The Development of Impact Analysis Methodology for CEDM Missile of APR1400

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An integrated head assembly (IHA) is equipped with the missile shield to absorb the missile energy from postulated control element drive mechanism (CEDM) missile during the dynamic event of accidental conditions. Once a CEDM nozzle breaks, reactor coolant jet discharges from the broken nozzle, then it impinges at the bottom of the CEDM, and gives a thrust force to the CEDM missile until it impacts on the missile shield. After the missile impacting on missile shield, it is necessary to evaluate the structural responses on the local area of the missile shield, as well as behaviors of overall IHA structure. The jet has been previously assumed to be a single-phase flow. However, in order to reduce excessive conservatism for the jet characteristic, the jet is assumed to be a two-phase critical flow, and accordingly Fauske slip equilibrium model is applied to estimate the jet velocity. In this paper, jet impingement models are proposed to estimate the missile velocity depending on jet expansions and size of objects. With the calculated missile velocities using the jet impingement models, the nonlinear CEDM missile impact analysis is performed to investigate structural responses of the missile shield of advanced power reactor 1400. Finally, the results show that the structural integrity of the missile shield and the IHA can be maintained due to CEDM missile impact. [DOI: 10.1115/1.4000368]

1 Introduction

The main function of the IHA, which is installed on the reactor vessel (RV) closure head, is to lift RV closure head and to provide cooling air path for the CEDM cooling. The IHA is designed to reduce the refueling outage time and radiation exposure according to the EPRI URD [1]. Therefore, the IHA is equipped with a missile shield to absorb the missile energy from postulated CEDM missile during the dynamic events of accidental conditions. The IHA of advanced power reactor 1400 (APR1400) is shown in Fig. 1 without cooling air shrouds, and the CEDM and missile shield are located inside the IHA. Because the missile shield is tied to three main columns and the missile impact force is transmitted to the IHA components through connections, in order to simulate the CEDM impact behavior, the missile shield should be analyzed together with the IHA.

Prior to perform impact analysis, it is important to determine the impact energy or velocity for both jet and missile. The previous calculation of the jet and missile velocity was based on the assumption that the jet is single-phase flow as presented in ORNL-NSIC-22 [2]. It only provides jet velocity in single-phase flow models and states difficulties in considering the two-phase flow models. The experience is that these models resulted in overly excessive velocity estimation. In addition, missile velocity equation has been presented, assuming that the jet expands with an angle. But it does not show jet expansion mechanism in detail. Information about missile kinetic energies arising from jet impingement is described in ANSI/ANS 58.2 [3]. This standard deals more with through-wall openings in pipes, which may be approximated by orifice type discharge, as opposed to what may be expected for longer nozzle. It is difficult to apply the basis of the standard for the jet through the longer nozzlelike CEDM nozzle.

Using the references, even though it is possible, to a certain extent, to calculate the jet velocity through the CEDM nozzle and missile velocity, it is evident that the results give the designer overly excessive data for the design and analysis of IHA because of lack of information. In order to reduce the conservatism, it is necessary for the jet to apply new flow model and to develop jet impingement models for jet and missile object.

In this paper, the jet is characterized into two-phase flow, in which the well-known Fauske model [4] is applied to calculate the jet velocity. Therefore, jet impingement models have been developed considering the jet expansion mechanism and size of missile. For structural analysis, considerations are required to represent nonlinear impact behaviors and plastic effects, such as in modeling, materials, and damping. Furthermore, in the structural evaluation, since the analysis includes the plastic deformation, method to demonstrate structural integrity in this condition is required.

2 Missile Velocity

2.1 Application of Fauske Model. As a well-known nonhomogeneous equilibrium theory for the two-phase critical flow model, the Fauske slip equilibrium model [4] is utilized to calculate the velocity of the jet.

Fauske [4] suggested use of the experimental data for the ratio P_c/P_o as a function of L/D, wherein P_c is the critical pressure at the nozzle throat, P_o is the stagnation pressure in the container, L is the length of the nozzle, and D is the diameter of the nozzle. Especially in the range of pipe length to diameter ratio of 12 or greater, one should notice that the ratio of P_c/P_o converges to the 0.55. If the L/D ratio is 12 or greater, we can use it to determine P_c. The ratio of L/D is in the applicable range for the CEDM nozzle length to diameter so that the ratio of critical pressure can be determined for the jet from CEDM nozzle. He also provided a plot of mass velocity as a function of stagnation enthalpy at various critical pressures for steam-water mixture. For any enthalpy and pressure, one can immediately locate the mass velocity. Prior to using the plot, one should also know the flow quality and saturated liquid enthalpy of reactor coolant. On the other hand, mass velocity can be calculated by solving the differential equations defining the Fauske model. The calculated values of mass velocity and flow quality appear to be in agreement with the data in the plot. This will be used for determination of jet velocity.

2.2 Models for Missile Velocity. The velocity of the missile can be calculated by Newton's second law with the following assumptions.

(1) The mass flow rate is constant through any cross section of the jet.
(2) The jet is assumed to be expanded to ambient pressure.
(3) The jet impact cross section area of missile is assumed to be a simple solid section.

2.2.1 Uniform Jet Impingement With Constant Area. The cross section area of the object is assumed to be larger than that of the

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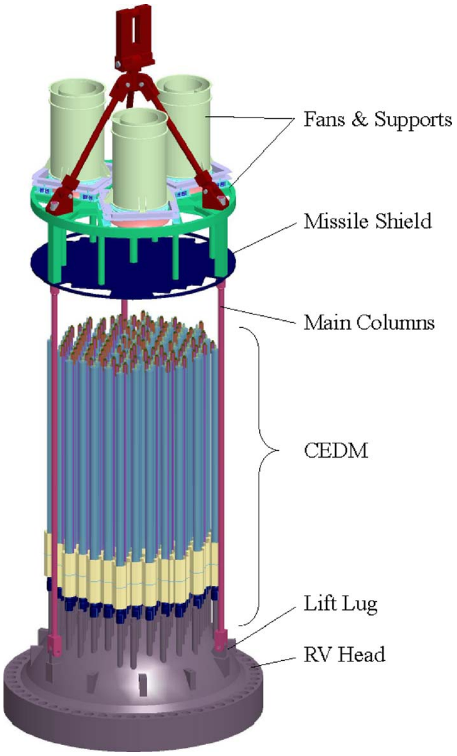


Fig. 1 Integrated head assembly with missile shield

jet so that all of the jet fluid impinges on the object. Flow exit model in uniform jet impingement with constant area is shown in Fig. 2(*a*) with variables used in derived equations. Based on Newton's second law, the velocity of the missile can be calculated by velocity equation.

$$m\frac{dV}{dt}=mV\frac{dV}{dx}=\rho_e V_e A_e (V_e-V) \tag{1}$$

If it is assumed that the missile object is resting, $V/V_e=0$ at $x=0$, Eq. (1) can be integrated to the given object velocity as a function of distance above exit plane of the jet. Then we have

$$\left[\left(1-\frac{V_h}{V_e}\right)-\ln\left(1-\frac{V_h}{V_e}\right)\right]=1+h\left(\frac{\gamma_e A_e}{W}\right) \tag{2}$$

This equation may be used to estimate the velocity (V_h) of the missile when it has reached a height (h) above the exit plane of the jet, and the jet does not expand during the travel.

2.2.2 Expanding Jet Impingement on an Object. The cross section area of the object is equal to or smaller than the cross section area of the jet. The flow exit model for this expanding jet impinging is shown in Fig. 2(*b*) with variables in equations.

The cross section area of the jet at height (x) above the exit plane is

$$A_h=\pi(R_e+x\tan\phi)^2 \tag{3}$$

The amount of jet fluid intercepted by the object is given by

$$\beta=\frac{A_0}{A_h}=\frac{A_0}{\pi(R_e+x\tan\phi)^2} \tag{4}$$

where A_0 is the cross section area of the object. With the same manner in Sec. 2.2.1, the velocity of the object can be formulated by

$$mV\frac{dV}{dx}=\rho_e V_e A_e \beta(V_e-V)=\rho_e V_e A_e\frac{A_0}{\pi(R_e+x\tan\phi)^2}(V_e-V) \tag{5}$$

Integrating this Eq. (5) from 0 to h and from $V=0$ to $V=V_h$, this yields

$$\left[\left(1-\frac{V_h}{V_e}\right)-\ln\left(1-\frac{V_h}{V_e}\right)\right]=1+\left(\frac{\gamma_e A_e A_0}{W\pi\tan\phi}\right)\left(\frac{1}{R_e}-\frac{1}{(R_e+h\tan\phi)}\right) \tag{6}$$

Equation (6) may be used to estimate the velocity when it has reached a height (h) above the exit plane of the jet, and the jet is expanded as much as or smaller than the cross section of the object.

2.2.3 Expanding Jet Impingement on a Large Object. The cross section area of the object is larger than the cross section area of the jet. The expanding jet impinging on a large object is shown in Fig. 2(*c*). This case may be evaluated in two parts: In the first part, all of the jet fluid is intercepted by the object. This occurs in the region between the jet exit plane and elevation (h_a) where the diameter of the jet has expanded to the diameter of the object. The

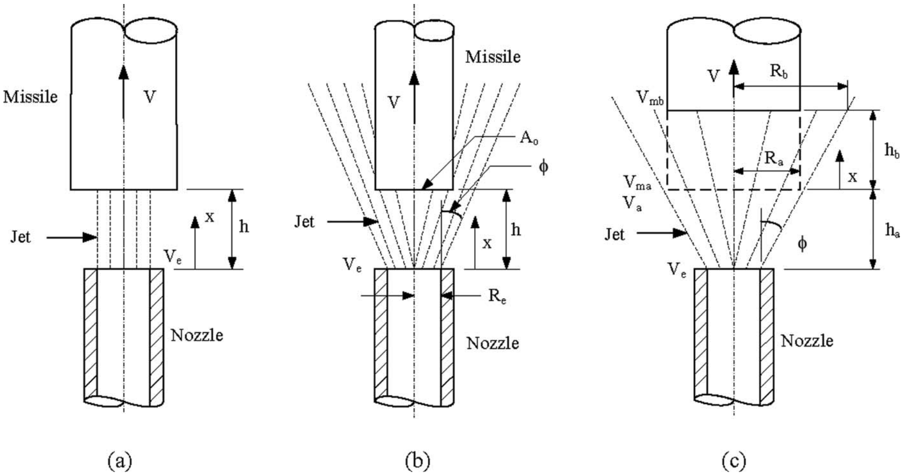


Fig. 2 Flow impingement models for (*a*) uniform constant jet impingement, (*b*) expanding jet impingement on an object, and (*c*) expanding jet impingement on a large object

velocity of the object at elevation (h_a) above the jet exit plane may be calculated using the equation developed for Sec. 2.2.1, for uniform jet with constant area. Let this velocity be designed as V_{ma}.

The second part of the evaluation is similar to Sec. 2.2.2, except that the left hand side of the equation is integrated from V_{ma} to V_{mb}, where V_{mb} is the velocity of the object at the designed elevation (h_a+h_b) above the jet exit plane.

A_a is the cross section area of the missile object. Based on the conservation of mass, jet velocity (V_a) at height (h_a) is obtained by

$$\rho A_e V_e = \rho A_a V_a \tag{7}$$

The cross section area of the jet at height (h_b) above the exit plane is

$$A_b = \pi (R_a + x \tan \phi)^2 \tag{8}$$

The amount of jet fluid intercepted by the object is given by

$$\beta = \frac{A_a}{A_b} = \frac{A_a}{\pi (R_a + x \tan \phi)^2} \tag{9}$$

With the same manner as in Sec. 2.2.2, the velocity of the object can be calculated by

$$mV\frac{dV}{dx} = \rho V_a A_a \beta (V_a - V) = \rho V_a A_a \frac{A_a}{\pi (R_a + x \tan \phi)^2}(V_a - V) \tag{10}$$

Integrating Eq. (10) yields

$$\ln\left[\left(\frac{1 - V_{ma}/V_a}{1 - V_{mb}/V_a}\right)\right] - \frac{1}{V_a}(V_{mb} - V_{ma}) = \left(\frac{\gamma_e A_a^2}{W\pi \tan \phi}\right)\left(\frac{1}{R_a} - \frac{1}{(R_a + h_b \tan \phi)}\right) \tag{11}$$

Equation (11) may be used to estimate missile velocity (V_{mb}) at elevation (h_b). In the application of this model, once the velocity (V_{ma}) at elevation (h_a) is calculated by Eq. (2) assuming uniform jet area, then Eq. (11) may be used to estimate the velocity when it has reached a height (h_b) above the exit plane of the jet and the missile has a large enough cross section compared to that of the jet.

For the condition, $V_{ma}/V_a = 0$, the integration then is

$$\left[\left(1 - \frac{V_{mb}}{V_a}\right) - \ln\left(1 - \frac{V_{mb}}{V_a}\right)\right] = 1 + \left(\frac{\gamma_e A_a^2}{W\pi \tan \phi}\right)\left(\frac{1}{R_a} - \frac{1}{(R_a + h_b \tan \phi)}\right) \tag{12}$$

This is identical to Eq. (6), when the area of the object is equal to the area of the jet.

Due to the complex nature of actual jet flow, models should be used with caution and may be used only over a limited region above the jet exit. Although the jet impingement models and assumptions developed are not expected to hold true, the developed equations for the missile velocity may produce higher velocities than real jet because of disregarding the energy loss, such as the flow resistances.

3 Missile Impact Analysis

SRP 3.5.3 [5] requires that missile shield shall be designed to be evaluated for local missile penetration as well as the overall structural integrity during and after missile impacting. Therefore, the finite element model includes all the important load carrying structural components affected by the missile impact and all the components with significant mass that may affect the dynamic characteristics of the missile shield. The finite element model is shown in Fig. 3, which is based on the structures shown in Fig. 1. The bottom of the main columns is anchored to the RV closure head of the model.

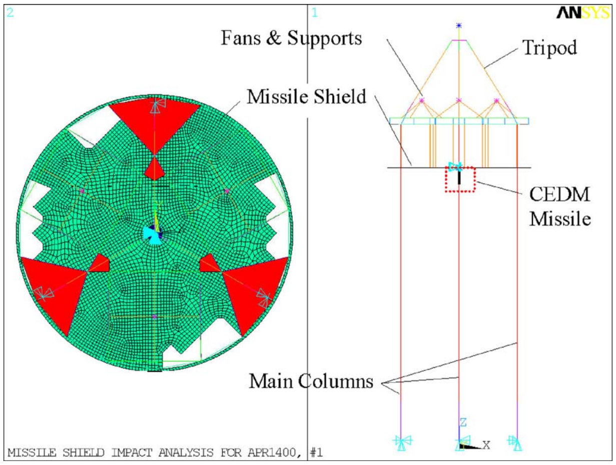


Fig. 3 Finite element model for the CEDM missile impact analysis

Because there are many CEDMs in the reactor vessel head region, several impact locations should be considered for missile impact model due to the possible impact scenarios. Each impact location is consistent with the corresponding CEDM location. By reviewing the case analysis, the CEDM location was determined to produce the largest responses of IHA and missile shield. The impact location of the missile shield is modeled in a separated region from other remaining regions due to mesh refinement.

The dynamic analysis for missile impact is performed using the ANSYS nonlinear transient method [6] with initial velocity condition, i.e., missile velocity. The missile impact is represented by applying an instantaneous initial velocity to the CEDM model that shows the missile. The direction of the applied velocity is assumed to be perpendicular to the missile shield with a conservative approach.

Two bounding material stress-strain characterizations, shown in Fig. 4, should be considered in the model of the missile shield. One stress-strain curve represents bilinear stress-strain behaviors with an elastic portion up to the yield stress of the missile shield material and with the remaining portion of the curve considered perfectly plastic. Similarly the other stress-strain curve has an elastic portion up to the ultimate stress of the material with the remaining portion considered perfectly plastic. The latter case represents potential strain-hardening effects due to the suddenly applied loads, which were described in BMI-1954 [7]. The effective yield stress varying strain rate is as high as the ultimate stress of the material.

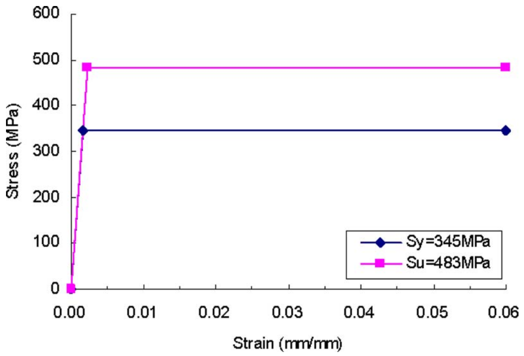


Fig. 4 Stress-strain curves of missile shield used for analysis

Table 1 Impact loadings and analysis results

	Case 1 (single-phase flow)	Case 2 (two-phase flow)
Jet velocities	147.2 m/s	78.0 m/s
Missile velocities	18.0 m/s	7.6 m/s
Maximum stress intensities	431.6 mPa	404.1 mPa
Maximum total strains	0.03355 mm/mm	0.00697 mm/mm
Maximum reactions	1246.9 kN	661.4 kN

(1) Jet is assumed to be single-phase flow in liquid state, and the velocity is calculated by Richard [2].
(2) Jet is assumed to be two-phase critical flow, and the velocity is calculated by Fauske's model.
(3) The fastest velocity among three impingement models.
(4) Total strain contains principal elastic strain and plastic strain.

In a transient analysis, alpha (or mass) and/or beta (or stiffness) damping may be used to represent the overall structural damping for the missile shield structure. Since stiffness damping plays a larger role in the structural response than mass damping in high frequency regions, it is only considered for the analysis. Critical damping ratio of the structure is determined by Regulatory Guide 1.61 [8] and an initial estimate was done to approximate the dominant frequency of the missile shield structure.

4 Evaluations of the Impact Analysis

The strain is used for guideline to evaluate the excessive deformation of the local impact area of the missile shield. The allowable strain can be determined by multiplying the elastic strain of the material to ductility ratio presented in the ANSI/AISC-N690 [9]. The allowable strain for the material of ASTM A588 [10] of missile shield is limited to 0.0167 mm/mm for evaluation. Therefore, reaction loads are reviewed to evaluate the overall structural responses of the IHA whether they are within the elastic limits.

Two different analyses were performed to compare the analysis results depending on assumptions of the flow models, in which Case 1 is for single-phase flow and Case 2 is for two-phase flow. The numerical data of jet and missile velocities and the analysis results of both cases are presented in Table 1. Since most extreme responses are occurred when a missile impacts near main column, this impact location is only considered in the analysis. From reviewing the analysis results, those of Case 2 are significantly lower than Case 1. Especially, the strain of Case 2 is limited in the allowable strain, whereas the strain of Case 1 exceeds the allowable strain limit above. It seems to require additional analysis to satisfy the limits.

Displaced shapes of the impact location for both cases are shown in Fig. 5 when the CEDM missile impacts near the main column. With respect to the displaced shape, full cycles of response are observed during the analysis duration, 0.1 s. By reviewing the curve shapes, it is found that plastic deformations on material are proceeding in both cases since the vibration of curves remains in the upper region of zero displacement line. Case 1 shows relatively large displacements and plastic deformation compared to those of Case 2.

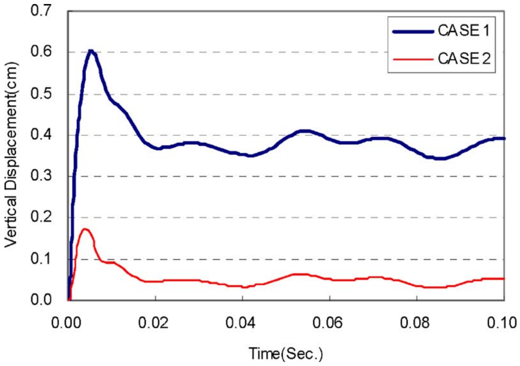


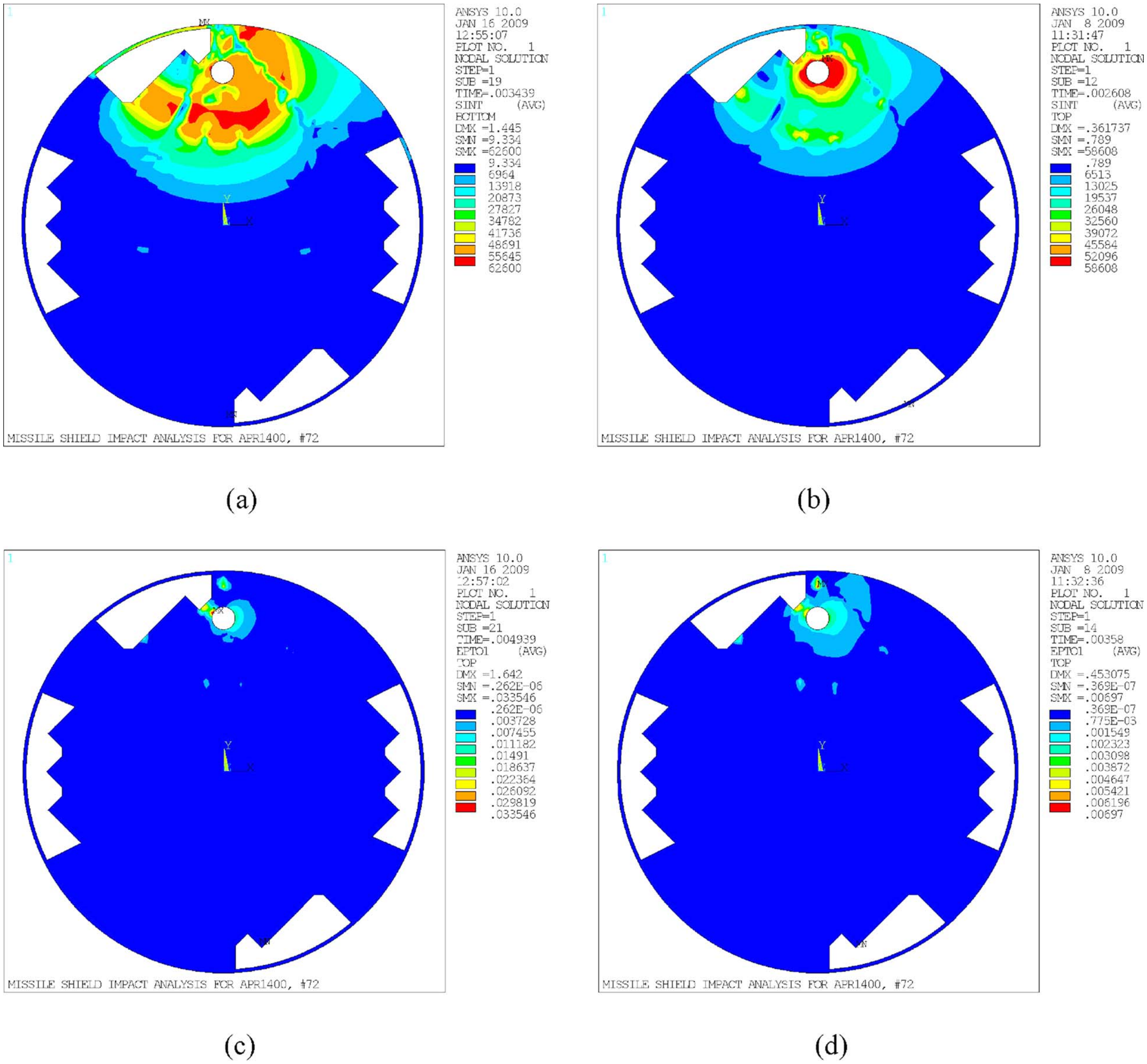
Fig. 5 Displaced shape at impact area of missile shield

Figure 6 shows the stress and strain distribution plots on the missile shield for Cases 1 and 2 when the maximum stress and strain happen at a certain time during impact behavior. The maximum values are included in Table 1. Higher stress intensities are distributed near the impact location and spreads out from it. Small radius of elements is excluded when obtaining the stress and strain results based on ANSI/AISC-N690 [9], and the hole by excluding the elements is shown in Fig. 6. It is justified that plastic deformation is proceeding near the impact location of missile shield. Strains are also distributed over the missile shield plate and are smaller than the allowable strain limits over the area of missile shield.

With respect to overall structural response, reaction at the lift lug of main columns, refer to Fig. 1, should be reviewed. As a supporting structure for the missile shield, the connection between lift lugs and main columns should maintain the structural integrity after missile impact. It is found that maximum reaction forces occur when the missile impacts near the main column in both cases and reaction forces in other main columns are much smaller. The curves in Fig. 7 show the reaction forces of the main columns for Cases 1 and 2. The thick solid lines are the reaction of main column near to missile impact, and the other lines are the reaction forces of two main columns apart from 120 deg of the main column. The reaction loads for Case 2 are much smaller than those for Case 1. The loads due to missile impact should be combined with other loads, such as safe shutdown earthquake (SSE), and as a result, they were satisfied with the allowable criteria in elastic range.

5 Conclusions

In this paper, the methodology and procedure for impact analysis with missile generation are extensively investigated in order to demonstrate the structural adequacy of the IHA and missile shield against the CEDM missile impact. Since the CEDM missile travels and hits on the missile shield by energy transferred from the jet impingement, the velocity of the fluid jet must be known. Fauske slip equilibrium model is utilized to determine the jet velocity with two-phase flow assumption for the jet fluid. In this paper, three different types of jet impingement model are proposed varying with jet expansions and size of the missile objects. Considerations, such as the finite element model, materials, damping, and mesh, are suggested for nonlinear transient analysis. The structural responses are evaluated to demonstrate structural integrity for the local damage as well as the overall damage of IHA. For local damage, strains are compared with the allowable strain limit extending to the plastic range and it is confirmed that the calculated value is within the allowable limit. For the overall damage, reactions between the IHA and RV head are obtained and these are acceptable to the elastic range. The methodology introduced in

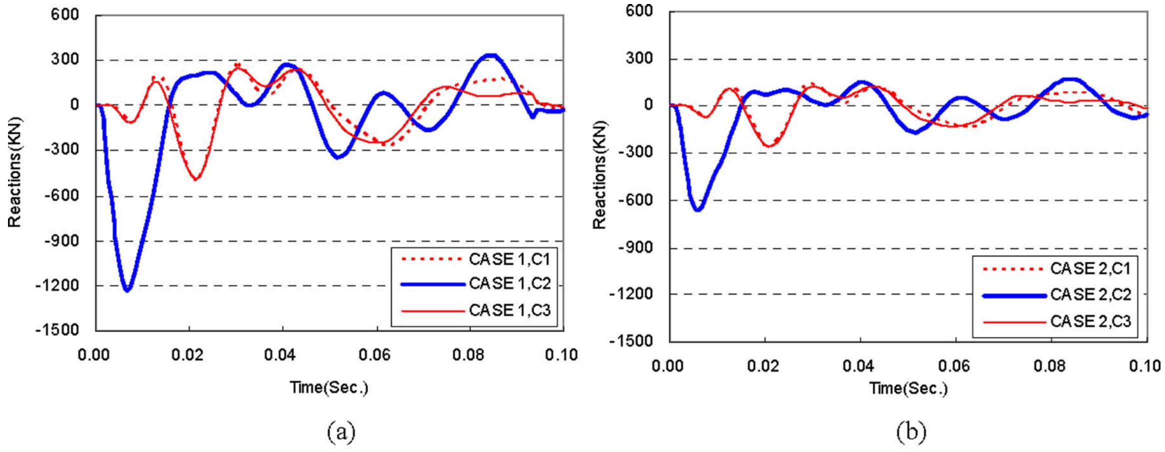


(a) (b)

(c) (d)

* Units are in psi for stress and in mm/mm for strain

Fig. 6 Stress and strain distribution of the missile shield for (*a*) Case 1 stress, (*b*) Case 2 stress, (*c*) Case 1 strain, and (*d*) Case 2 strain



(a) (b)

C1 and C3 : Vertical reactions of main columns far away from CEDM impact
C2 : Vertical reaction of main column near to CEDM impact

Fig. 7 Reaction loads of the three main columns for (*a*) Case 1 and (*b*) Case 2

this study can be practically used to the design of reactor vessel head lifting device with missile shield, which is broadly used for operating plants and newly constructed plants.

Nomenclature

A_a, A_b = cross section areas of the jet at the elevation, h_a and h_b, respectively
A_e = cross section area of the jet at the exit plane
A_h = cross section area of the jet at the elevation, h
A_0 = cross section area of the missile object, jet impinged
g_c = acceleration of the gravity
h = elevation from jet exit plane along x-axis
m = mass of the object weight (W), $m = W/g_c$
R_a, R_b = radii of the jet at the elevation, h_a and h_b, respectively
R_e = radius of the jet at the exit plane, same as the radius of nozzle
V = missile velocity at any elevation
V_a = jet velocity at the elevation, h_a
V_e = jet velocity at the exit plane
V_h = jet velocity at the elevation, h
V_{mz}, V_{mb} = missile velocity at the elevation, h_a and h_b, respectively
ρ_e = mass density of fluid at the jet exit, $\rho_e = \gamma_e / g_c$, where γ_e is the specific weight of fluid.
ϕ = angle of the jet expansion

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