A Strain-Rate-Based Reassessment of the Equivalent Free-Fall Drop Height

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1. Introduction

Spent nuclear fuel (SNF) transportation casks must maintain their safety functions during severe transport and handling events. Aircraft-engine impact is therefore considered in assessments of nuclear facilities and transport systems [1-3]. Because full-scale engine-impact tests require specialized facilities and substantial cost, explicit dynamic finite element analysis (FEA) is widely used to evaluate impact response. The calculated response, however, is affected by numerical modeling conditions and rate-dependent material behavior.

In this study, free-fall drop tests were conducted on an SM355A plate at release heights of 0.25 and 1.0 m, and corresponding ABAQUS/Explicit analyses were performed. The measured and calculated strain histories were compared at the instrumented locations. On the basis of the observed agreement, the calculated maximum positive strain rates were compared with the reported KAERI aircraft-engine impact test response.

2. Test and Finite Element Analysis

The reference aircraft-engine impact condition used a mass of 4,300 kg and a velocity of 60 m/s. With the reported impact area of 0.5683 m² and cask wall thickness of 0.215 m, the corresponding impact energy density was 63.339 MJ/m³. For the 3,963 kg drop assembly, a target plate thickness of 0.010 m, and a drop impact area of 0.1534 m², the same energy density corresponds to a free-fall height of approximately 2.5 m. This value was a derived reference condition and was not a performed test height.

The test article was a 2,000 x 2,000 x 10 mm SM355A plate. The drop assembly consisted of a 3,821 kg striker and a 142 kg auxiliary mass, giving a total falling mass of 3,963 kg. Accelerometers A1-A3 and strain gauges S1-S4 were installed on the bottom surface of the plate. Free-fall tests were performed at 0.25 and 1.0 m. During the 1.0 m test, the strain-gauge signals were affected by progressive gauge detachment after the initial impact response.

A quarter-symmetry finite element model was developed for the corresponding drop analyses. The model contained 264,360 elements and 314,536 nodes. The plate and support components were represented by deformable solid elements, whereas the striker was idealized as a rigid body. The measured SM355A properties were used, and rate-dependent plastic behavior was represented by the Johnson-Cook model [4,5]. The striker was constrained to vertical motion, and frictionless contact was defined between the striker and plate. The analyses were performed using ABAQUS/Explicit [6] under initial and boundary conditions corresponding to each test.

3. Results and Discussion

At both drop heights, the calculated strain histories reproduced the rapid initial response and the subsequent overall trends observed in the tests. For S1 and S4, the measured/calculated peak strains were 0.0172/0.0131 and 0.0140/0.0109 mm/mm at 0.25 m, and 0.0237/0.0150 and 0.0230/0.0148 mm/mm at 1.0 m, respectively. The calculated peak values were lower than the measured values, and interpretation of the 1.0 m response was limited by gauge detachment. Nevertheless, the analysis showed reasonable overall agreement with the principal trends of the measured strain response.

The calculated maximum positive principal strain rates at S1 and S4 were 1.2730 and 2.1423 s^{-1} at 0.25 m, and 3.0947 and 3.9455 s^{-1} at 1.0 m, respectively. These values were compared with the maximum positive principal strain rate of 6.4641 s^{-1} reported at gauge S15 in the KAERI aircraft-engine impact test [3]. At the instant of maximum positive strain rate, the reported KAERI S15 strain was 1.546 x 10^{-4} mm/mm. The corresponding calculated strains at S1 and S4 were 1.555 x 10^{-4} and 1.548 x 10^{-4} mm/mm at 0.25 m, and 5.394 x 10^{-4} and 5.342 x 10^{-4} mm/mm at 1.0 m. The calculated strain rates increased with drop height, while both tested drop conditions remained below the reported KAERI rate.

4. Conclusions

Free-fall drop tests were performed at heights of 0.25 and 1.0 m, and corresponding ABAQUS/Explicit analyses were conducted. The calculated strain histories reasonably reproduced the overall trends observed in the tests, despite some differences in peak magnitude. Based on this agreement, the calculated maximum positive strain rates were compared with the reported response from the KAERI aircraft-engine impact test.

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