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NONLINEAR ANALYSIS OF PRESTRESSED CONCRETE CONTAINMENT DELAMINATION REPAIR

Bill D. Hovis[1], Joonghwan Kim[2]

[1] Consulting Engineer, URS Nuclear Center, Fort Mill, SC, USA (bill.hovis@urs.com)
[2] Consulting Engineer, URS Nuclear Center, Fort Mill, SC, USA

ABSTRACT

In the US, a large number of concrete containments for commercial nuclear power plants typically have prestressing tendons that act as a countermeasure for internal pressure during a loss of coolant accident (LOCA). The curvature effect of the tendons introduces radial tensile stresses in the concrete shell. If the prestressing tendon force is excessive and radial reinforcement is not provided, this condition can potentially cause delamination. This phenomenon is most likely to occur during creation of a construction opening in the side of the containment for a steam generator replacement. Subsequent to the investigation of the delamination phenomenon, rehabilitation of the containment needs to be initiated. This paper presents the finite element analysis for a prestressed concrete containment delamination repair. Structural behavior of the cylinder type prestressed concrete containment with a shallow dome is evaluated for the initial delaminated condition, during the repair activity, and post-repair condition. Non-linear construction sequential analysis of the structure is performed during concrete removal and replacement activities including tendon-by-tendon de-tensioning and re-tensioning analysis. Application of nonlinear gap elements is used to represent nonlinear properties of reinforced concrete, such as concrete cracking due to force re-distribution and elastic rebound after tendon de-tensioning.

INTRODUCTION

A large number of the first generation of prestressed concrete containment in the United States was constructed in 1960/1970's. Typical layout of the containment is shown in Figure 1. One of primary concerns of this type of containment was the level of prestressing to be provided. As one of the controlling load combinations involved a term containing the maximum design pressure multiplied by a factor of 1.5, the maximum prestress level, combined with any acting gravity load, should be such that membrane compression would remain throughout when the structure was subjected to a loading of one and one half times the design pressure in LOCA condition (Reuter and Whitcraft, 1975). The prestressing tendon force is usually excessive in the first generation prestressed concrete containment. This high prestressing condition can potentially cause delamination particularly during creation of a construction opening in the side of the containment for a steam generator replacement within an existing structure with loaded tendons present and without enough radial reinforcement. Subsequent to the delamination, rehabilitation of the containment needs to be initiated. The objective of the repair is to restore the containment building to its original licensing basis condition. Containment restoration involves tendon de-tensioning, concrete removal, repair and concrete replacement, tendon re-tensioning, testing, confirmation of integrity and return to service.

Detailed analyses are needed to determine the de-tension and re-tension sequences, to assess the effects of concrete removal/replacement on the existing cylinder wall and ring girder, and to evaluate design prestress levels. For these analyses, ANSYS (ANSYS User's Manual, 2010) finite element models were developed and analyzed. ANSYS is a finite element analysis code widely used in the nuclear power industry. ANSYS allows engineers to construct computer models of structures, machine components or systems; apply operating and accident loads and other design criteria; and study physical responses, such as stress levels, displacements, temperature distributions, pressure, etc. A non-linear model was used to simulate concrete cracking at new-to-old concrete interfaces, throughout construction. Non-linear gap/spring elements allow gaps to form at the concrete interface which simulates concrete cracking due to secondary load effects. The non-linear model was used to capture the effects of concrete cracking due to elastic rebound, creep recovery, and shrinkage. A linear model can also be used to apply earthquake, wind, and accident pressure loads. The linear model does not simulate cracking. The response of the two models was combined, which included the residual effects concrete cracking throughout construction. The analysis results were evaluated in the post-processor to verify that the construction and final condition of the containment remains code compliant.

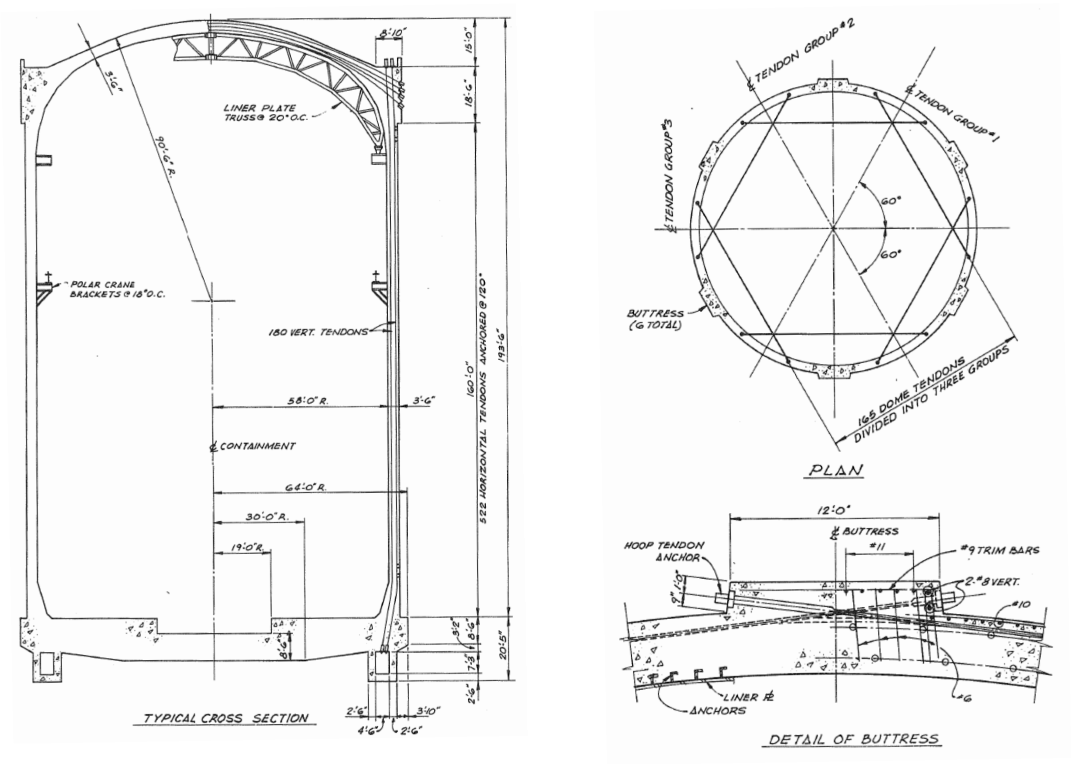


Figure 1. Typical first generation prestressed concrete containment (Reuter and Whitcraft, 1975).

Establishing a construction sequence for the repair of the containment delamination is important. The construction sequence includes partial tendon detensioning of the containment structure to support the concrete removal and replacement without loss of structural stability against lateral loadings. Stress and deformation analysis may be used to provide a construction sequence that remains code compliant throughout its duration. This analysis includes the loading from dead, live, prestress, wind, and seismic loads that are applied to the containment while bays are being repaired.

NUMERICAL METHODOLOGY

Finite Element Meshes

Figure 2 shows that mesh and principal outline of the FE-model representing the concrete and cylinder tendon layout. Shell elements were used to model the containment shell, buttresses, dome, the liner plate and its stiffeners. The ring girder and basemat foundation was modeled using brick elements and link elements were used to model the tendons.

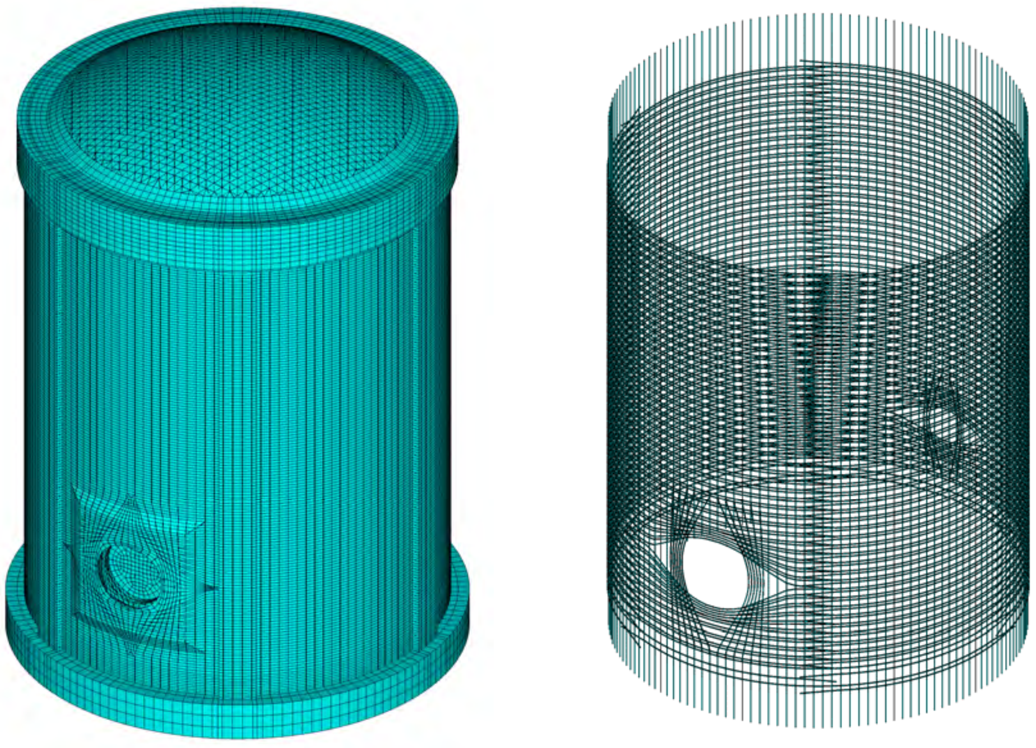


Figure 2. ANSYS FE concrete model (left) and cylinder prestressing tendons (right).

The major penetrations and buttresses were modeled accurately to capture the extra stiffening provided by local thickening of the cylinder and deviations in the tendon layout as shown in Figure 3. Such features provide local stiffening which influences the structural behavior and prevent uniform radial expansion of the cylinder (Prinja et al, 2005). Other small penetrations are not considered to be sufficiently large enough to affect the general stresses in the containment.

Shell elements were used for layered applications for modeling composite shells. For example, one layer for old concrete and another layer for new concrete, with an appropriate offset. Options are available for specifying the thickness, material, orientation, and number of integration points through the thickness of the layers. Unlike a conventional shell element, which has only bending and membrane behavior, the shell elements used in this study are suitable for analyzing moderately-thick shell structures, like the concrete containment, because they include the effects of transverse shear deformation. By using shell elements, analysis data is output in the form of forces and moments. This optimizes the accuracy of results by eliminating the need for stress integration to get forces, and lowers the risk of computational errors. If brick elements are used in the general cylinder area, section cuts need to be specified to obtain forces, which results in additional work, including post-processing of load outputs. Another advantage of using a shell element versus a brick element is model size. To model moment across a thickness, more than three brick elements are required. However, a single shell element is able to model a through-thickness moment.

The cylinder shell and buttress elements are connected by constraint equations with side shell elements. Nodal displacements and forces of the tendon link elements are related to cylindrical shell elements by rigid links through application of constraint equations. Two separate models were created in order to address the concrete and liner forces individually. The liner plate contributes zero stiffness to all concrete sections and is not considered as a strength element in the model as described in ASME Section III Division 2 (2001). The liner plate is subjected to the same loads and load combinations as the containment shell, but is not considered active in resisting loads on the concrete containment shell except where permitted during repair configurations. The liner plate must be checked during construction when concrete sections are removed, leaving an exposed liner plate subject to external loading, such as wind loads. Therefore, to check the liner plate stress, a separate model was created for the sole purpose of analyzing the liner plate. When concrete sections are removed, the exposed liner plates and its stiffener/anchors are added to the model, only at the concrete removal sections. When concrete is replaced, the liner plate is removed from the model.

Using the layered shell capabilities, the cylindrical shells may be divided into layers that are assigned different properties to model the delaminated concrete of the damaged bays. The depth of the delaminated portion of the containment bays in the model need to be determined. This is usually the distance from the outside face of the containment shell to the center of the hoop conduit, which is the approximate average depth of the delamination. These delaminated sections were defined as having mass, but contributing no stiffness to the structure.

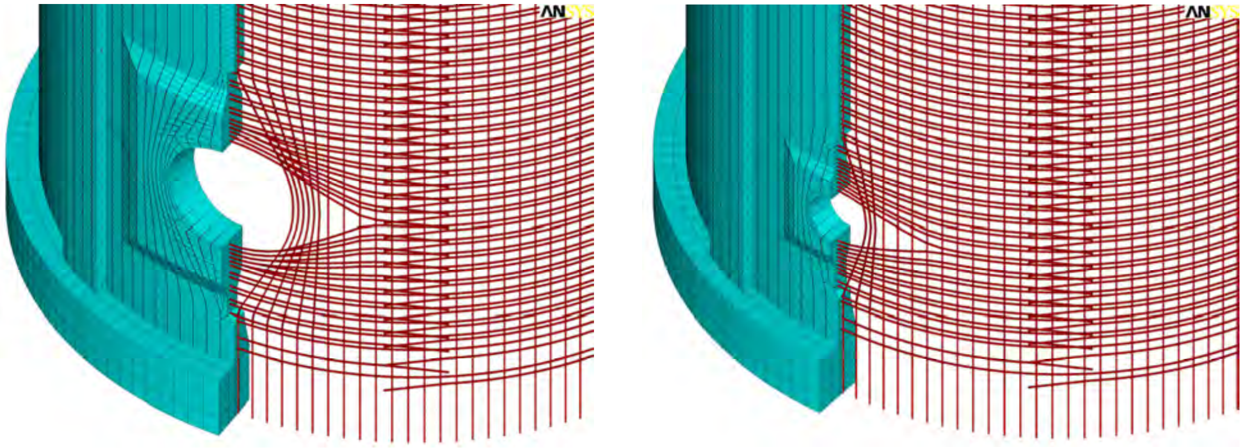


Figure 3. Concrete and prestressing tendons at equipment hatch (left) and personnel hatch (right).

Delamination Repair Approach and Analysis Sequence

Sound delamination repair approach is to remove and replace all concrete in all bays between the buttresses with known delamination and is usually best option to restore the containment to the original design and licensing basis. Depending on severity of delamination, all damaged concrete in all bays can not be removed and repaired at the same time due to structural stability issues during repair construction. Removing concrete requires tendon detensioning and removal of tendons. The excessive loss of the vertical tendon forces may cause the loss of stability against lateral loadings such as the seismic and wind. Also, the potential for the development of concrete vertical cracks needs to be considered due to steel liner stress reversal. After initial tendon tensioning in original new construction, the steel liner increases in compressive elastic strain due to concrete creep. After the tendon detensioning for the repair, the steel liner elastic strains reverses, but the concrete does not, due to the concrete creep. This causes tensile stress in the concrete in hoop direction. Partially detensioned hoop tendons are expected to maintain a level of circumferential compression in the concrete to minimize the potential for concrete vertical cracks to form. Therefore, the tendon detensioning and concrete removal/replacement needs to be sequential and staged.

The construction sequencing for a repair of the containment may be broken down into three stages with the primary goal of maintaining symmetrical loading to the extent possible as shown in Figure 4. Each stage includes partial detensioning and a specific portion of concrete removal and repair. Non-linear construction sequential analysis of the structure is performed during concrete removal and replacement activities. Since the analysis of the construction sequence is nonlinear and path/status dependent, it is necessary for the analysis to follow the construction sequence. The analysis steps are outlined in Table 1. When the status of the physical system changes, its stiffness shifts abruptly. ANSYS program offers solutions to such phenomena through the use of nonlinear contact elements and element birth and death options with restart simulations. For example, the concrete elements are deactivated in the step 7 using the element death option to simulate the load redistribution. Also, the concrete elements are activated in the step 8 using the element birth option to simulate a strain/stress free state in the new concrete.

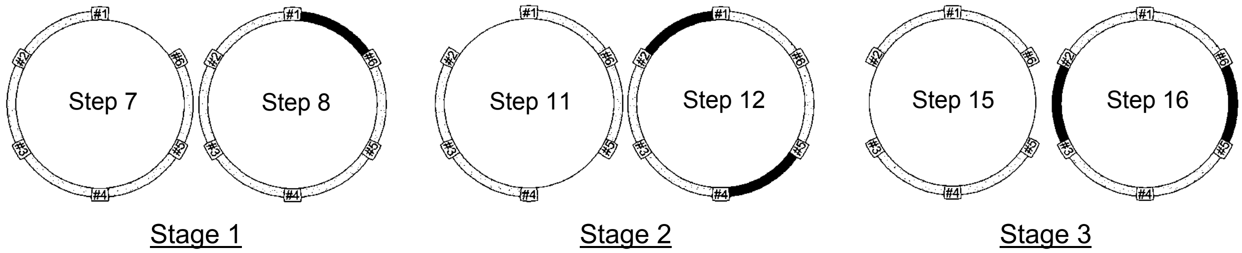


Figure 4. Repair construction sequence.

Table 1: Non-linear construction sequential analysis step.

Step	Description	Step	Description
1	Normal condition, before SGR	11	Demolition (Bay 1&4)
2	De-tension for SGR	12	New Concrete (Bay 1&4)
3	SGR Concrete/Liner Removal	13	Creep/Shrinkage
4	Delamination at all bays	14	Stage 3 Detension for Bay 2&5 Repair
5	Tendon Partial De-tensioning	15	Demolition (Bay 2&5)
6	Stage 1 Detension for Bay 6 Repair	16	New Concrete (Bay 2&5)
7	Demolition (Bay 6)	17	Creep/Shrinkage
8	New Concrete (Bay 6)	18	Tendon Re-tension (lock-off)
9	Creep/Shrinkage	19	Creep Recovery Reversal
10	Stage 2 Detension for Bay 1&4 Repair	20	End-of-Life Tendon Force

Constitutive Models

When the concrete is loaded by the tendon force, an instantaneous elastic strain develops. If this load remains on the member, creep strains develop with time. The concrete elastic rebound is instantaneous elastic recovery of concrete after tendon detensioning/unloading and the creep recovery is the delayed recovery (MacGregor, 1996). Tensile forces are created from secondary loads such as concrete elastic rebound, creep recovery, and shrinkage, which act at the boundary between the existing and newly placed concrete during construction. In reality, these loads will cause some concrete cracking, which will release energy that controls the magnitude of the load. However, if linear material properties are used in the model, concrete cracking is not accounted for, resulting in artificially high tensile demands at concrete interfaces. To create an accurate representation of the boundary between newly placed and existing concrete, spring and non-linear gap elements were used in the model. Concrete elements are modeled with six degrees of freedom, three translational and three rotational. Five of the six degrees of freedom are coupled between the new and old concrete. One translational degree of freedom is modeled as a spring element as shown in Figure 5. Before the delaminated concrete is removed, the interface between the sound and delaminated concrete is modeled with a rigid translational spring, as shown in Figure 6. This is because both sections act as one and move together, i.e., both displacement and force are continuous through the interface.

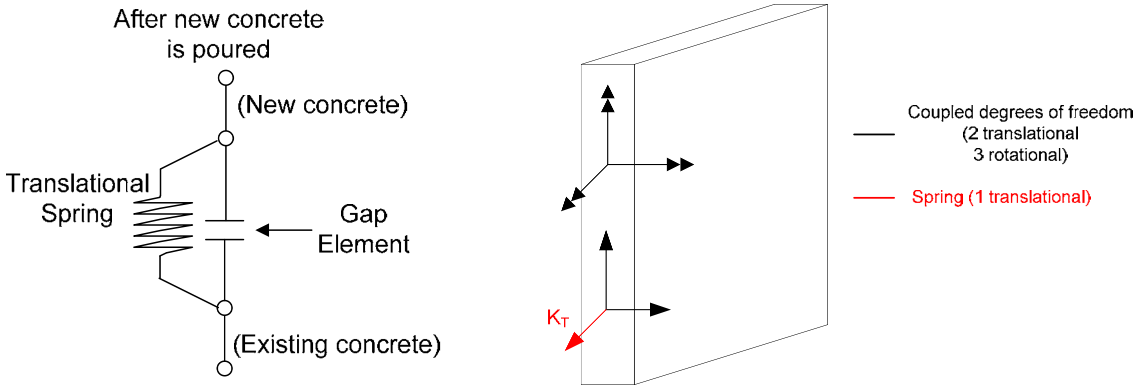


Figure 5. Gap and spring element (left) and degree of freedom at concrete crack (right).

After the new concrete is poured, it will experience shrinkage, creep recovery, and other effects. This will cause the new concrete to crack and separate slightly from the old concrete. Elastic rebound also happens due to the tendon partial detensioning stages during construction. After further detensioning, the existing concrete tries to expand to release the compressive strain, but the new concrete has a zero strain. This will cause the new concrete to crack. The interface between the old and new concrete will no longer be rigid once cracking occurs. In order to model this cracking, the rigid spring element is eliminated, a spring with finite reinforcement stiffness is introduced, and a gap element is used. The gap element allows movement in the same direction as the crack opens. If there is movement sufficient to close the gap during the tendon re-tensioning, contact is re-established between the surfaces separated by the gap element. Gap elements were used all along this boundary to model the discontinuity between old and new concrete. This is shown in Figure 6.

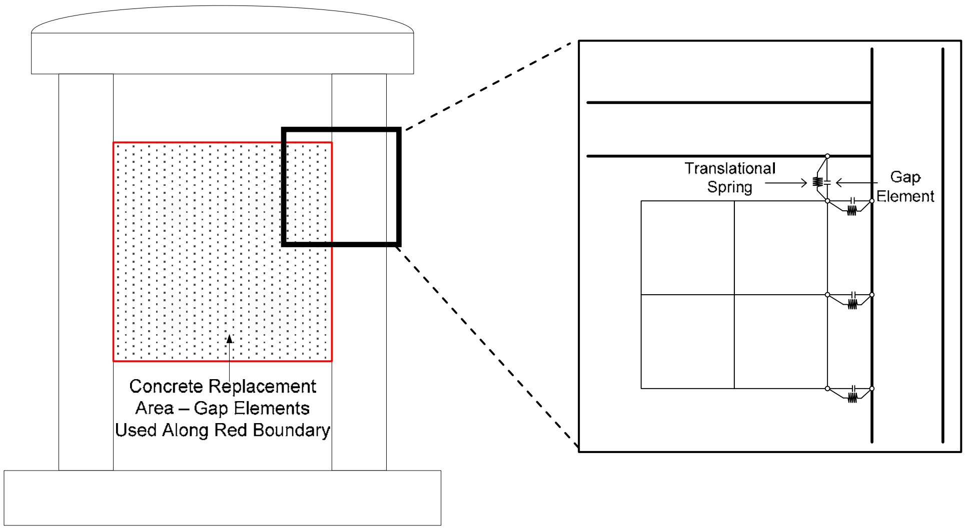


Figure 6.Gap/spring element location at typical concrete replacement area.

RESULTS AND DISCUSSION

Effect of Mesh Resolution

Mesh sensitivity/convergence study was performed with the general type of the prestress concrete containment to determine the appropriate mesh refinement. The mesh convergence study was used to review the influence of shell element size on the output results of cylindrical containments. See Table 2 for a summary of the case studies used to demonstrate the appropriateness of the mesh density used in the containment repair model. Five mesh densities (Cases 1 thru 5) and two loading conditions (pressure and earthquake) combined for a total of ten models developed for the mesh convergence study. The results of each model were compared to the classical theoretical design solutions (Timoshenko and Krieger, 1964).

Table 2: Typical element size of mesh sensitivity study models.

Case	Shell Element Size (ft)		Number of layers through thickness
	Meridional	Hoop	
1	15	12	3
2	7.5	6	3
3	3	2.4	3
4	1.5	1.2	3
5	1	0.8	3

It was concluded that Cases 1 and 2 are generally too coarse and do not provide an acceptable level of detail to capture the differences in shear, moment, and membrane force effects as shown in Figure 7. In all calculation the convergence was in the order of 3 ft element size. The containment analysis model mesh configuration was represented by Cases 3 and 4.

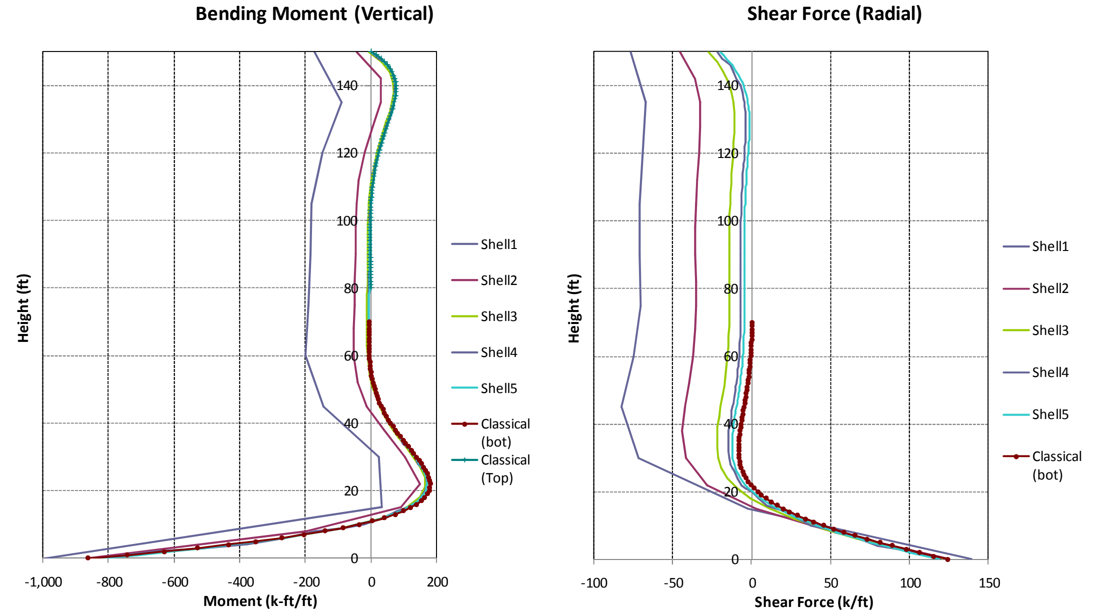
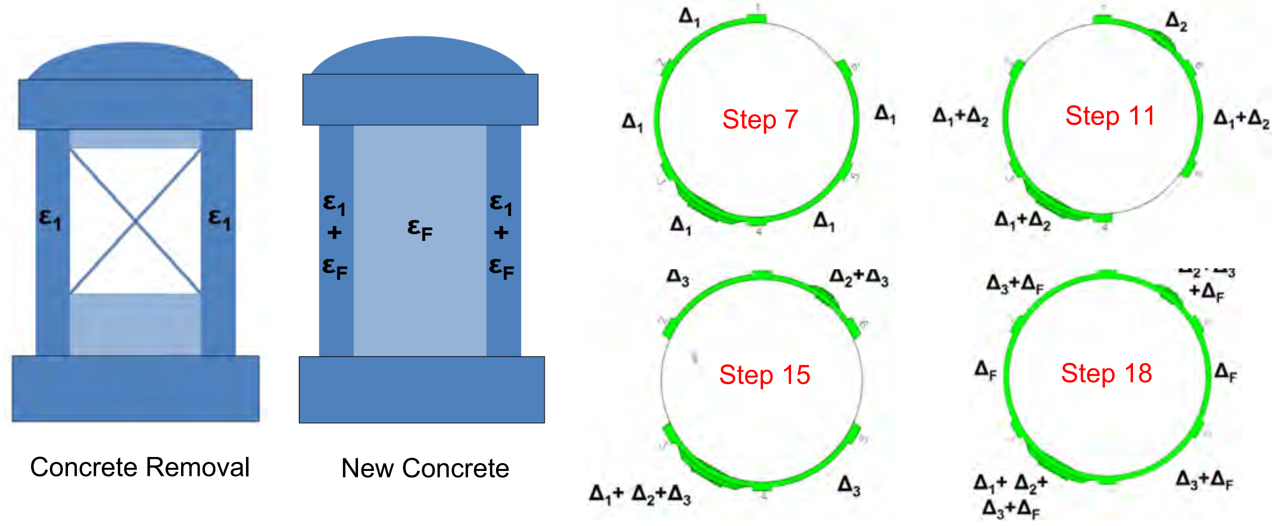


Figure 7. Results of mesh sensitivity from pressure loading, moment (left) and shear force (right).

Load Redistribution and Elastic Rebound

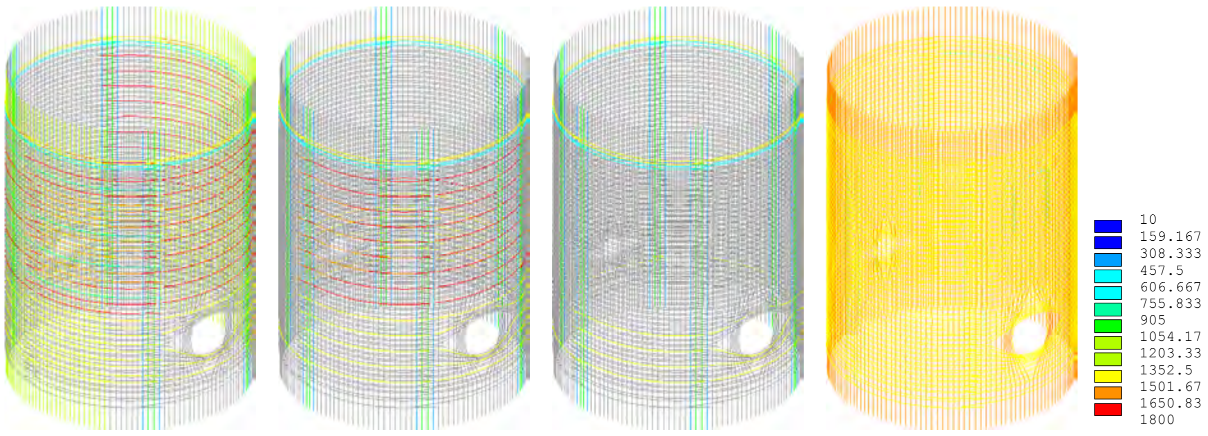
When concrete is removed from the cylinder, vertical loads are redistributed to the remaining sections of the containment. When concrete is removed and replaced, the strain in buttresses and remaining bays increases but the new concrete only has the strain due to its own self weight. As shown in Figure 8, the last bays, which are bay 2 & 5 in this case, will have the least amount of vertical compressive force after repair construction as explained in Figure 8.



Concrete Removal New Concrete

Figure 8. Load redistribution effect.

Vertical cracks might be developed in de-tensioned sections of the containment due to the containment elastic rebound and creep recovery. These cracks may also be developed from tensile hoop stress created by the liner plate stress reversal due to long-term accumulated creep strain in concrete. In order to minimize the risk of vertical cracks occurring, some hoop tendons need to remain at their current prestressing levels within sections of the containment that are not being removed. There is lateral loading during construction such as the seismic and tornado wind. In order to keep the lateral stability, some vertical tendons need to remain within sections of the containment that are not being removed as shown in Figure 9.



Stage 1 Stage 2 Stage 3 Re-tension

Figure 9. Tendon force contour during construction stage (unit: kips).

Elastic rebound happens due to the partial detensioning during construction. The new concrete acts as an extra vertical tendon element when the concrete cracking is not simulated in the model during the elastic rebound. The new concrete prevents the containment's full elastic rebound. Artificial tensile forces are developed in the new concrete, but the artificial compressive forces are developed in buttresses and remaining bays. If spring and gap elements are used at the boundary between newly placed and existing concrete to simulate the concrete cracking, the new concrete does not act as the extra vertical tendon element and there is no artificial forces in the model.

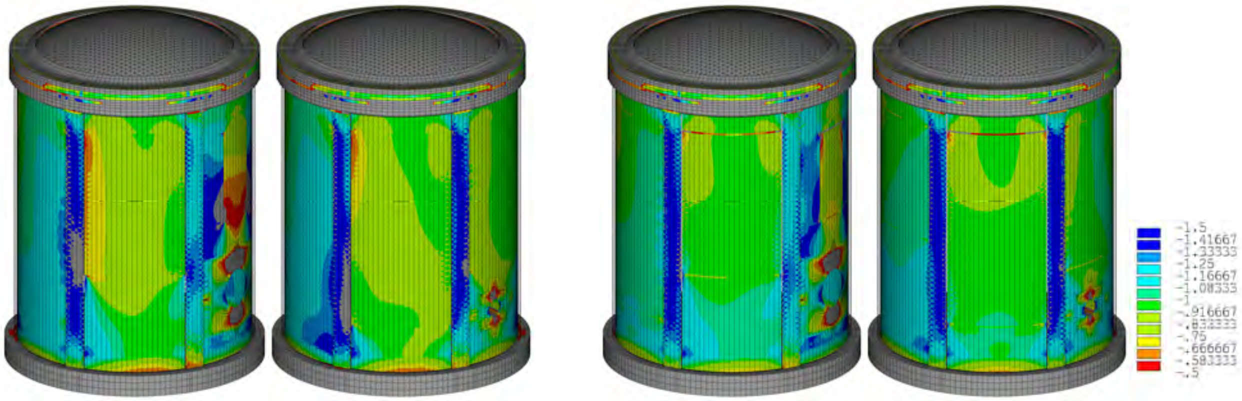
Two non-linear construction sequential analysis of the structure were performed during concrete removal and replacement activities. Application of nonlinear gap/spring elements is not used for Model 1, but is used for Model 2. Model 1 & 2 have the same construction sequence and loading condition. Resulting vertical forces were compared in the buttresses (Table 3) and in the bays between buttresses (Table 4). Comparison plots of vertical stress contour after re-tensioning are shown in Figure 10. Load redistribution happened in both models, but the true elastic rebound effects were realized in Model 2, but not in Model 1. For comparison purpose, the tendons were re-tensioned after repair construction using the same tendon forces as those before repair construction. From the results presented here, it is evident that the vertical force reduction in the last two bays, which are bay 2 & 5, is mitigated significantly in Model 2.

Table 3: Buttress vertical force change before & after repair construction (unit: kips).

Buttress #		1	2	3	4	5	6
Before Construction		10,230	10,269	9,991	10,182	10,281	10,026
After Re-Tension	Model 1	15,244	14,301	11,574	12,140	13,667	13,408
	Difference (%)	32.9	28.2	13.7	16.1	24.8	25.2
	Model 2	14,959	13,436	11,846	12,705	13,616	13,716
	Difference (%)	31.6	23.6	15.7	19.9	24.5	26.9

Table 4: Bay vertical force change before & after repair construction (unit: kips).

Bay #		1	2	3	4	5	6
Before Construction		32,288	32,104	31,994	32,502	31,864	32,096
After Re-Tension	Model 1	32,526	24,621	32,835	32,933	25,814	27,871
	Difference (%)	0.7	-30.4	2.6	1.3	-23.4	-15.2
	Model 2	29,731	28,021	32,225	30,234	27,581	28,939
	Difference (%)	-8.6	-14.6	0.7	-7.5	-15.5	-10.9



Model 1

Model 2

Figure 10. Vertical stress contour after re-tensioning (unit: ksi).

CONCLUSION

It is important to simulate the concrete cracking due to the secondary loading condition, such as the elastic rebound, creep recovery, and shrinkage during the non-linear construction sequential analysis to capture more reasonable structural behavior of the prestressed concrete containment. From the results presented here, it is evident that without the concrete cracking simulation, significant tendon vertical re-tensioning increase might be required to meet the containment pre-stress to accident pressure ratio. However, in this paper it was demonstrated that with the concrete cracking simulation, there is less need to increase the tendon vertical re-tensioning values, which provides engineers with the better information to make the prudent engineering judgment regarding the appropriate tendon re-tensioning levels.

Three dimensional finite element analyses using the composite shell elements with the detailed explicit tendon modeling is a suitable analysis method for the prestressed concrete containment delamination repair. Linear elastic concrete material is usually acceptable for the new construction analysis for the design basis loading. However, the results of the present study are an indication for further detailed simulation considering non-linearities, particularly the concrete cracking due to the secondary loading condition. Instead of using the non-linear concrete brick model, using the shell model with non-linear gap at the boundary between newly placed and existing concrete to simulate the concrete cracking is fast, reliable, and more practical for the prestressed concrete containment delamination repair.

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