EF were accidentally detensioned. “H” stands for horizontal tendon; “5” is the number of the tendon group; “D” and “E”, “E” and “F” are buttress IDs where these tendons start and end, respectively. The concern is whether these two tendons being inactive could create an unsatisfactory plant condition.

In a prestressed cylindrical concrete shell, hoop tendons impose radial pressure on concrete, which then induces hoop stress within the shell. For a condition with two relatively adjacent hoop tendons to be temporarily detensioned at the same time, localized hoop prestress reduction is expected. In particular, the region of most concern is between buttresses D and F, at the elevation where tendons detensioned (H5DE & H5EF) are located (Section 1-1 in Figure 2).

As demonstrated in Figure 3, this region (Section 1-1) may “bulge out” locally in radial direction, due to lacking radial pressure from detensioned tendons. However, because of the compatibility with sections above and below, this region will continue to maintain considerable magnitudes of compression strain and stress in hoop direction. A three dimensional (3D) finite element model is developed to further investigate the remaining hoop prestress in the containment.

FINITE ELEMENT MODEL

A 3D finite element model (FEM) is developed using ANSYS Version 13.0 (2013), as shown in Figure 4. The model represents a concrete segment tributary to 39 hoop tendons (groups H1 - H13). Note each hoop tendon group includes three tendons (DE, EF and FD as shown in Figures 2 and 3). The FE model was generated using a coordinate system with its origin at the center of the containment cross section. The global X and Y axes are oriented along the assumed N-S and E-W directions, respectively, and the global Z-axis is oriented in vertical direction (positive up).

The ring including the containment cylindrical wall and buttresses was modeled with element type SOLID185, which is a 3D 8-node structural solid (brick) element. Using brick elements allows predicting a nonlinear through-thickness stress distribution in the wall. A detail view of meshing is presented in Figure 5. There are a total of 8 layers of solid elements through the thickness of the cylindrical wall, with additional 6 layers of elements for buttresses. Symmetrical boundary conditions are applied at top and bottom to simulate reaction from the rest of the structure. This boundary condition is rather accurate for problematic segment located in the middle of the containment, i.e., away from the dome and basemat. If the accident scenario occurs near the dome or basemat, on the other hand, using the proposed boundary condition is still conservative because the additional constraints from the dome or basemat will further limit the "bulge out" deformation due to detension (see Figure 3). The model is generated using ANSYS Parametric Design Language (APDL) so that it could be easily revised and applied to various design cases.

Hoop prestress generated by any 1 of 39 tendons in the modelled concrete segment is simulated by applying uniform pressure between two buttresses 240-degree apart and anchorage forces on the far edges of these buttresses. The pressure is applied uniformly through the height of the segment tributary to one hoop tendon group, at the location of hoop tendons.

Results of finite element analysis are summarized in Figures 6 thru 8, in terms of hoop prestress.

As expected, the lowest hoop prestress is observed in the region between buttress D and F, at the elevation where tendons detensioned (H5DE & H5EF) are located. The minimum average hoop prestress is 160 ksf, which is equivalent to 600 kip/ft. It is also worth mentioning that this hoop stress magnitude is localized within an area with a height less than 4 ft. In the rest of the cylinder, the average hoop stress is generally larger than 166 ksf (620 kip/ft).

Due to the unbalanced moment introduced by unsymmetrical post-tensioning loads, a localized hoop stress of 145~150 ksf is also observed near the buttress.

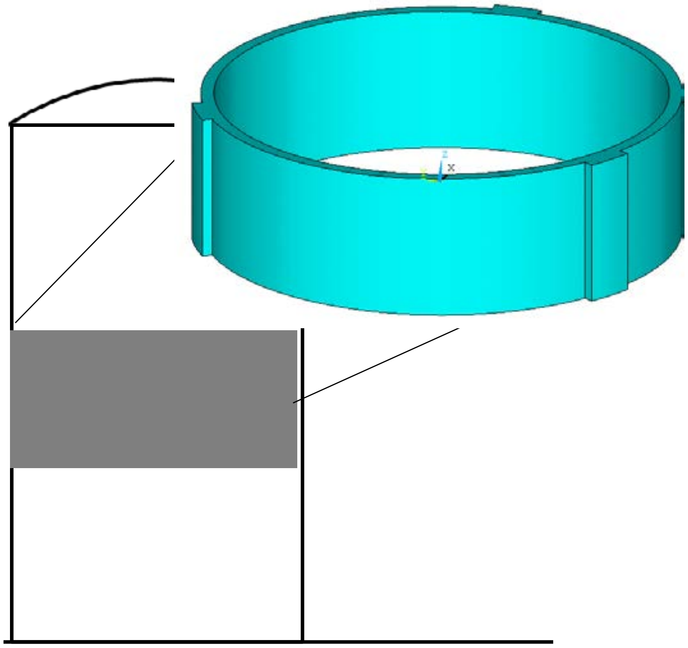

Figure 4: Cylindrical segment represented by FEM

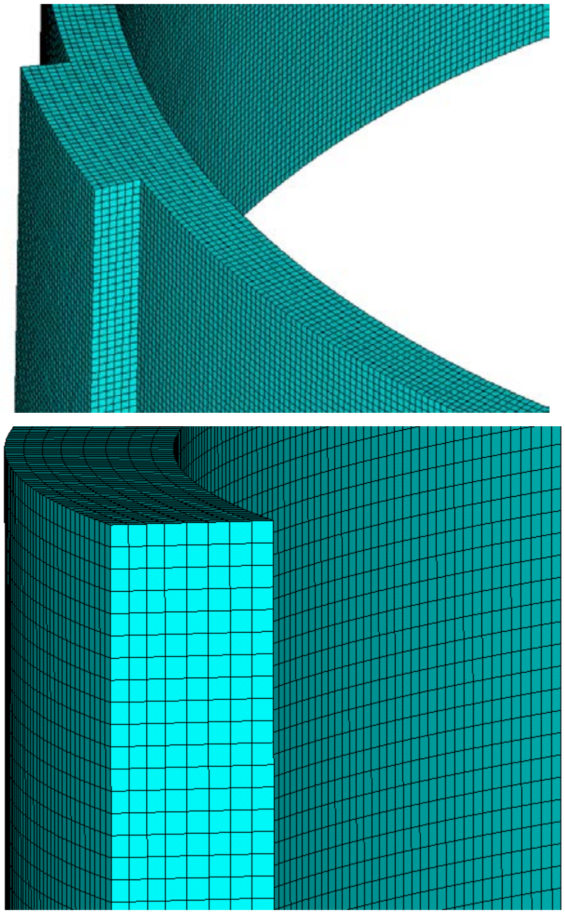

Figure 5: Mesh Detail in FEM

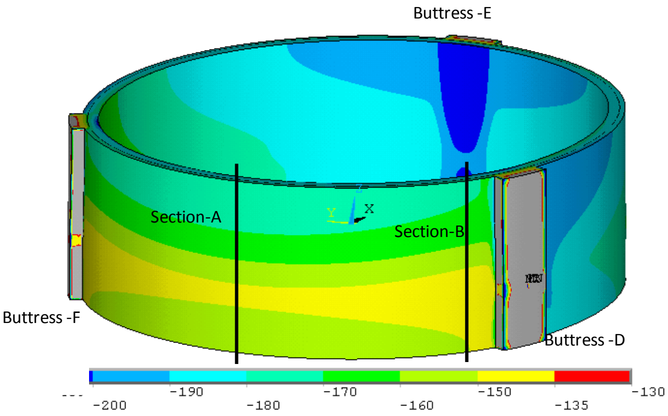

Figure 6: Global contour plot of hoop prestress

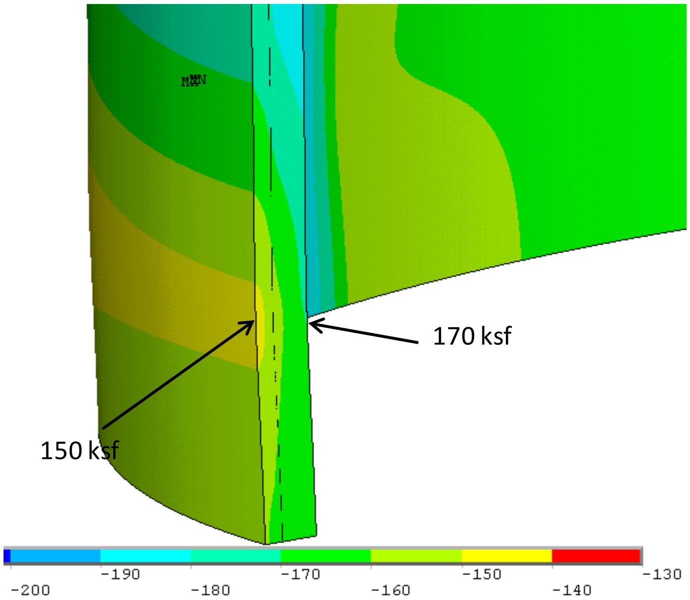

Figure 7: Contour plot of hoop prestress at Section A

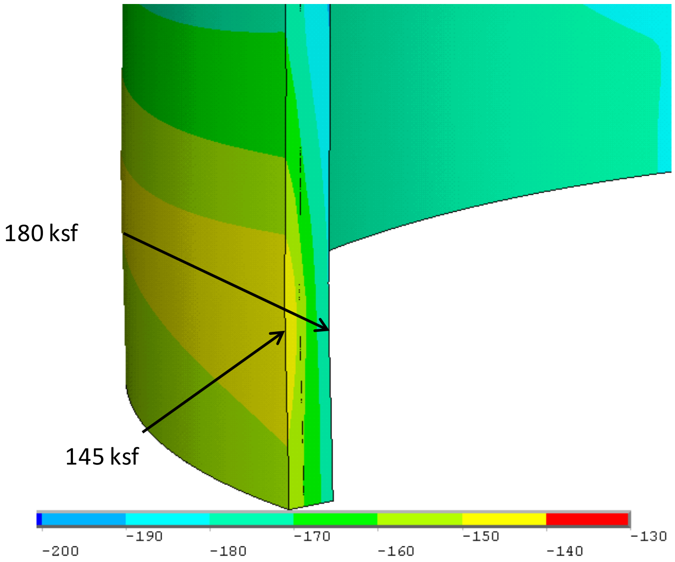

Figure 8: Contour plot of hoop prestress at Section B

EVALUATION AND DISCUSSION

The containment design pressure is p = 54 psi based on pressure transients resulting from a LOCA which, by a simple calculation, results in an effective tension on the cross section of:

$$\sigma_c = \frac{p \times 2R}{2t} = 936\text{psi} \quad (\text{or } 134.8 \text{ ksf})$$

Where: σ_c = concrete stress in psi (positive as tension) due to an internal pressure "p"

R = containment internal radius = 65 ft

t = concrete wall thickness = 3'-9" or 45"

Converting this value to kip/ft (P):

$$P = \frac{\sigma_c \times 45in}{1000\frac{lb}{kip}} \times 12\frac{in}{ft} = \frac{936psi \times 45in}{1000\frac{lb}{kip}} \times 12\frac{in}{ft} = 505\ \frac{kip}{ft}$$

Thus the hoop tension, without prestress, is *505* kip/ft during an accident condition. The effective prestress is needed to produce a compression stress in the concrete that is at least this great, or greater (as discussed below) during the accident condition.

Based on a current 1100 kip average tendon force with an average hoop tendon spacing of 19.125”, the compression stress in the concrete due to the tendons is:

$$F\ = \frac{1100\ kip}{19.125in} \times 12\frac{in}{ft} = 690\ \frac{kip}{ft}\ \ (or\ 184\ ksf)$$

The actual current prestress level is about 690/505 = 1.37 which exceeds the design limit. The analysis results show that generally in the area of the detensioned tendons the effective prestress locally is reduced to about 600 kip/ft, which means that the effective prestress is about 600/505 = 1.19 , which is slightly below the original design value of 1.23 but close to the generally-accepted guideline of 1.2. There is a condition, very local, near the buttress where the effective prestress reduces to 145~150 ksf. This locally becomes less than the guideline of 1.2 prestress level, but since the prestress (compression in the concrete) remains higher than the potential tension in the concrete due to the accident pressure, the concrete, even in this local area, will remain in a general state of compression, which is the ultimate objective of the post-tensioning process.

In conclusion, based on the discussion in the body of this paper, having two adjacent tendons inactive will not create a condition that would violate the design, however the ultimate disposition of the power plant would be subject to the rules of the applicable regulatory agency. Although there are very localized areas where it cannot readily be shown by simple calculation that a 1.2 prestress level is maintained, a general state of compression will be maintained, thus the containment can withstand an accident pressure at least equal to the design pressure.

CONCLUSION

In this paper, a simple but accurate approach is presented to evaluate effect of an accident with several adjacent tendons detensioned. In lieu of modeling the whole containment, a localized 3D finite element model (FEM) is created to study this phenomenon by carefully choosing applied boundary conditions. The model is developed using parametric coding so that it could be easily revised and applied to various design cases. Results of FEM analysis are interpreted using established formula and then the evaluation is carried out. An example is provided to illustrate the use of the proposed methodology which may be useful during design or evaluation. It is concluded that such explicit finite element evaluation is worthwhile in developing a higher degree of confidence with expected performance of the containment. Future investigations will compare the results from this paper with those from detailed full size finite element analysis.

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