

A Methodology for Evaluating Operating Loads during Fuel Insertion into Fuel Handling Equipment

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1. Introduction

The fuel handling system, designed to perform fuel loading and unloading within the reactor core, comprises various types of specialized fuel handling equipment. Specifically, the equipment designed to receive and transfer a fuel assembly are the new fuel elevator(NFE) and fuel transfer system(FTS).

As components of NFE and FTS, the fuel cavities are provided to receive a fuel assembly from the spent fuel handling machine and the refueling machine. During the insertion of a fuel assembly into the fuel cavity, the fuel cavity experiences impact loading upon initial contact. This impact load must be factored into the estimation of operating loads, which serves as the design for the embedded steel plates supporting the fuel handling equipment.

This paper proposes a methodology for evaluating operating loads on embedded steel plates under fuel impact loads by theoretical formulation and verified through finite element method.

2. Theoretical Formulation

2.1 Fuel Grappling Mechanism

In APR1400, the gripper which is a device to engage a fuel assembly is installed in the spent fuel handling machine and the refueling machine. It is designed with four latches arranged at regular 90-degree intervals. Each latch descends into the empty space of the top nozzle center post of the fuel assembly, rotates, and then ascends to engage with the top nozzle center post.

Through this fuel grappling mechanism, a fuel assembly is lowered at a constant velocity until it is seated in the cavity of NFE or FTS. Simultaneously, the gripper engagement is released, isolating the fuel assembly from external driving forces and allowing the impact response to be governed strictly by the conservation of energy.

2.2 Governing Equation

In accordance with the law of conservation of energy, the sum of the external energy(U_e) is equal to the sum of the internal energy(U_i). Consequently, starting from the instant of fuel seating, the combined kinetic and potential energy throughout the impact duration is fully converted into elastic strain energy[1].

Based on the law of conservation of energy in Equation 1, the dynamic effect caused by the impact velocity is evaluated using the impact factor(n) as shown in Equation 2. The value of impact factor(n) is determined by the stiffness(k) of the equipment, the velocity(v) of the impacting fuel assembly, the mass(m) of the fuel assembly and gravity(g). Since the corresponding equation assumes that all energy from the fuel assembly is converted into the elastic energy of the impacted equipment, energy dissipation such as fuel deformation is not considered. Furthermore, although fuel handling operations occur underwater, buoyancy effects are conservatively neglected.

The operating load($L_{operating}$) on embedded steel plates generated by the impact load of the fuel assembly is determined by the dead weight of the equipment($D.W_{equip}$), the dead weight of a fuel assembly($D.W_{fuel}$) and impact factor(n) as shown in Equation 3.

$$\text{Equation 1. } U_e = U_i$$

$$\text{Equation 2. } n = 1 + \sqrt{1 + \frac{kv^2}{mg^2}}$$

$$\text{Equation 3. } L_{operating} = D.W_{equip} + n \times D.W_{fuel}$$

2.3 Result

To determine the operating load acting on the embedded steel plates based on the theoretical formula, the impact factor(n) needs to be calculated. For the impact factor(n) calculation, the stiffness(k) of the fuel handling equipment(NFE or FTS) depending on the equipment geometry, material properties and component connection methods is assumed to be a value of 5E8 N/m. The assumed stiffness value is based on reference plant design data and engineering judgement that accounts for the actual mechanical and structural compliance, including steel framing, bolted joints, and wire/cable flexibility. A velocity of 0.015 m/s is applied for the fuel lowering speed to reflect the actual operating condition. As a result, the impact factor(n) is calculated as 2.67.

For operating load estimation, the equipment weight is assumed to be 1,000 kg, while the fuel weight is assumed to be 650 kg based on fuel specification. .

Consequently, taking into account the impact during fuel seating, the operating load on the embedded plate from the fuel handling equipment(NFE or FTS) is calculated to be 2.68E4 N using Equation 3.

3. Finite Element Analysis

3.1 Configuration of Geometric Model

To maintain consistency with theoretical formula, the fuel assembly is modeled as a rigid body shaped as a rectangular parallelepiped based on the geometric data of fuel assembly, thereby preventing energy dissipation within the fuel assembly. Detailed modeling of the fuel assembly is deemed unnecessary, as its structural integrity including stresses and displacements is not of primary interest.

The equipment is also modeled as a rectangular parallelepiped, incorporating the same target stiffness of $5E8$ N/m, as applied in the theoretical formulation. Furthermore, to capture the contact initiated by the fuel descent at $t=0$, the bottom surface of the fuel assembly and the top surface of the equipment are positioned to be in direct contact at the start of the simulation.

The finite element model employs 3D 8-node solid elements(SOLID164) with an approximate element size of 30 mm for both the fuel assembly and the equipment. To simulate the mechanical interaction upon contact, an automatic surface-to-surface contact option(ASTS) is applied between the two components.

The FE models of the fuel assembly and fuel handling equipment are shown as Fig. 1.

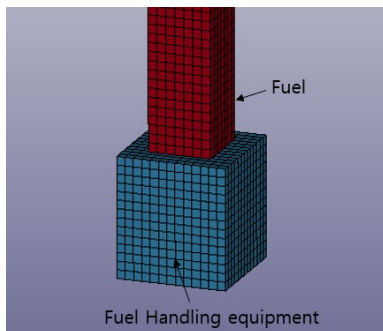


Fig. 1. FE Models of the fuel assembly and fuel handling equipment.

3.2 Boundary Condition

To reflect the descending motion, an initial axial velocity($V_0=0.015$ m/s) is applied to the fuel assembly, while gravitational acceleration(g) is enforced throughout the analysis duration to replicate actual operating conditions. Also, the bottom surface of the equipment to extract the reaction force is fully constrained.

3.3 Result

The results of reaction force from the bottom surface of the equipment is shown as Fig.2. It is shown that the reaction force has a maximum value of $2.53E4$ N. Thereafter, it gradually approaches and ultimately converges to $1.62E4$ N. The maximum value of $2.53E4$ N aligns with the theoretically derived value of $2.68E4$ N by approximately 94.4%.

Furthermore, the gradual convergence of the transient response to the steady-state static value demonstrates the natural dissipation of transient vibrational energy, driven by the inherent numerical characteristics of the explicit solver and contact algorithms, allowing the system to settle stably into its final static equilibrium state.

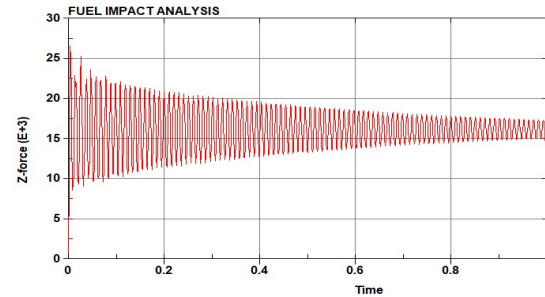


Fig. 2. Time-dependent variation of reaction force.

4. Conclusions

To determine operating loads on the embedded steel plates during fuel insertion into the fuel handling equipment, the methodology is developed using theoretical formulation and verified through finite element analysis.

A comparison of the maximum reaction force induced by impact load between the theoretical formulation and finite element analysis demonstrated an agreement of 94.4%. By obtaining the stiffness values for each fuel handling equipment according to this methodology, the operating load resulting from impact forces during fuel insertion is expected to be straightforwardly calculated using the theoretical formulation.

In future research, a fuel assembly will be modeled as an elastic body to reflect realistic behavior and the degree of conservatism in the results of this paper will be examined.

REFERENCES

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