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Guidance Document – Use of Explicit Finite Element Analysis for the Evaluation of Radioactive Material Transport Packages and Storage Casks in Energy-Limited Impact Events



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NTB-6-2025

Guidance Document Use of Explicit Finite Element Analysis for the Evaluation of Radioactive Material Transport Packages and Storage Casks in Energy-Limited Impact Events

Prepared by:

ASME Special Working Group on Computational Modeling for Explicit Dynamics



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FOREWORD

This guidance document sets out current "good practice" in using the explicit finite element analysis method for the evaluation of the behavior of radioactive material transport packages and storage casks in energy-limited impact events. This document provides guidance for developing quality finite element models to ensure, with reasonable certainty, that the model produces accurate results for comparison with the strain-based or stress-based acceptance criteria of Section III, Division 3 of the ASME Boiler and Pressure Vessel Code.

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ABBREVIATIONS AND ACRONYMS

ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CFR	Code of Federal Regulations
DU	Depleted uranium
FE	Finite element
FEA	Finite element analysis
IAEA	International Atomic Energy Agency
SRI	Selectively reduced integration
TF	Triaxiality factor
US-NRC	United States Nuclear Regulatory Commission

DEFINITIONS

aspect ratio – The proportional relationship between the maximum and minimum edge length of an element. This value describes how the element shape differs from an ideal element shape (e.g., a square in 2-D, a cube in 3-D). This value can be used to describe the quality of each finite element. See Section 8.3.

brick element – An 8-node solid finite element formulated in three-dimensional space, also known as a hexahedral element. See Section 8.4.1.

canisters – Containers (e.g., steel shell with a baseplate and lid) used to store or transport spent nuclear fuel or high-level waste within storage casks or transport packages.

constrain (constraint, constraining) – A method of controlling nodal motion (i.e., degrees of freedom). The simplest example of a constraint is setting the displacement or rotation of a node to zero. Constraint may also be used to force nodes to move in a specific manner relative to the motion of other nodes (e.g., coupling of nodes). See Section 11.2.

constraint equation – Constraint equations are analytical expressions between degrees of freedom in the model to represent physical behavior. See Section 8.5.

contact energy – Contact energy is the sum of the energies resulting from the forces and displacements at the contact interfaces. The contact energy may also include frictional forces acting on the interface. See Section 9.6.

containment boundary – Assembly of components of packages intended to retain the radioactive material during transport or storage.

conservative (results, assumptions, etc.) – A conservative analysis or set of assumptions predict results that are closer to a limit state than reality. Conservatism can depend on the limit state being evaluated. Different limit states often result in opposing targets for conservatism.

critical timestep – The stability of the explicit dynamic solution is dependent on the size of the timestep. The critical timestep (i.e., stable time increment) defines the largest time increment to ensure convergence of the transient solution. See Section 12.2.

energy-limited event – Dynamic loading event (e.g., drops, impacts) where behavior of the structure is controlled by the absorption of a finite amount of kinetic energy.

equivalent plastic strain – A cumulative, positive, scalar, non-decreasing strain measure that accounts for the entire deformation history. It is an integral of the plastic strain at each timestep. Some FEA software programs refer to this as effective plastic strain.

explicit finite element analysis/explicit dynamics – A numerical procedure to solve the equations of motion for the structure being analyzed by calculating the system status at a given time directly from the system status at a previous time. This method does not require establishing equilibrium at each timestep, nor the inversion of the stiffness matrix.

homogenization – A modeling technique that permits certain parts of the model to be simplified by removing details while still representing the overall behavior. See Section 7.3.2.2.

hourglass energy – Artificial energy absorbed by numerical techniques to control hourglassing. See Section 12.5.

hourglassing – Nonphysical modes of element deformation from reduced-integration finite elements. These modes are historically called hourglass modes because they deform the elements into an hourglass shape (i.e., zigzag shape). See Section 12.5.

impact limiter/shock absorber – These are components used to limit the accelerations and resulting damage experienced by the package/contents due to accident conditions. These are typically made of crushable materials. See Section 10.4.

implicit finite element analysis – A numerical procedure to solve a transient or static problem, in which the system status at a given time or at the steady state is calculated by solving the equilibrium equations. This method requires the inversion of the stiffness matrix to solve the equilibrium equations.

integration point – Location(s) associated with a finite element where stress/strain values are calculated. See Section 8.2.

mesh connectivity – The connection status between adjacent elements (e.g., share common nodes, tied contact, independent contact surfaces). See Section 8.5.

mesh discontinuity – Different mesh densities between two interfacing surfaces. See Section 8.6.

nonlinear behavior – The behavior of a system in which the change of the output is not proportional to the change of the input. This behavior can be caused by phenomena such as material nonlinearity (e.g., plasticity) or geometrical nonlinearity (e.g., gaps, contact). See Section 10 for material nonlinearity, Section 18 for modeling of gaps, and Section 9 for contact.

reduced integration/single-point integration –A technique that does not fully integrate either the shear or the volumetric contribution to stiffness. For elements with a linear shape function typically used in explicit analyses, Gaussian integration using a single point at the element centroid is typical. See Section 8.4.1.1.

selectively reduced integration (SRI) – A technique that fully integrates the shear contribution to stiffness, whereas the volumetric contribution uses reduced integration. See Section 8.4.1.2.

strain-rate effects – The material behavior where the stress-strain curve is dependent on the rate of change in strain. See Section 10.1.2 and Figure 2-1 of Section 2.

submodel – A portion of the structure being analyzed with additional details than in the overall model. The submodel must maintain continuity and boundary conditions with the overall model. See Section 7.3.2.3.

tied interfaces (tied contact, tie constraint) – A form of contact used to join separately meshed regions together. See Section 9.

1 INTRODUCTION

The finite element analysis (FEA) method has evolved over the decades such that it is now capable of accurately predicting the nonlinear response of complicated structures subject to energy-limited events and undergoing significant deformations. In recent years, the explicit FEA method has increasingly been used in the development of transport packages, storage casks, and as part of approval applications to prove compliance with regulatory requirements. Finite element models of spent fuel transport packages, storage casks, and canisters typically used in nonlinear impact analyses may contain hundreds of thousands or even millions of elements, resulting in a large analysis effort.

Proficient analysis of a structure exhibiting significant nonlinear behavior takes years of dedicated learning and experience. Even the best analysts have a healthy respect for pitfalls when using the FEA method. The impressive graphical output can lead to the false impression that answers emanating from an FEA are automatically valid and usable, when, in fact, generating accurate results requires significant care and skill on the part of the user.

Virtually any finite element model can produce results. The question is, how accurate are they? Did the analyst follow good practice in developing the model, or did inadequacies in the modeling introduce unintended behavior into the structure?

The goal of a structural FEA is to produce stress, strain, and displacement results to compare to acceptance criteria defined for the structure under analysis. In the design of any structure, incentives to minimize cost and weight could drive designers to develop structures that come close to the acceptance criteria limits. This places a high importance on developing accurate models. In this context, "accurate" means that the calculated stresses and strains would, within some tolerance, be representative of the actual stresses and strains that would occur in the structure as a result of the event under analysis.

This guidance document sets out current "good practice" in using the explicit finite element analysis method for the evaluation of the behavior of radioactive material transport packages and storage casks in energy-limited impact events. This guidance document was developed in support of the strain-based acceptance criteria of Section III, Division 3, WB/WC-3700 of the ASME Boiler and Pressure Vessel Code (Reference [1]). It may, however, be used as a means by which the quality of a finite element model may be evaluated, whether the analyses are for demonstrating compliance with strain-based or stress-based acceptance criteria. While much of the document discusses the modeling of radioactive material transport packages and storage casks, it also applies to structural and stress analysis of other types of structures using explicit dynamics finite element programs to evaluate the response to energy-limited events.

This document is not intended as a substitute for the theory and users' manuals of available explicit dynamics programs. It also assumes that the analyst has experience using at least general-purpose finite element software. When necessary, use technical support from the software developers who know the internal workings of the selected program to provide advice on its appropriate use and limitations.