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Cavity structural integrity evaluation of steam explosion using LS-DYNA

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1. Introduction

For investigating the mechanical response of the newly-designed NPP against an steam explosion, the cavity structural integrity evaluation was performed, in which the mechanical load resulted from a steam explosion in the reactor cavity was calculated. In the evaluation, two kinds of approach were considered, one of which is a deterministic manner and the other is a probabilistic one. In this report, the procedure and the results of the deterministic analysis are presented

When entering the severe accident, the core is relocated to the lower head. If any of mitigation measures such as IVR-ERVC were failed, the wall of reactor vessel is breached and corium could be expelled out of the vessel and interact with the coolant. In this case, an Ex-Vessel Steam Explosion(EVSE) can occur. It can threaten the structural integrity of the cavity due to the load applied to the walls or slabs of the cavity.

The large amount of the energy transmitted from interaction between the molten corium and the water causes a dynamic loading onto the concrete walls resulting not only to affect the survivability of the various equipment but also to threaten the integrity of the containment. In this report, the response of the cavity wall structure is analyzed using the nonlinear finite element analysis (FEA) code. The resulting stress and strain of the structure were evaluated by the criteria in NEI07-13[1].

2. Finite element analysis code

The data of the pressure and the impulse due to the steam explosion were obtained from the TEXAS-V code calculation results. Using these data, the mechanical response of the cavity structures were assessed using LS-DYNA which is a non-linear FEM software generally used in the shock, blast or crush field.

In this study, the non-linear material models were utilized from the LS-DYNA material library to model steels and concrete parts. The structural steel portions including a liner plate and rebar were modeled using the elastic-plastic material model to implement the plastic behavior of the strain. Moreover, we applied linear interpolation of the stress-strain curve to implement the strain hardening. Meanwhile, we use Winfrith concrete model to implement the discontinuous behavior of cracking, crushing, and shear retention that are distributed throughout the elements, depending on the size of the aggregate and the crack width, as a material model for concrete. Strain rate effect that must be taken into account in the crushing and explosion analysis was applied to each material via the dynamic increase factor. The material models for rebar and liner plates were implemented using the bilinear stress-strain curve for taking accounts for the strain-hardening.

3. Application of steam explosion load

Dynamic loads for the very short time during the steam explosion are in the form of non-vibrating impact onto the impact area resulting from the pressure wave along with the high-temperature and high-pressure gas, fragments generated by remains of explosives or structures and the high-temperature heat.

In this study, the steam explosion pressure curve shown in Figure 1 calculated by TEXAS-V code in the previous studies was used. In order to apply the pressure time history corresponding to the position of the explosion , the distance from the explosion point to the wall were implemented in calculating the scale factor through the Eq(1)[3].

$$\Delta P_m(r) = k\left(\frac{1}{r}\right)^{1.13} \quad (1)$$

Here, $\Delta P_m(r)$ represents the pressure function of each region, k is the pressure-time curve and r indicates the distance to the wall from the explosion point.

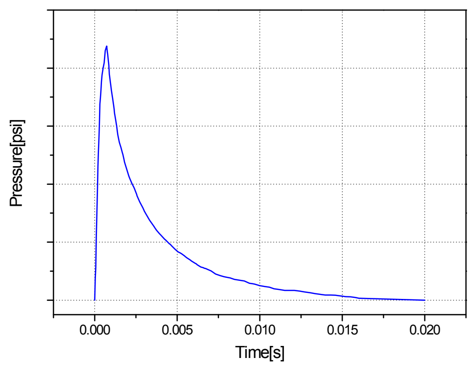

Figure 1. Pressure-Time curve by steam explosion

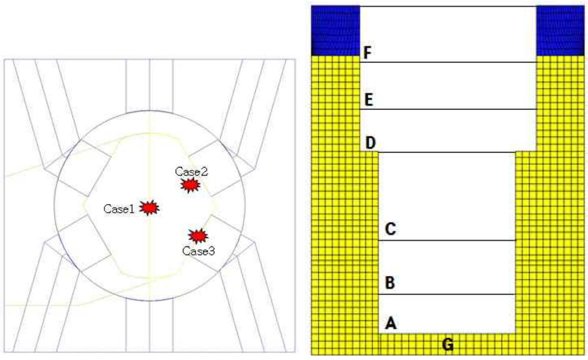

Figure 2.Location of cases and region elevation

Assuming that the same pressure curves are applied on inner circumferential area of each region, the different load scale factors are applied to each region based on the location of the explosion. This distance-scaling is reflecting the damping effect of the pressure wave. Three explosion positions were considered as following, which is presented in the left diagram of Figure 2.

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- Case 1 : Bottom center of the reactor cavity
- Case 2 : Bottom of the reactor cavity at some distance from the cavity wall
- Case 3 : Bottom of the reactor cavity contacting the vertical cavity wall

For applying the most conservative explosive loads, the explosion load is assumed to be same in each regions regardless level. So as the number of regions increase, the result of the calculation accuracy would be further increased. Table 1 shows the scale factor of each region according to cases.

Table 1. Load Scale Factor of each Region

Region	Elevation		Scale Factor		
	From(ft)	To(ft)	Case1	Case2	Case3
G	0.0 H	0.0 H	1.000	1.000	1.000
A	0.0 H	0.12 H	0.101	0.777	1.000
B	0.12 H	0.31 H	0.079	0.139	0.143
C	0.31 H	0.56 H	0.043	0.049	0.049
D	0.56 H	0.69 H	0.024	0.026	0.026
E	0.69 H	0.83 H	0.020	0.020	0.020
F	0.83 H	1.0 H	0.016	0.016	0.016

4. Material model that takes into account the explosion load

Explosion load, because in general it is loading on the structure during the very short time, generate a very high strain rate of about 10^2 ~ 10^4. This high Strain rate can cause a change in the mechanical properties of the several structural materials resulting in a change of the fracture behavior in the structure. In particular, the strength of general construction materials, such as concrete and steel, is increased by the strain rate effect.

Figure 3 shows the range of the strain rate found under various load conditions. The level of strain rate induced by the explosion is found to be the largest compared to any other loading conditions.

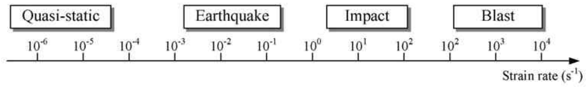


Figure 3. Strain rates associated with different types of loading [2]

Therefore, in order to carry out the explosion load analysis considering the strain rate effect, analysis must be performed using the property values obtained by multiplying the dynamic increase factor suitable for material properties. Dynamic increase factor of each material that is recommended in NEI07-13[1] is as Table 2.

Table 2. Dynamic Increase Factor[1]

<table>
<tr><th rowspan="2">Material</th><th colspan="2">DIF</th></tr>
<tr><th>Yield Strength</th><th>Ultimate Strength</th></tr>
<tr><td>Carbon Steel Plate</td><td>1.29</td><td>1.1</td></tr>
<tr><td>Stainless Steel Plate</td><td>1.18</td><td>1.0</td></tr>
<tr><td>Reinforcing Steel Grade 40</td><td>1.2</td><td rowspan="2">1.05</td></tr>
<tr><td>Reinforcing Steel Grade 60</td><td>1.1</td></tr>
<tr><td>Pre-stressing Steel</td><td>1.0</td><td>1.0</td></tr>
<tr><td>Concrete Compression Strength</td><td>-</td><td>1.25</td></tr>
<tr><td>Concrete Shear Strength</td><td>-</td><td>1.1</td></tr>
</table>

*MAT_WINFRITH_CONCRETE model provided in LS-DYNA was applied for the material model of the concrete similarly with the NPP aircraft-impact analysis cases. This Winfrith concrete model of LS-DYNA has been developed over the last two decades and validated through bunch of impact and blasting problems.

There are two types of Winfrith concrete models available in LS-DYNA, one of which is MAT084 and the other is MAT085. The main difference of these two is that MAT084 deals strain rate effects and MAT085 does not. In overall NPP containment impact cases, NEI07-13[1] is considered as a general guide, which suggested that an increase in the material strength due to the strain rate effect be embodied by using the DIF (Dynamic Increase Factor) of each material. Thus, MAT085 option was adopted in this study on the basis of usage of the DIFs of the materials.

*MAT_PLASTIC_KINEMATIC model was adopted in the material model of rebar and liner plate. There are *MAT_PIECEWISE_LINEAR_PLASTICITY and *MAT_PLASTIC_KINEMATIC frequently used in LS-DYNA for steel models. *MAT_PIECEWISE_LINEAR_PLASTICITY material model takes into account the strain rate effect using the Cowper Symonds model which the dynamic increase factor is multiplied to the yield strength of rebar.

*MAT_PLASTIC_KINEMATIC model is non-linear elastic-plastic material model, dealing with not only strain rate effect but also an isotropic hardening and kinematic hardening. While isotropic hardening behavior is fixed to the center point of the yield surface, the radius of it is varied based on a function of the plastic strain. On the other hand, kinematic hardening behavior is that the radius of the yield surface is fixed and the center point moved to the direction of the plastic strain. Like concrete, the effect of strain hardening of the steel was implemented in a way to enhance the strength of material properties through the dynamic increase factor.

5. Cavity dynamic load analysis

If using an implicit analysis technique, in the case of explosion load with various displacements in 1/1000 seconds or less short time, a lot of time is consumed in the calculation of the stiffness matrix associated with the time step and the problem occurs in the convergence of the analysis results. But, in the explicit analysis technique, because computation time associated with the time step is short, storage capacity is consuming less and there is no convergence problem of the analysis results, it can be useful for non-linear analysis such as explosions analysis and high-speed impact analysis. In explicit analysis, it is not required to calculate the overall stiffness matrix but the acceleration by the kinematic constraints of the concentrated mass of each node from the stress of the element is calculated. From the explicit time integration, the velocity and displacement at each node of the next time step are calculated directly. By the calculated velocity and displacement, the displacement gradient and velocity gradient of each element are calculated and the stress of each element is calculated from a constitutive equation of the material.

5.1 Geometry

The range of the structures of interest, as shown in Figure 4, were selected from the bottom of the cavity to the concrete structure of hot legs and cold legs penetration hole. In addition, in order to determine the impact of the peripheral structure, a Chamber room and HVT near the cavity were included in the range.

The structures are composed of concrete which is the main material of the reactor building. The liner plate is located under the concrete outside of the cavity. Because underground structures not explicitly modeled can affect the responses of the structures of interest, it is needed to set the boundary conditions so that the underground structures can act as a reaction force against the explosion load. The boundary condition was simply modeled by assuming a peripheral underground structure to be an elastic body as shown in Figure 5.

The spring coefficient(k_i) was calculated through the Eq (2) using the elastic modulus of concrete(E_c), the thickness of the foundation concrete(D_i), the area of underground structure(A_i) and the number of nodes(N_i). The resultant spring coefficients of each direction of the elastic body are enlisted in Table 3.

$$k_i = \frac{E_c A_i}{D_i N_i} \tag{2}$$

5.2 Failure criteria

Generally, failure criteria of the structure subjected to blast loading is a reference point for limiting the deformation or displacement of the member, which is permitted variances depending on the degree of damage to the structures and structural members.

The level of the local damage is determined by the strength and rigidity of the structural members and the distance from structure to the explosion point. The local damage can induce the structural failure or not depending on the level of the damage.

Table 3. Spring Coefficient of Boundary condition

Direction	Area (in2)	Thickness(in)	Nodes	Spring Coefficient (lbf/in)
Y1	482706	672	3060	1361508
X1	229042	240	1406	3936829
Y2	482706	672	3060	1361508
X2	229042	240	1369	4043230
Z	489056	132	3212	6690169

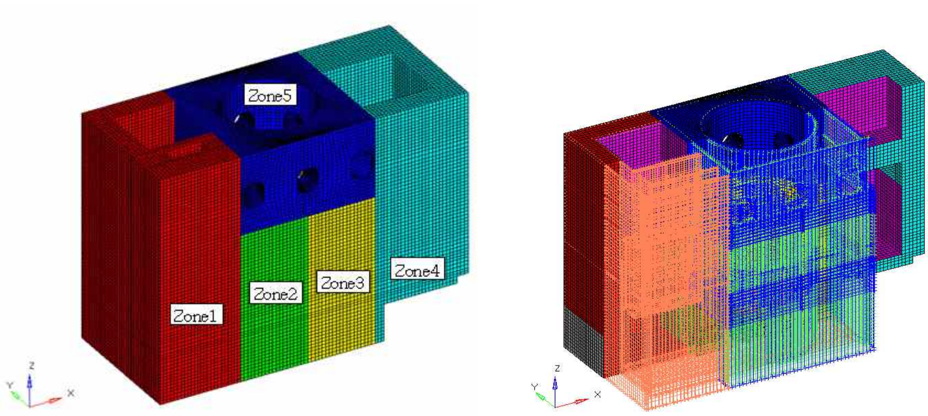


Figure 4. Object structure and rebars

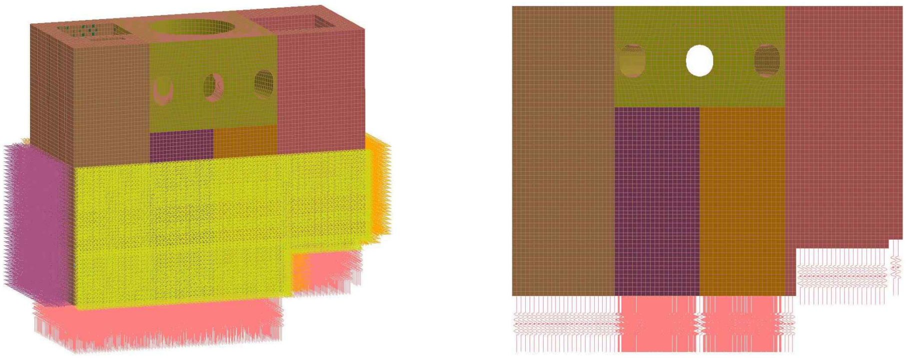


Figure 5. Constrained spring condition

According to the knowledge from experiments, the fracture ductility of the steel materials considered herein is in excess of 20%, and excess of 30% for stainless steel.

A guideline, Structural Design for Physical Security[4], suggests some failure criteria for each of the reinforced concrete structural member with respect to the strain concerns as shown in the following Table 4.

Table 4. Failure Criteria of plastic strain

Part	Mild damage	Normal damage	Severe damage
Beam	0.04	0.08	0.15
Slab	0.04	0.08	0.15
Colum	0.01	0.02	0.04

It is recommended to adopt the results of uniaxial test to judge failure in a structure, because the effects of stress-strain, stress concentrations, and granularity of the finite element mesh may make the failure strain considerably less than result of a uniaxial test. Considering that above, the failure strain of rebars and liner plate is assumed to be 5%[1]

The failure of structure is defined by rebar failure and simultaneous complete concrete failure because the concrete failure only will not cause the all structures to be broken. Moreover, without failure of external steel liner, the leak-tight integrity would still be maintained as suggested by one of the studies [5].

In this study, the leak-tightness of the cavity is considered as the key parameter for determining the failure of the cavity region. Therefore, it is judged that the cavity is failed if the concrete is fully damaged and the outer carbon steel liner plate and rebar have reached 5% effective plastic strain.

5.3 Results of each cases

The results of the LS-DYNA analysis for the three cases having different explosion positions are presented in Table 5 giving a number of contours and figures. The resultant values of consequences are summarized in Table 6. And it shows the following characteristics.

- Final displacement of the foundation concrete slab is very small, which is below 0.5 inches in all cases.
- Crack is generally formed in the foundation slab and concrete part of Zone1, Zone2, Zone3 and Zone4.
- In the external liner plate, even though the dynamic load causes the plastic deformation, its degree is small enough compared to the NEI 07-13 criterion so that the leak-tightness of the liner plate surrounding the concrete can be maintained.

- Also a small plastic deformation occurs in the rebar and most of the plastic deformation occurring in rebar is concentrated on the wall of Zone 2 & 3 and foundation slab.
- In all cases, the rebar and the liner keep their integrity so that the leak-tightness of the cavity can be secured even though the concrete media experiences some damages.

6. Conclusions

Until now, deterministic analysis was performed via finite element analysis for the dynamic load generated by the steam explosion to investigate the effect on the cavity structure. A deterministic method was used in this study using the specific values of material properties and clearly defined steam explosion pressure curve.

The results showed that the rebar and the liner are kept intact even at the high pressure pulse given by the steam explosion. The liner integrity is more critical to judge the preservation of the lean-tightness. In the meantime, there were found cracks in concrete media. However, the level of the deformation or fracture of the wall and floor would not be serious because the overall strain of the rebar and liner are limited enough. Thus, it can be concluded that the integrity of the cavity structure would be preserved against the steam explosion from a perspective of the leak-tightness.

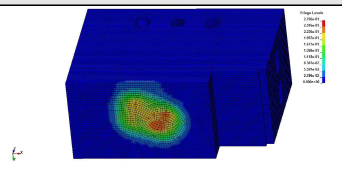
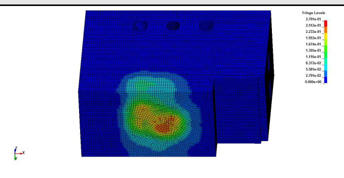
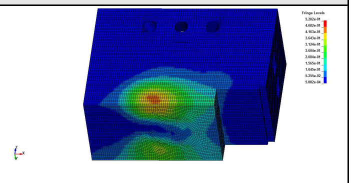
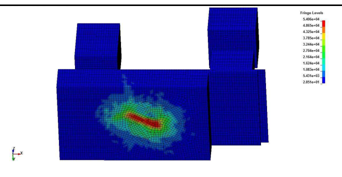
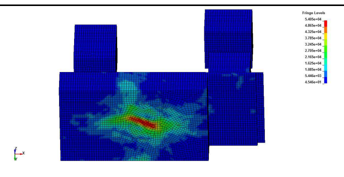
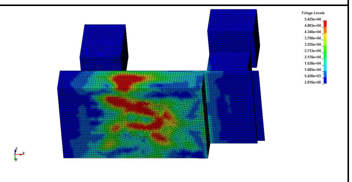
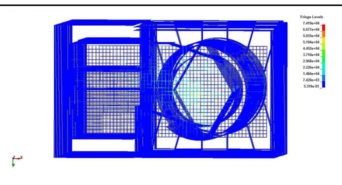
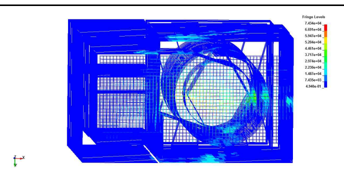
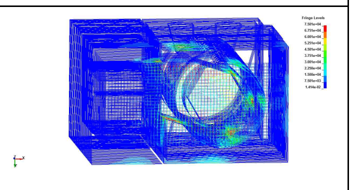
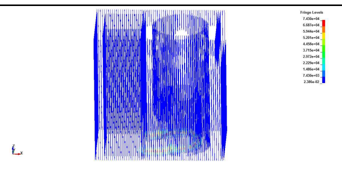
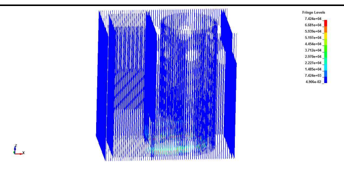
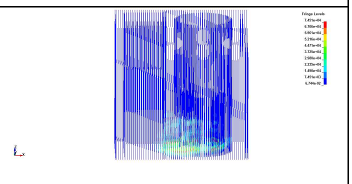
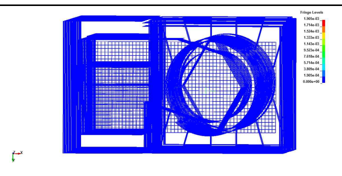
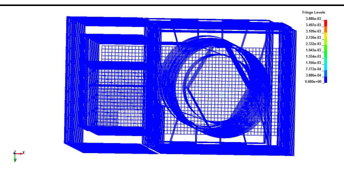
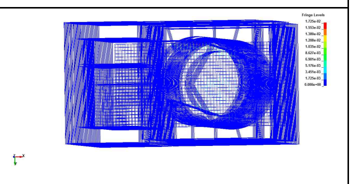
Meanwhile, this deterministic kind of analysis has uncertainties inevitably to some degree so that the conclusion would not be able to be decisive.

Therefore, in the next study, a probabilistic assessment will be performed in which a cavity fragility curve in the form of the pdf(probability density function) and the pdf of the explosion load are produced to obtain the cavity failure probability by convolution of the two pdfs.

Acknowledgement

This study was supported by the project, Development of APR+ Common Core Technology and this paper is one of the outcomes established in the stage of development of the steam explosion analysis methodology.

Table 5. Contours and cracks of each case

Variable	Case 1	Case 2	Case 3
Displace-ment			
VM stress			
Stress for vertical Rebars (ksi)			
Stress for horizontal Rebars (ksi)			
Eff. Plastic Strain Rebar			

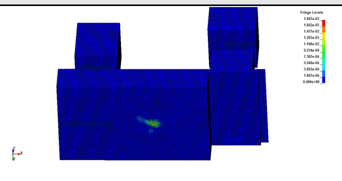
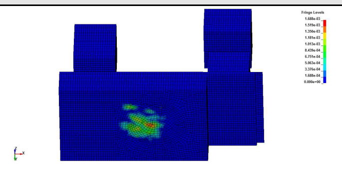
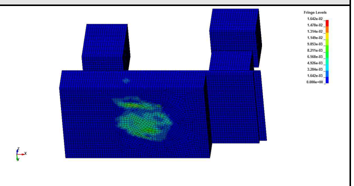
Variable	Case 1	Case 2	Case 3
Eff. Plastic Strain Liner			

Table 6. Results of analysis

Veriable	Case 1	Case 2	Case 3	Remarks
Max Displacement for Concrete(in)	~ 0.3	~ 0.3	~ 0.5	Concrete Damage
Max VM stress on Liner (ksi)	0.818 α	0.819 α	0.822 α	Local Yielding Tensile Strength(α ksi)
Stress for Rebars (ksi) Vertical	0.682 β	0.681 β	0.679 β	Local Yielding Tensile Strength(β ksi)
Stress for Rebars (ksi) Horizontal	0.681 β	0.682 β	0.684 β	
Eff. Plastic Strain Rebar	< 0.01	< 0.01	< 0.01	All less than the failure criteria 0.05(NEI 07-13)
Eff. Plastic Strain Liner	< 0.01	< 0.01	< 0.01	

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