

## Implicit vs Explicit Finite Element Analysis for Equipment Drop on a Nuclear Code Class Component

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### ABSTRACT

This paper presents a comparative analysis of implicit and explicit finite element analysis (FEA) methods for evaluating the impact of equipment drops on nuclear code class components, specifically the vault isolation bulkheads in CANDU nuclear plants. The implicit method treats the impact force as a static load, while the explicit method simulates the dynamic interaction between the dropped object and the component. The study reveals that the implicit method accurately predicts stresses and reactions for low impact momentum values. However, for higher momentum values, it significantly overestimates stresses and underestimates boundary reactions due to unaccounted inertial effects. Consequently, the implicit method is not suitable for high impact scenarios without adjustments. The explicit dynamics analysis, which considers time-dependent behaviours, inertial effects, and energy dissipation, provides more accurate results for high impact momentum scenarios. Therefore, it is recommended to use explicit dynamics analysis for high impact events or to apply the implicit method with caution, understanding its conservative nature regarding stresses and less conservative nature regarding boundary reactions. This study emphasizes the importance of selecting appropriate FEA methods based on the impact scenario to ensure the structural integrity and safety of critical nuclear components during refurbishment activities.

### INTRODUCTION

A significant number of nuclear reactors are undergoing life extension programs as many critical components, such as heat exchangers and piping systems reach the end of their operational life (J. Froats, 2007). The refurbishment work inside the reactor vault involves rigging and lifting various equipment, steel panels, and pipes. These activities pose a risk to critical nuclear code class components in the event of a drop accident, which could be caused by a seismic event or faulty rigging procedures. If a dropped object impacts a code-class component, the resulting stresses may exceed the allowable limits upon which the component was originally qualified. Such scenario does not necessarily cause any visible damage to the component. In such cases, inspection, repair, and requalification of the component are essential to continue refurbishment activities. Alternatively, simulating the drop scenario using Finite Element Analysis (FEA) can determine whether the stresses exceed the allowable limits or remain within acceptable ranges, potentially eliminating unnecessary inspections and delays. One of the most critical components which are prone to such drop loads is the vault isolation structure (Bulkheads) in CANDU plants. This structure acts as an alternate containment boundary during the refurbishment activities. There are two main purposes for this structure. Firstly, it isolates the Calandria Vessel from the Fuelling Machine Duct (FMD). Such isolations create a safer environment for the workers doing refurbishment activities on top of the bulkhead. Secondly, it acts as a platform for the replacement activities in the Calandria. This feature makes the

bulkheads susceptible for drop load rigging accidents during refurbishment activities. Usually, shielding layers are added on top of the bulkheads which acts as radiation shielding and counter upward pressures coming from the FMD. Moreover, it acts as a structural shielding to the bulkheads acting as a safeguard for any drop load. Such shielding does not fully protect the bulkheads from any possible drop load scenarios since the drop load will still be transferred to the bulkheads as a bearing pressure. The stresses induced from the bearing pressure might be exceeding the code allowable. In this case, the structure will need extensive inspection and might cause schedule delays.

This paper presents a comparative study of two modelling approaches for such events: an implicit equivalent static structure approach, where the impact force is treated as a static force, and an explicit dynamics analysis that simulates explicitly the dropped object and its interaction with the existing Code Class Component. The presented study considers a supporting structure that is qualified as ASME Section III, Div. 1 Class MC component.

## EXPLICIT DYNAMICS MODEL

The chosen component for this analysis is the vault isolation bulkheads. The structure is installed on both side of the Calandria in the vault slab. Once installed, the structure acts as alternate containment boundary and vault airlocks can be opened for vault access.

ANSYS LS-DYNA model was developed for explicit dynamics analysis to accurately simulate an equipment drop over the bulkheads. Explicit dynamics analysis allows for accurate capturing of the complex interaction between the two bodies (the equipment and the bulkhead) and considers energy dissipation in both bodies, deformations, contact forces, and stress wave propagation in the material. Moreover, it considers for time-dependent behaviours, including inertia and damping effects, which are crucial in dynamic loading situations.

For the equipment drop geometry, the geometry is simplified to a cube with unit volume, and it impacts the bulkhead with its sharp corner on the mid span of the bulkhead. The density of the cube is set to be  $10000 \text{ kg/m}^3$  and the impact velocity is varied to correspond to a range of impact momentum studied in this report. Figure 1 (a) shows the cube geometry, location and orientation.

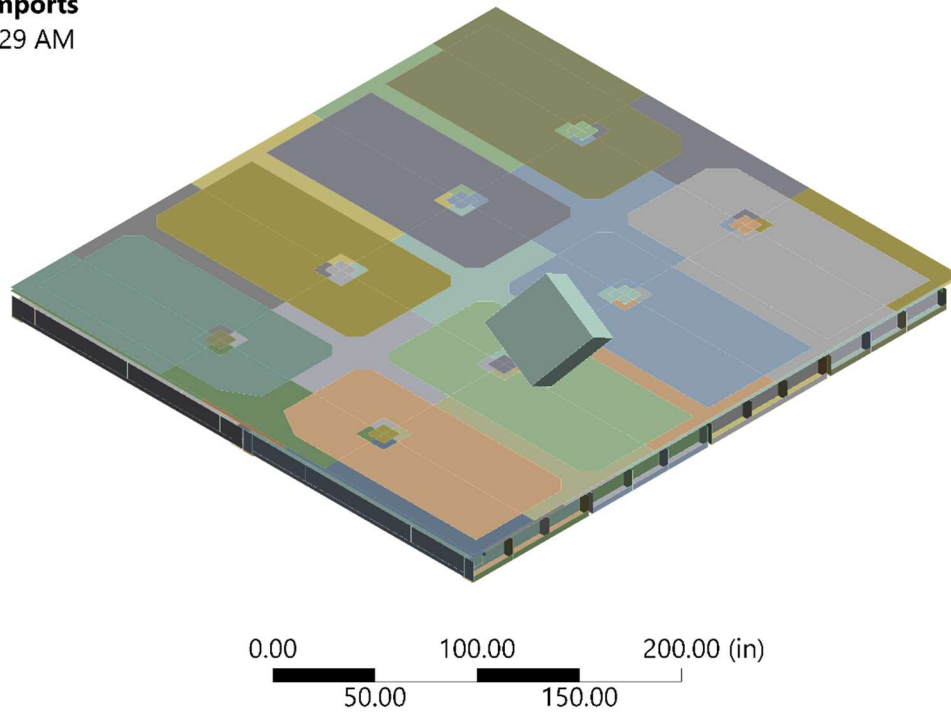
Figure 1 (b) shows the bottom of the structure with the panel holes where a rigid fixed support applied. It is important to note that the fixation of those holes in the model induces pseudo peak stresses around those holes which are due to rigid fixation. Those stresses are excluded from the analysis.

To ensure the accuracy of the model, the critical time step shall be monitored to ensure model accuracy. To initially guess the time step to be used in the analysis, the cube (drop load) mesh size is controlled through body sizing to be 63 mm, and the bulkheads are set to have a close sizing. Based on the average characteristic length extracted from LS-DYNA, the critical time step (CTS) is calculated as follows

$$CTS = \frac{l}{C_{Steel}} = \frac{0.063}{5200} = 1.2 \times 10^{-5} \quad (1)$$

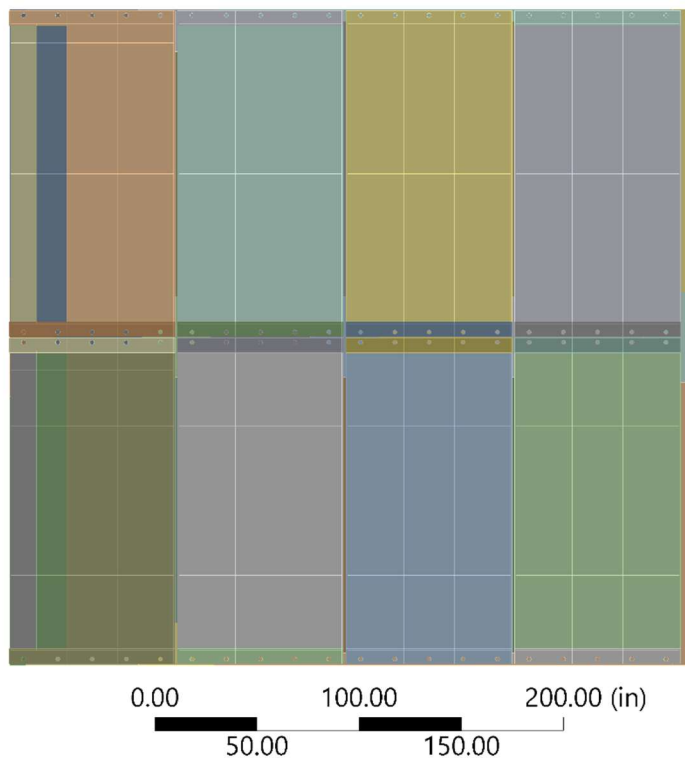
Where  $l$  is the average characteristic length and  $C_{Steel}$  is the speed of sound in steel ( $\sim 5200 \text{ m/sec.}$ ). Such calculations compute the time taken for a stress wave to travel across one element. However, it is an approximate calculation that is used to have an initial guess for the CTS. This CTS is used as an initial guess for a test case and the model is run with automatic mass scaling ON. Mass scaling is activated to speed up the simulation runtime, due to small elements in the impact zone and high number of load cases. The added mass of the cube is plotted and found to be exceeding 50% of the original mass. Hence, the CTS was reduced by an order of magnitude to  $10^{-6} \text{ sec.}$

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(a) Bulkheads Arrangement with Drop Object.

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(b) Bottom of the Structure Showing the Panel Holes.

Figure 1 Model Geometry Arrangement with Cube (Drop Object)

The added mass for the impact area and the cube was found to be zero. This means that mass scaling didn't take place in the area of interest and no change in the density in this area. Such check ensures that the time step chosen is small enough to accurately capture the stress wave propagation upon impact with no jeopardize to the material set metrics.

Hourglass energy: This is the energy associated with hourglass modes, which are nonphysical, zero energy deformation modes that can occur in under-integrated elements (like single integration point solid and shell elements). So, the increase in this energy in the area of interest would result in an inaccurate mode of deformation and pseudo-induced internal energies. The hourglass energy coefficient is set to be 0.001 and as a rule of thumb we aim for hourglass energy to be less than 10% of the peak internal energy for the impacted area. For all the cases the hourglass energy is found to be less than 1% of the peak internal energy at the area of impact.

It is important to note that the stresses are checked at the time when the stresses are maximum. This time doesn't coincide with the time of peak contact force. This is because the stress wave that propagates from the point of contact to spread through the bulkheads travels at the speed of sound in steel. So, there is a time delay between the moment of peak contact force and point of peak stresses. Figure 2 and Figure 3 shows a sample of the contact force and maximum stresses on the bulkhead bottom plate. It is clear that there is a time delay between the two peaks. For all the studied cases, the stresses are checked at the time of peak stress.

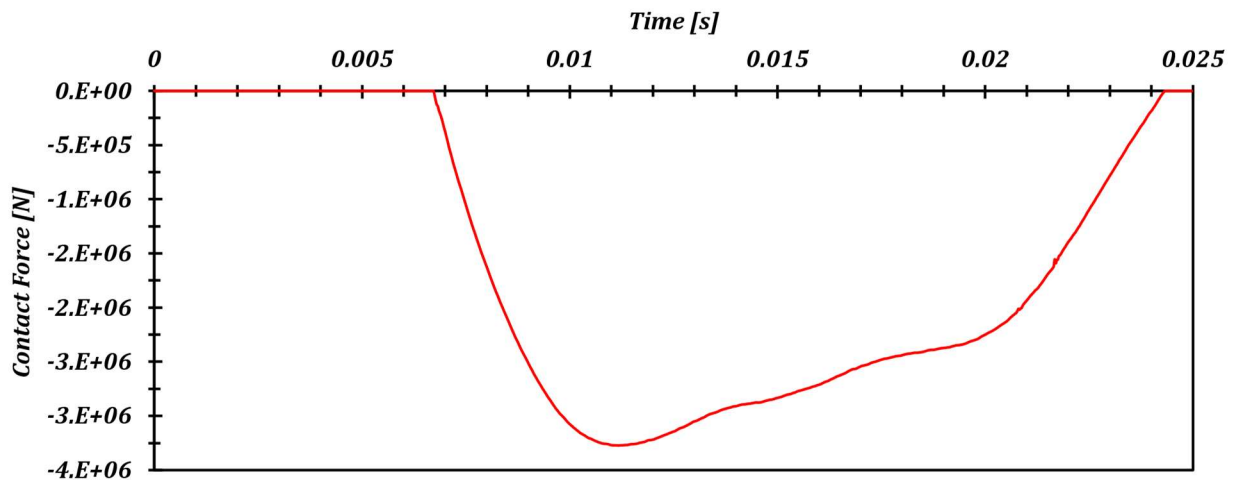


Figure 2 Sample of Drop Object (Cube) Contact Force

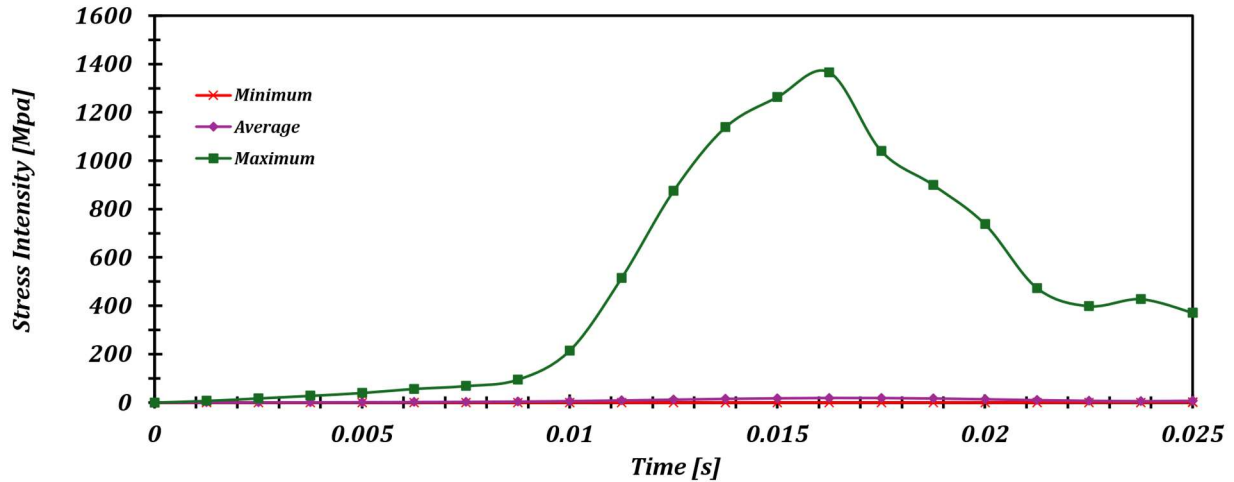


Figure 3 Sample of Stress Intensity in the Bottom Plate

### IMPLICIT DYNAMICS MODEL

A static structure model is developed using ANSYS Mechanical to compare with the explicit dynamics results in an attempt to see if the equivalent quasi-static method would be accurate and sufficient to qualify the bulkheads against the code allowable. The same model used for explicit dynamics is used for static structure solver (implicit dynamics) except that the drop object (cube) is removed and instead an equivalent static force is applied as a point force at the same node that the cube hit in the explicit dynamics model. The method used to get the equivalent static force that should be applied to the static structure model is adapted from Craig and Roy (1996). The cube's kinetic energy  $K$  just before impact is given by

$$K = \frac{1}{2}mv^2 \quad (2)$$

Where  $m$  is the mass of the cube and  $v$  is the impact velocity

When the cube impacts the plate, it deforms and the plate experiences displacement. If you assume the deformation of the plate is small and quasi-static. Using the elastic deformation theory (assuming linear elasticity)

$$\delta = \frac{F_{Static}}{k} \quad (3)$$

Where  $k$  is the plate stiffness,  $F_{Static}$  is the equivalent static force, and  $\delta$  is the localized plate deformation at the point of force application.

The total kinetic energy of the cube will be converted into the energy absorbed by the plate during the impact (assuming no energy losses like friction, heat, etc.). The energy absorbed by the plate during static deformation is given by

$$E_{Static} = \frac{1}{2}k\delta^2 \quad (4)$$

For the system to be in equilibrium between dynamic and static forces, equate the total kinetic energy of the cube to the static energy absorbed by the plate

$$\frac{1}{2}mv^2 = \frac{1}{2}k\delta^2 \quad (5)$$

Now, substitute  $\delta$  from the earlier equation

$$F_{Static} = \sqrt{mk} \times v \quad (6)$$

This gives the equivalent static force that, if applied statically, would result, theoretically, in the same displacement as the dynamic impact.

To get the structural stiffness at the point of contact, a test run was done with a force within the same order of magnitude of the studied cases. The deflection at the point of contact is extracted and the stiffness is calculated as follows

$$k = \frac{F_{Static}}{\delta} = 6.32 \times 10^8 \text{ N/m} \quad (7)$$

Table 1 shows the 6 studied cases. The mass of the cube is constant and set to be  $10000 \text{ kg/m}^3$ .

Table 1 Studied Cases

<i>Case Number</i>	<i>Impact Velocity (m/s)</i>	<i>Impact Momentum (kN.s)</i>	<i>Equivalent Static Force (kN)</i>
<i>1</i>	0.5	5	1258
<i>2</i>	1	10	2515
<i>3</i>	1.5	15	3773
<i>4</i>	2	20	5030
<i>5</i>	2.5	25	6288
<i>6</i>	3	30	7545

## ACCEPTANCE CRITERIA

The component will be qualified against ASME BPVC Section III Subsection NE, 2010. The drop loads analysed herein can be justified as a service Level D load due to the unlikely occurrence of this event. As per CSA N285.0 Clause 7.3.1, “Level D service conditions are unplanned but anticipated events that do not occur more than twice in the life of the system. The structural integrity of the system shall be preserved but gross deformation requiring shutdown for repair is acceptable. The material is assumed to be SA-516 Gr70.

## RESULTS AND DISCUSSION

Figure 4(a) shows the maximum membrane stresses excluding the peak stresses at discontinuity for two types of analyses for different impact momentums. It is obvious that the implicit dynamics method overpredicts the membrane stresses. The error in the implicit dynamics method is directly proportional to the impact momentum. While only the 0.5 kN.s momentum is passing the code allowable for the implicit model, the explicit model shows a value up to 2.25 kN.s passing the NE limit. Figure 4(b) shows the maximum membrane plus bending stresses excluding the peak stresses at discontinuity for two types of analyses for different impact momentums. The figure shows a similar behaviour like the membrane stresses except that the two methods show a higher threshold for the impact momentum. The total bolt reaction forces for both implicit and explicit dynamic analyses are presented in Figure 4(c). The results indicate that the explicit dynamic method exhibits a higher bolt reaction force compared to the implicit approach. Additionally, the variation in impact momentum has a minimal influence on the difference between the two methods. This can be attributed to the inertia of the bulkhead, which is captured in the explicit dynamic analysis but not in the static force calculations of the implicit method. The deceleration of the bulkhead after impact, combined with its mass, leads to an increased total bolt reaction force. The peak contact forces for both methods are presented in Figure 4(d). The discrepancy between the two methods increases linearly

with rising impact momentum, with the explicit dynamics method yielding lower peak contact forces than the implicit method. This deviation in the implicit dynamics approach can be utilized to establish an impact momentum threshold at which the difference between the two methods becomes acceptable.

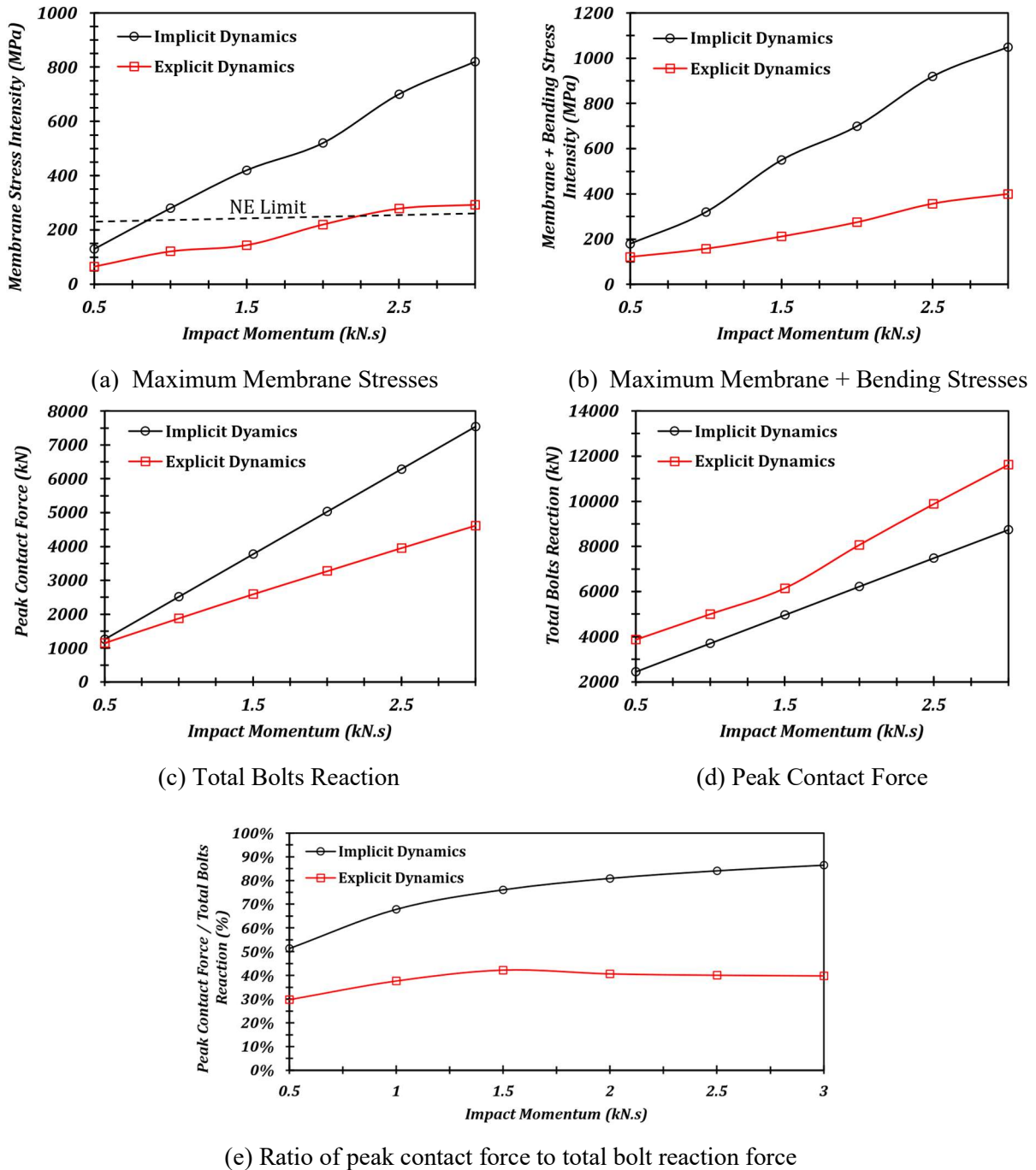


Figure 4 - Stress and force results against impact momentum

Lastly, the ratio of peak contact force to total bolt reaction force for both methods is presented in Figure 4(e). In the explicit dynamics method, accounting for the post-impact inertia of the bulkhead significantly increases the total bolt reaction force compared to the implicit method, which reduces the ratio of the peak

contact force to total bolt reaction to an average of 35%. Consequently, the percentage of peak contact force relative to the total bolt reaction is higher in the implicit dynamics solution, where bulkhead inertial forces are not considered, and the total bolt reaction is primarily a response to the impact force and static weight, with the ratio averaging about 80%.

## CONCLUSION

This paper conducts a comparative analysis of two modeling approaches for the impact of equipment drops on nuclear code class components: one approach utilizes an implicit equivalent static structure method, where the impact force is treated as a static load, while the other employs an explicit dynamics analysis to simulate the dropped object and its interaction with the existing Code Class Component. The study specifically examines a supporting structure qualified as an ASME Section III, Class MC component, which is particularly susceptible to rigging accidents during refurbishment activities.

The results indicate that the implicit dynamics method can accurately predict the stresses and reactions on the supporting structures for low impact momentum values. However, for higher momentum values, the stresses and reactions deviate from those predicted by the explicit dynamics model. Specifically, for higher momentum values, the implicit method significantly overestimates the stresses and underestimates the boundary reactions due to the inertial effects not accounted for in the implicit dynamics model. Consequently, applying a correction factor to align the implicit method with the explicit method is not feasible due to the divergence in stress and reaction values with increasing impact momentum. Therefore, it is recommended to use explicit dynamics analysis for high impact momentum scenarios or to use the implicit method with the understanding that it will be more conservative in terms of stresses and less conservative in terms of boundary reactions, i.e., implanting correction factor is required.

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