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FINITE ELEMENT ANALYSIS AND DESIGN OF LARGE OPNEINGS IN PRESTRESSED CONCRETE NUCLEAR REATOR CONTAINMENT STRUCTURES

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ABSTRACT

Large openings are categorized as having a diameter greater than or equal to two and half (2½) times the containment thickness. In a nuclear containment structure, the personnel air lock and equipment hatch openings fall into this category. A large opening with increased wall thickness causes geometric discontinuity of a cylindrical containment and results in deviation from the stress resultant of the membrane ideal. This paper provides guidelines for achieving an effective structure design at the discontinuity.

The critical loads to be considered are prestress, pressure, thermal, dead and seismic loads. In order to be more realistically to represent the behavior of structures under various load cases and more accurate to evaluate the local stresses around the opening, the opening is modeled as a segment of the full containment structure with layers of solid elements. It can represent the local stiffened wall around the opening. It allows properly applying the post-tensioning forces due to the deflected tendons and considering the non-linear temperature distribution due to LOCA. Finite element modeling, analysis results, thermal moment relaxation and the optimum design procedures per ASME code will be presented.

INTROUDUCTION

Large openings are categorized as having a diameter greater than or equal to two and half (2½) times the containment thickness. In a nuclear containment structure, the personnel air lock and equipment hatch openings fall into this category. The cylindrical containment is structurally ideal for a pressure vessel because the stress condition in the wall resulting from the single most important design load, the internal pressure, is almost purely membrane. A large opening with increased wall thickness causes geometric discontinuity and results in deviation from the stress resultant of the membrane ideal. It disrupts a great amount of typical membrane rebar and causes large discontinuity forces, moments and shears. Design of a typical equipment hatch opening in a PWR concrete containment will be used in this paper for illustrating the modeling, analysis and optimum design procedures per ASME code.

FINITE ELEMENT MODELING OF STRUCTURE

The overall containment structure considered in this paper is approximately 213 feet in height with an outside radius R_o = 77 feet. The center of equipment hatch opening is located at 74.25 feet above the basement of the containment. The radius of hatch opening is R_{open} = 11.5ft. The thickness of the containment wall is typically 4 feet. The area around the opening reaches a thickness of 7.72 feet. In order to be more realistically to represent the behavior of structures under various load cases and more accurately to evaluate the local stresses around the opening, the equipment hatch opening is modeled as a segment of the full containment structure as shown in Figure 1. The segment of the model is a cut in a circumferential direction of 101.3 feet wide with a height of 110.0 feet from the top of mat. This is approximately 75.4 degrees sector of the containment with the opening at the center of the sector. It should be pointed out that the boundaries of the model should have sufficient distances from the opening so that the behavior of the model along the boundary is compatible with that of the undisturbed cylinder.

The finite element model of the concrete wall segment is modeled with four layers of “BRICK” elements through the wall thickness as shown in Figure 2. The mesh layout used to develop the finite element mode is shown in Figure 3. It is on the developed surface of the cylindrical wall segment. The use of layered “BRICK” elements is due to the consideration of thickening around opening, deflected tendons and nonlinear temperature distribution as discussed previously. Tendons are modeled with “TRUSS” elements follow the tendon layout pattern at actual location as shown in Figure 4. Prestressing forces are applied as temperature drops in truss elements. The liner shall not be used as a strength element per ASME code. Therefore, it is excluded from finite element analysis (FEA) model. However, in order to consider the effect of high temperature in liner, a layer of “MEMBRANE” elements is added to the inside layer of finite element model for thermal load analysis.

The boundary conditions and seismic excitation directions are shown in Figure 5.The bottom boundary D is fixed. The top boundary B is free as a forced boundary. The two vertical side boundaries A and C are forced boundaries for Dead and seismic loads. For symmetric loads such as pressure, prestress and thermal loads, they are restrained in circumferential direction.

The three seismic excitations are excitation #1 along X-axis (normal to opening), excitation # 2 along vertical Y-axis and excitation # 3 along Z-axis.

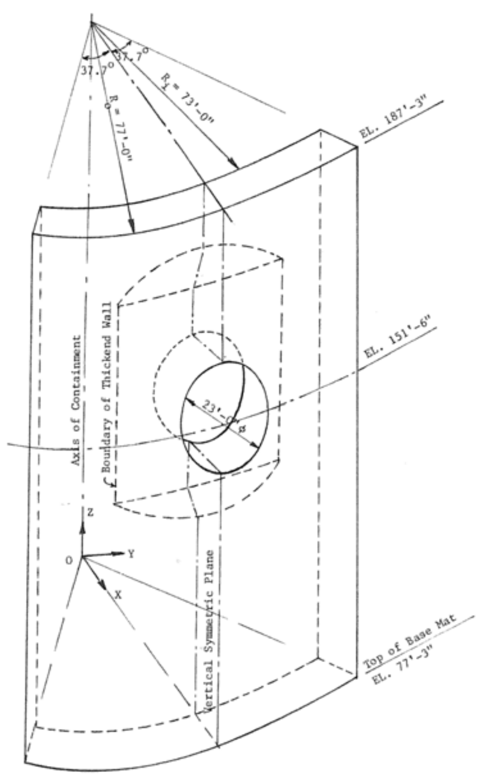

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Figure 1. Segment of containment wall

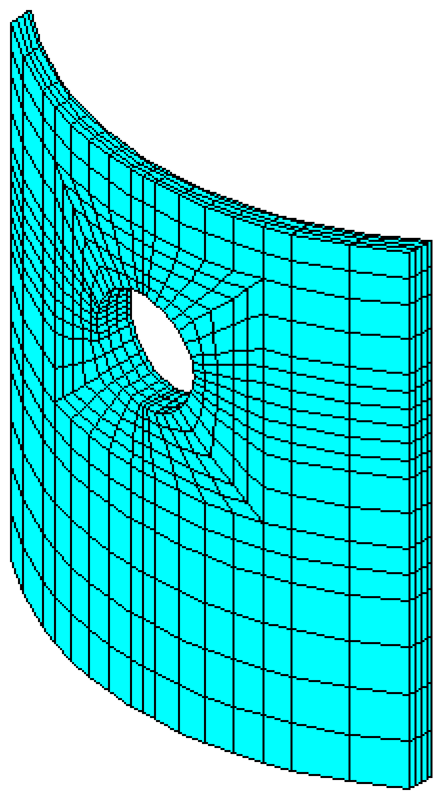

Figure 2. Finite element model

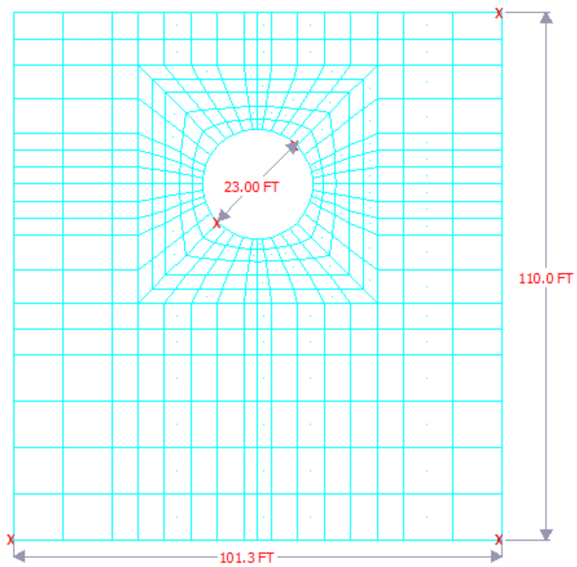

Figure 3. Meshes of FEA model

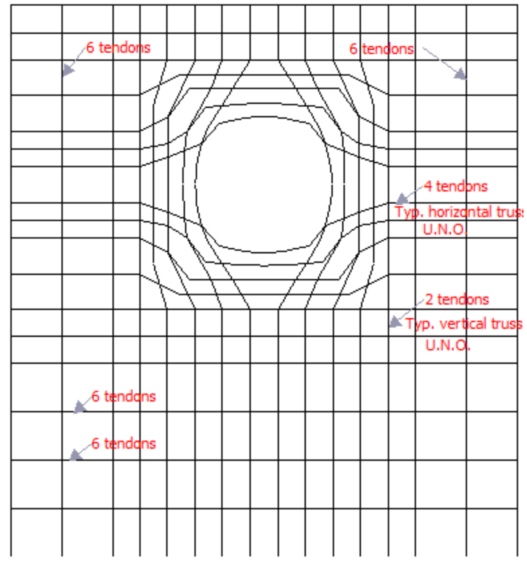

Figure 4. Truss elements for tendons

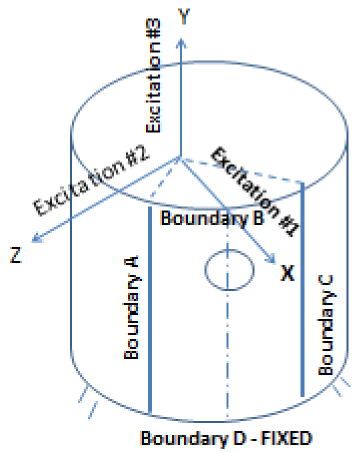

Figure 5. Boundary conditions and Seismic excitations

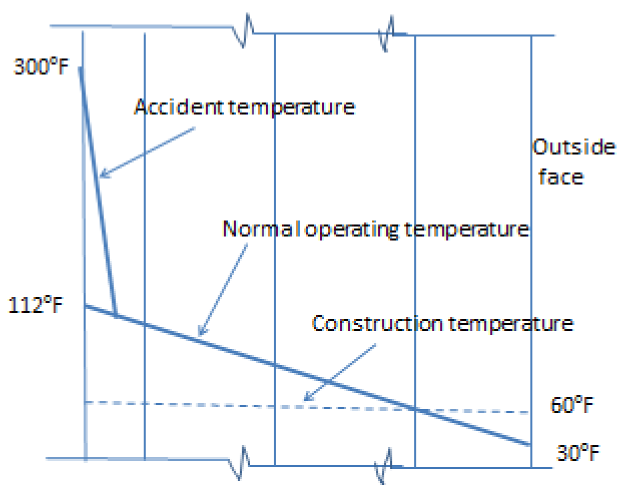

Figure 6. Temperature profiles

MODELING OF LOADS

The critical loads included in this paper are dead load, accidental pressure, prestress, seismic and thermal loads. Wind and tornado loads are excluded from the presentation because they are not governing design loads in comparison with seismic loads.

Dead loads (D)

Dead loads include structural self-weight of the model and total dead weight above the top boundary of the model for upper portion of containment wall, dome and polar crane. The self-weight of the model is applied by specifying the weight density to the model. The total weight above the model is applied as downward uniform pressure (14 ksf) at the top boundary B.

Pressure loads (P)

The internal pressures considered in this paper are Design Basis Accident (DBA) pressure P_a (60psi) and the test pressure P_t. The test pressure is 1.15 times of DBA pressure. Internal pressures are applied on the inside face of wall. The pressure on the hatch itself is applied as concentrated nodal forces at the edge of opening. In addition, a vertical upward uniform pressure is applied as a positive stress at the top boundary B to account for the effect of internal pressure on dome. The intensity of the pressure is calculated as follows:

The total upward pressure acting on dome is:

$F = P(\pi R_i^2)$ where R_i is the inside radius of the containment

The total cross-sectional area of the containment shell is:

$A = \pi(R_o^2 - R_i^2)$ where R_o is the outside radius of the containment

Thus, the uniform distributed upward pressure acting on the top boundary B is $P_b = F/A$.

For R_i = 73ft, R_o = 77ft and ***Pa*** =60psi, the upward pressure at top boundary B is P_b= 76.75ksf.

Prestresss (F)

The vertical and horizontal prestressing forces are applied as pseudo-thermal loads to truss elements as discussed previously. The truss elements are located at the tendon layer with the pattern being the same as that of the actual prestressed tendon pattern as shown in Figure 4. The thin bar force-temperature relationship, $F_{axial} = \alpha E_f A_f(\Delta T)$, is used to achieve an equivalent prestress force. It is noted that α, E_f and A_f are pseudo values for thermal coefficient of expansion, Young's modulus of elasticity and the cross-sectional area of the truss elements. The equivalent prestress force F, can be easily reproduced by assigning a set of α, E_f and A_f. In order to eliminate any secondary stress induced by the existence of truss elements, a small value of elastic modulus "E_f" should be used. Negative temperature differences ΔT for the truss elements are prescribed to give the correct prestressing forces in the hoop and meridian direction independently. As an example, for a prestressing force F =1437kips with E_f =10ksi, A_f=1.0in^2 and α =1.0in/in/^{o}F, then the temperature drop is ΔT= -1437^{o}F.

In the calculation of prestressing force, the loss of prestress due to friction, tendon relaxation, concrete creep and shrinkage are considered. It should be pointed out that in computing the friction loss in the tendon force around the opening, the effect of deflected curvature should be considered.

For the containment structure under consideration, the average stresses F_a are 135.6ksi and 144.28ksi for hoop tendon and vertical tendon, respectively.

For the load combination 1.0*D*+1.5*Pa*, tendon will develop stress up to maximum prestress F_m. Therefore, the usable prestress can be increased to about 1.2 times of the average stress F_a.

It is noted that top boundary B is considered free since the temperature drop itself develops the required prestress inside the model. The two vertical boundaries A and C are restrained in hoop directions.

Thermal load (T)

There are two kinds of temperature profiles to be considered, one is the operating temperature (T_o) profile having a linear temperature distribution through the wall thickness, the other is the accident temperature (T_a) profile which normally a non-linear temperature distribution through the wall thickness. However, a 3D BRICK element generally permits to have only a constant temperature change. In this case, the temperature is specified at element centroid. Figure 5 shows the two types of temperature profiles considered in this paper. An average temperature during construction is also shown in the figure.

A thermal moment should be applied at the top boundary B to account for the continuity of the structure above the model. The thermal moment are obtained from an overall uncracked containment shell analysis. The meridian thermal moments are 1010ft-kips and 560ft-kips for accident and normal operating conditions, respectively. The thermal moment are converted into equivalent couples of nodal forces at the top boundary.

Seismic loads (E)

The seismic loads considered in the analysis are Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE). At the model area, the average accelerations for SSE are 0.45g (horizontal) and 0.34g (Vertical) whereas for OBE are 0.25g (horizontal) and 0.17g (vertical). Each seismic loading has three seismic excitations as shown in Figure 5. The seismic forces applied at the top boundary B can be obtained from a separate dynamic analysis of an overall containment structure. They include the shear force V and moment M due to horizontal excitations and the axial force from vertical excitation. It is noted that the horizontal excitation perpendicular to the hatch (Excitation #1) produces a maximum membrane (meridian) force whereas the horizontal excitation parallel to the hatch (Excitation #3) produces a maximum tangential shear force at the opening area. These distributed forces can be modeled as a series of nodal forces applied at the top boundary. In addition, the inertial loads are applied to the model as acceleration in corresponding directions of excitation

The three directional excitations are analyzed as independently load cases in the finite element analysis. The computed stress resultants for each of the three components of earthquake motion are combined by the square root of the sum method. Alternatively, the component factor load method ($\pm$1.0, $\pm$0.4, $\pm$0.4) may be used.

LOAD COMBINATIONS AND ALLOWABLES

Table CC-3230-1 of ASME Boiler and Pressure Vessel Code (2010) list the load combinations and applicable load factors for which containment shall be designed. The service category includes test, construction and normal operating conditions whereas the factored load category includes severe environmental, extreme environmental, abnormal, abnormal/severe environmental and extreme/severe environmental conditions.

Per section CC-3400, the containment is required to keep basically elastic under service load conditions and below the range of general yield under factored primary loads. The allowable stresses for factored and service compression loads are summarized in Table CC-3421-1 and Table CC-3431-1, respectively. The most probable governing load combinations and design allowable stresses are shown in Tables 1 and 2.

Table 1: Governing Service load combinations and design allowable stresses

Stresses	Load Combinations	Allowable Concrete compression		Allowable Reinforcing		Tendon Allow.	Remarks
		Memb.	Memb. + Bending	Tension	Comp.		
Primary	D + F +Pt	$0.3f'_c$	$0.45f'_c$	$0.5f_y$	$0.5f_y$	$0.8\ f_{pu}$ ($0.94f_{py}$)	Test
	D + F	$0.3f'_c$	$0.45f'_c$	$0.5f_y$	$0.5f_y$	$0.73f_{pu}$	Normal
	D + F + Eo	$0.35f'_c$	$0.45f'_c$	$0.5f_y$	$0.5f_y$	$0.73f_{pu}$	Serve Envir.
Primary Plus Secondary	D + F + To	$0.45f'_c$	$0.60f'_c$	$0.67f_y$	$0.67f_y$	$0.73f_{pu}$	Normal
	D + F + Eo + To	$0.45f'_c$	$0.60f'_c$	$0.67f_y$	$0.67f_y$	$0.73f_{pu}$	Serve Envir.

Table 2: Governing Factored load combinations and design allowable stresses

Stresses	Load Combinations	Allowable Concrete compression		Allowable Reinforcing		Tendon Allow.	Remarks
		Memb.	Memb. + Bending	Tension	Comp.		
Primary	D + F + Ess	$0.60f'_c$	$0.75f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Extreme Envir.
	D + F + 1.25Pa + 1.25 Eo	$0.60f'_c$	$0.75f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Abnomal/ Serve Envir.
	D + F +1.5Pa	$0.60f'_c$	$0.75f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Abnomal
	D + F +Pa +Ess	$0.60f'_c$	$0.75f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Extreme/ Serve Envir.
Primary plus Secondary	D + F + To +Ess	$0.75f'_c$	$0.85f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Extreme Envir.
	D + F + 1.25Pa + Ta + 1.25 Eo	$0.75f'_c$	$0.85f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Abnomal/ Serve Envir.
	D + F + 1.5Pa + Ta	$0.75f'_c$	$0.85f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Abnomal
	D + F + Pa + Ta + Ess	$0.75f'_c$	$0.85f'_c$	$0.9f_y$	$0.9f_y$	$0.9f_{py}$	Abnomal/ Extreme Envir.

FINITE ELEMENT ANALYSIS

Finite element analysis is carried out for all individual mechanical and thermal loads. The allowable stresses for primary loads are different from primary plus secondary (thermal) loads as shown in Tables 1 and 2. Therefore, mechanical loads, excluding thermal loads, are combined for service and factored load combinations. The mechanical load combinations are then combined with thermal loads during design phase. It is noted that the thermal moment from FEA analysis results are based on the uncracked concrete section. The thermal moment will be decreased due to concrete cracking. The calculation of cracked thermal moment will be discussed in following section.

The FEA analysis results of BRICK elements are stresses at element centroids. Element stresses need to be integrated through the containment wall thickness to obtain stress resultants for concrete design. General FEA programs do not have the capability of converting element stresses to element stress resultants of bending moments, shears and axial forces on the cross-section. Therefore, Bechtel in-house program BSAP (Bechtel Structural Analysis Program) is used for analysis. It integrates with a post processor program RESULT to calculate the stress resultants through the wall thickness systematically for each mesh shown in Figure 3. As discussed previously in the modeling section, each mesh has four layers of BRICK elements. For thermal load cases, additional layer of MEMBRANE elements is included.

The stress resultants from FEA analysis are presented in Figures 7 through 12. The sign conventions in the figures are positive moment causing tension at outside face of the concrete wall and the positive force causing tension on the section. Figures 7 shows the uncracked accidental and operating thermal moments. The stress concentration factors are about 3.0 for thermal moments. Pressure and prestress forces are shown in Figure 8. The stress concentration factors are 2.9 and 2.2 for pressure and prestress forces, respectively. The reasonable stress concentration factors confirm that all loads have been properly applied. The longitudinal forces and moments for critical factored and service load combinations along the horizontal and vertical centerlines of opening are plotted in Figure 9 through 12.

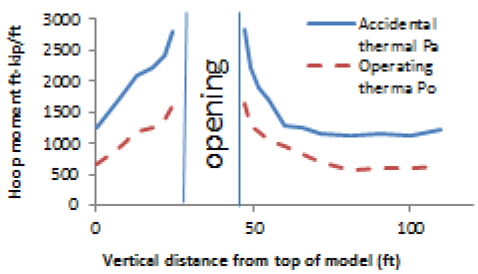

Figure 7. Uncracked thermal moments

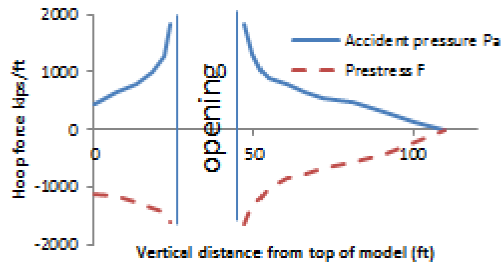

Figure 8. Pressure and prestress axial forces

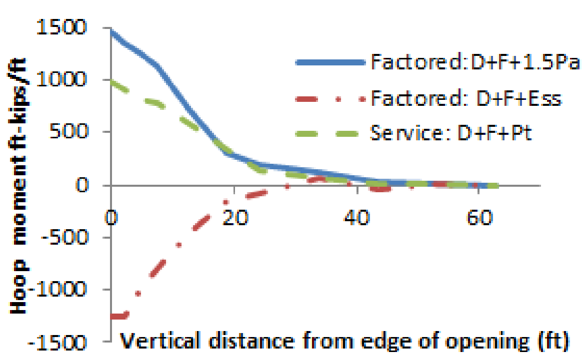

Figure 9. Hoop moments of mechanical loads

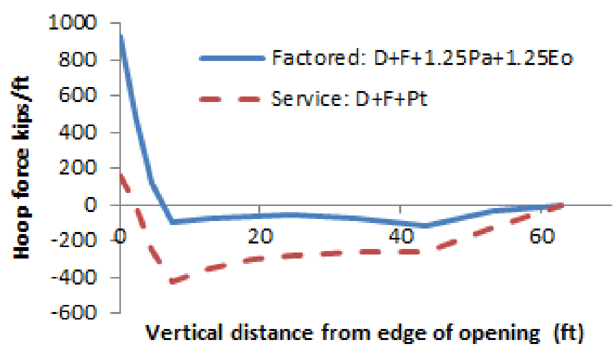

Figure 10. Hoop forces of mechanical loads

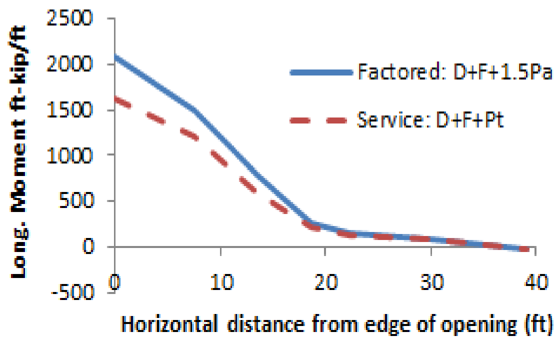

Figure 11. Longitudinal moments of mechanical loads

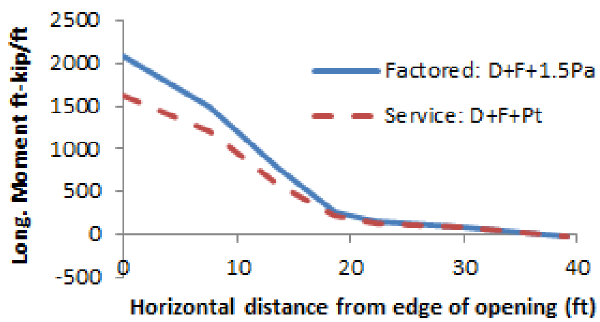

Figure 12. Longitudinal forces of mechanical loads

CONCRETE DESIGN

The ASME B&PV Section III, Division 2 (2010) code, requires that nuclear containments be designed for both service and factored load conditions. In consideration of complex seismic, prestressing and thermal loads, the total number of load combinations is very excessive. The allowable stresses for primary stresses and for primary plus secondary (thermal) stress are also different as shown in Tables 1 and 2. In addition, consideration of thermal effects is usually required. It is virtually impossible to "design" a section directly which will result in optimum reinforcement for such a large amount of load combinations with complex stress-strain limitations. Therefore, Bechtel developed "OPTCON" program for optimizing the reinforced concrete design. OPTCON is integrated with BSAP/RESULTS programs so that it can obtain stress resultants directly from analysis results for automatic design process. The procedure of combining mechanical and thermal loads in OPTCON is based on a conservative approach suggested in the Commentary to Appendix E of ACI 349 -06 (Item 3 of Section RE.3.3) for the thermal effects. It considers the structure to be uncracked under mechanical loads and to be cracked under the thermal effects due to self-relieving nature of thermal stress due to concrete cracking.

In the calculation of cracked thermal moment, OPCON considers the containment dome exerts rotational restraints on wall. The thermal gradients cause changes in curvature and thus bending moment in meridional direction of containment. Since the bending moment due to thermal differential is dependent on existing state of stress, it is necessary to determine the stress and strain distribution under each given loading combinations. A direct solution to this problem is not possible since both the concrete and reinforcement stress-strain relationships are nonlinear. To resolve the problem, OPTCON adopted an iterative approach to determine thermal moment with assumptions that the change in axial force of mechanical load is zero, ($\delta P = 0$) and the change in thermal curvature is given by $\delta\phi_t = (\alpha\Delta T)/h$, where h = section thickness. The procedure of determining thermal moment involving following steps:

Step1: Determine the strain distribution, ε_i, and curvature, ϕ_i, under a given mechanical load P_{di} and M_{di}.

Step2: Compute $\phi_f = \phi_i + \delta\phi_t$ which states that the final curvature ϕ_f is equal to the sum of initial curvature ϕ_i and change in curvature $\delta\phi_t$ due to thermal differential.

Step3: By iteration, determine the location of neutral axis such that the allowable load on the cross section is equal to the mechanical load P_{di} and the curvature ϕ equals to the final curvature ϕ_f. Based on the determined neutral axis, compute the final design moment, M_{df}, and the thermal moment is computed from $\delta M_T = M_{df} - M_{di}$.

In order to optimize the design of reinforcement, OPTCON adopted an optimization process proposed by Orhan & Kholi (1976) which reduces the "design" problem to an "analysis" problem with iteration on sizes of reinforcement. For each trial set of tension and compression reinforcement, OPTCON first optimizes reinforcement for primary load only and then check for primary plus secondary loads with thermal moment calculation. If the trial reinforcement satisfies all service and factored load combinations required by the ASME code, the iteration will stop and the trial reinforcement is the optimized final design reinforcement. Otherwise, OPTCON will increase reinforcement for new design iteration. In addition to checking the required flexural reinforcement, OPTCON checks the shear stresses against the shear capacity of the section in accordance with ASME and ACI 349 code requirements.

OPTCON design results at edge of opening are presented in Table 3 for critical service and factored load conditions. For the factored load combination of D+F+1.25Pa+1.25Eo+Ta, the concrete section in hoop direction is cracked through the wall thickness due to large tensile force of the mechanical loads. Consequently, the thermal moment is completely released. For the service load combination of D+F+Eo+To, about 40% of operating thermal moment is released.

The calculated reinforcement as shown in Table 3 is placed at each face, vertically at the sides of the opening and horizontally at top and bottom of the opening. Circular bars are added to meet requirement at intermediate locations around the perimeter of the opening. Radial ties are added at sections with excessive punching shear around the opening.

Table 3: Critical design loads at edge of opening

	Mechanical Loads		Thermal Loads		Reinforcement (in^2/ft)	
	Moment (ft-kips)	Force (kips)	Moment (ft-kips)	Force (kips)	Inside face As'	Outside face As
Factored Load (Hoop) D+F+1.25Pa+1.25Eo+Ta	1089	929	2834	25.1	6.1	12.6
Service Load (Long.) D+F+Eo+To	162	-2329	2215	53	1.2	16.9

CONCLUSIONS

A large opening with increased wall thickness causes geometric discontinuity and results in deviation from the stress resultant of the membrane ideal resulting from the internal pressure which is the single most important design load for a nuclear containment. The developed FEA model with layers of “BRICK” (solid) elements can precisely represent the local stiffened wall around the opening. The post-tensioning forces due to the deflected tendons and the non-linear temperature distribution due to LOCA can be properly applied to the model. For thermal load cases, “MEMBERANE” elements can be added to the inside face of the model for considering the temperature effect of the steel liner plates . The FEA model is applicable for both symmetric and asymmetric loadings. The effect of high temperature can either be considered in FEA model for thermal load analysis or in concrete design phase. Bechtel developed RESULTS program can effectively perform integration of the layered BRICK element stresses through the wall thickness to obtain the stress resultants of moments/shears/axial forces for concrete design.

The cracked thermal moment calculation per the Commentary to Appendix E of ACI 349-06 (Item 3 of Section RE.3.3) is adopted in this paper to account for the thermal effects. In this analytical approach, concrete is considered uncracked in finite element analysis for both mechanical and thermal load. The service and factored load combinations of mechanical loads are then combined with thermal loads in the design phase to reduce the thermal moment due to concrete cracking.

The iteration procedure used in OPTCON can effectively achieve an optimum reinforcement for containments with extensive loading combinations, complex stress and strain and consideration of thermal effects.

REFERENCES

ASME Boiler and Pressure Vessel Code (2010) Section III, Division 2, Article CC-3000.

ACI Manual of Concrete Practice (2006), Part 4, ACI 349-06.

Kohli, T.D. and Gurbuz O. (1975). “Optimum Design of Reinforced Concrete For Nuclear Containments, Including Thermal Effects”, Second ASCE Specialty conference on Structural Design of Nuclear Plant Facilities, New Orleans, Louisiana, USA, Volume 1-B , 1292-1319.