TCSC 1087 **March 2018**

TCSC
Transport Container Standardisation Committee

Transport of Radioactive Material Code of Practice

Good Practice Guide – The Application of Finite Element Analysis to Demonstrate Impact Performance of Transport Package Designs

Publisher	TCSC
Acknowledgement	This Code of Practice has been prepared by Ove Arup & Partners Ltd on behalf of the TCSC. It has also been reviewed by a range of individuals chosen by the TCSC for their technical expertise in the field of Finite Element Analysis.
Note	The information embodied in this Code of Practice has been compiled and agreed by the TCSC. Neither the TCSC members nor the organisations that they represent shall be liable for any detrimental consequences resulting from following the recommendations in the document.

This Code of Practice has been prepared by the Transport Container Standardisation Committee (TCSC).

The purpose of the TCSC is “to examine the requirements for the safe transport of radioactive material with a view to standardisation and, as appropriate, produce and maintain guidance in the form of standards documentation”. The TCSC began as an industry forum in the 1960’s and has supported the radioactive materials transport industry for more than fifty years. In 2013 the TCSC was registered at Companies House as a company limited by guarantee.

The TCSC member organisations are:

- Arup
- AWE plc
- Croft Associates Ltd
- Cyclife
- Dounreay Site Restoration Ltd
- EDF Energy
- Frazer-Nash
- GE Healthcare Ltd
- GNS
- International Nuclear Services
- LLW Repository Ltd
- Magnox
- Nuvia Limited
- Radioactive Waste Management
- Rolls-Royce Power Engineering plc
- Sellafield Ltd
- Westinghouse

Comments and suggestions relating to the improvement of this Code of Practice should be addressed to the TCSC Secretariat at admin@tcsc.org.uk.

www.tcsc.org.uk

CONTENTS

Foreword

The Finite Element Method (FEM) is a powerful tool for the simulation of structural and thermal behaviour of structures. In recent years, the explicit FEM has increasingly been used in the development of transport packages and as part of approval applications to demonstrate the performance of packages.

This Guide sets out current ‘good practice’ in using the explicit FEM for the analysis of impact behaviour of transport packages and specifically for the demonstration of compliance with the UK regulations for public domain transport when applying for the necessary approval from the UK Office for Nuclear Regulation.

The objective is to raise the standard of Finite Element (FE) analyses so as to improve the confidence that can be placed in FE analyses to enable them to take a more central role in demonstrating regulatory compliance.

1. Introduction

IAEA *Regulations for the Safe Transport of Radioactive Material* [1] (Transport Regulations) refers to testing, reference to previous satisfactory demonstrations of a sufficiently similar nature, calculations or reasoned arguments, or a combination of these, as methods to demonstrate compliance with performance standards.

The roles of testing and calculations (which include analysis), and the relative prominence of the two, may vary between Competent Authorities in different countries. This can range from analysis being regarded as the primary mode of demonstration with testing as confirmatory, to testing being the primary mode of demonstration supplemented by analysis. The UK Competent Authority, Office for Nuclear Regulation (ONR), has no prescriptive requirements in this regard; it is the applicant's responsibility to justify the combination [2].

The Finite Element Method (FEM) is a powerful tool for the simulation of structural and thermal behaviour of structures. The implicit method is best suited to simulate the static behaviour of structures while the explicit method is best suited to simulate dynamic non-linear problems in the time domain. FEM allows the simulation of structural and thermal behaviour which hand calculations cannot reasonably do and can provide detailed information about the behaviour which even testing cannot provide. Over the years, it has been demonstrated by many users that if used properly, it can produce results that replicate test results faithfully even for complex geometry under complex loadings.

In recent years, the explicit FEM has increasingly been used in the development of transport packages and as part of approval applications to demonstrate the performance of packages.

This Guide sets out current 'good practice' in using explicit FEM for the analysis of the structural behaviour of transport packages in impact events and specifically for the demonstration of compliance with the UK regulations for public domain transport when applying for the necessary approval from the ONR. The objective is to raise the standard of Finite Element (FE) analyses (i.e. analyses using the FEM) so as to improve the confidence that can be placed in FE analyses, and so that FE analyses can take a more central role in demonstrating regulatory compliance.

This is a "Good Practice Guide", and not strictly a "Code of Practice", a primer of FE analysis or a training manual of any specific FE analysis code. Although the context of this guide is the application for approval from the ONR for public domain transport, the good practices are equally relevant in the application of licences for on-site transport.

2. Managing the FE Analysis Process

Whether it is a single FE analysis of a single drop scenario, or a complete campaign of many drop scenarios to demonstrate the impact performance against the IAEA drop test requirements, FE analysis is a process and it should be managed as a process. The soundness of the process is crucial to the soundness of the output.

The process should consist of the following stages:

- Planning – from defining the needs to deciding on the requirements of each analysis.
- Modelling – from taking the requirements of each analysis, to deciding on the details of the model and to building the model to a stage when it is ready for analysis.
- Analysis – using the FE software to analyse the completed model.

- Checking and results evaluation – checking the analysis and evaluating the results from the analysis (a) to evaluate the adequacy of the model and the analysis, and (b) to understand the behaviour of the structure analysed.
- Evaluation of the transport package – evaluating the performance of the transport package against the defined criteria, based on the results of the analysis.
- Post-processing and reporting – extracting appropriate results and presenting the case to demonstrate performance of the package.
- Documentation - documenting the models, the analysis, the results and the evaluations.
- Review - reviewing the process and continuous improvement.

If drop tests are carried out to accompany the analysis, the process would also include the following additional steps to validate the model against drop tests:

- Modelling of the drop test packages.
- Simulation of the drop tests.
- Comparison of the analysis results with tests results.

Very few FE analyses can be completed in a single pass through the above stages. It is likely that the FE model may need to be re-run to correct initial errors, modelling assumptions may need to be modified in the light of analysis results, the mesh may need to be refined considering the extent of deformation, and so on. Nonetheless, each FE analysis, or campaign of FE analysis should consist of all of the above stages.

In addition, sensitivity analyses to demonstrate the robustness of the analyses with variation of modelling parameters (e.g. mesh refinement, stress-strain modelling assumptions) or to demonstrate the robustness of the package with variation of uncertainties (e.g. friction), should be included as part of the process.

A well-managed process would consist of the following ingredients:

- Strong leadership.
- Clearly defined objectives.
- Clearly defined plan of action.
- Clearly defined responsibility within the analysis team.
- Clearly defined programme.
- Sufficient and good use of time and resources.
- Suitably qualified and experienced analysis team.
- Good communication within the team and with stakeholders.
- Buy-in from stakeholders.
- Stringent quality assurance procedures

Advice from the ONR on the analysis programme should be sought at the earliest opportunity.

3. Planning

Careful planning of the analysis campaign must precede any modelling or analysis.

Given that analysis and testing are often used in combination to demonstrate the performance of a package against the Transport Regulations, the objectives of the analyses in relation to the testing that are to be carried out, need first to be defined. Then the questions: “what analyses need to be carried out”, “how to model”, “how to analyse”, “how to check”, etc need to be addressed. The decisions and justifications should then be documented in an analysis plan. The analysis plan should be agreed with all the stakeholders before any modelling and analysis is to be carried out. It should also be presented to the Competent Authority for comment at the earliest opportunity. It should be reviewed and revised at suitable intervals during the campaign.

An analysis plan should define the following items:

3.1. Objectives of the Analyses

As analysis and testing are often used in combination, it is important to define the purpose of the analyses within the approval application, e.g. are the analyses the main demonstration of the performance with testing as confirmatory; are the analyses expected to predict drop test results; are they to produce bounding predictions of behaviour, etc.

The relationship of the impact analyses with the work to demonstrate the performance in other areas, e.g. shielding, thermal and criticality, should also be defined.

If drop tests are carried out, the analyses should be validated against the drop tests. The requirement of this should be defined.

3.2. The Analysis Matrix

The analysis matrix should define the analyses that need to be carried out, the order in which the analyses need to be carried out, and the relationship of the analyses with each other. For each analysis, it should state the initial conditions of the analysis, including internal and external pressure condition, temperature condition and thermal analyses from which the temperature distribution should be taken, initial deflections and deformations, bolt pre-stress, assumption regarding geometric tolerance, assumption regarding fit-up tolerance and position of components with respect to each other at the start of the analysis (e.g. location of spent fuel basket in the cavity of the package). It should state the drop height, drop orientation, target, impact position in the drop onto a punch scenarios.

Sensitivity analyses, if required, should be included in the analysis matrix.

3.3. Basis of the Modelling – Drawings and Material Data

Geometry and material are the two key components of any model. Drawings on which the geometry of the model are to be based and the material data on which the material input are to be based need to be defined.

3.4. Methodology of the Modelling

The methodology for modelling should be defined. This will define the “what” and the “how” of the modelling. That is, what components need to be modelled, and how the components need to be modelled.

3.5. FE Analysis Code, Pre-processor and Post-processor

The FE code for the analyses, including the version and the platform on which it is to be used, needs to be defined. Similarly, the pre-processor for building the model and the post-processor for viewing the results should also be defined.

3.6. Design Criteria and Approach to Evaluating Performance

Although the requirements of the Transport Regulations are performance based, structural design codes are often used in supplement to assess the adequacy of the design. The choice of design criteria will also have an influence on how the package is modelled. ASME Boiler and Pressure Vessel Code Section III Division 3 [3], for example, has been developed specifically for the evaluation of the design of transport packages for spent fuel and high level wastes.

3.7. Output Requirements

Output from impact analyses are often used as input for the demonstration of performance in other areas e.g. thermal, shielding and criticality. The requirement from these other areas should be defined up front.

3.8. Analysis Team

Besides the quality of the FE code, quality of the analysis team is the other key ingredient to produce good FE analyses. The plan should define the team that will be carrying out the work.

3.9. Checking and Review Regime

The plan should define the checking and review regime required for the analyses and the evaluations. This should include the names of the persons who will be responsible for the checking, the timing of the checking the extent of the checking at these times, and the checking procedures/check list etc that need to be used. Programme of the work may also include hold points at which checking or review must be carried out before the analyses could proceed further.

3.10. Verification and Validation (V+V) Regime

The plan should define the V|+V requirement for the software, the model and the analyses, including for example, benchmarking against drop tests, benchmarking against sufficiently similar packages, component level benchmarking and material benchmarking.

3.11. Reporting

Reporting requirements should be defined in the analysis plan.

3.12. Programme

The analysis plan should include a programme of the work that defines the start date and completion date, the timing of individual activities, interdependence of these activities, personnel for these activities, milestones and hold points.

4. Definition of the Analysis Matrix

An analysis matrix serves as a map of the analyses that need to be carried out, the initial conditions of the analyses, the order in which the analyses need to be carried out, and the relationship of the analyses with each other. For each analysis, the analysis matrix should state the drop height, drop orientation, target, impact position in the drop onto a punch scenarios, as well as other initial conditions e.g. internal and external pressure condition, temperature condition and thermal analyses from which the temperature distribution should be taken, initial deflections and deformations, bolt pre-stress, assumption regarding geometric tolerance, assumption regarding fit-up tolerance and position of components with respect to each other at the start of the analysis (e.g. location of spent fuel basket in the cavity of the package).

For packages designed for the safe transport of radioactive material, impacts may occur under both normal and accident conditions of transport. For a typical Type B package, this will include a normal conditions of transport free drop from a drop height dependent on its mass and as defined in the Transport Regulations onto a flat and essentially unyielding target, an accident conditions of transport drop from 9m onto a flat and essentially unyielding target, and an accident conditions of transport drop from 1m onto a solid mild steel penetrating bar.

The combination of drop orientation, puncture location, and the order of the drops, must lead to the maximum impact damage being inflicted on the package. Where packages are also required to withstand the thermal test (commonly referred to as the fire test) of the accident conditions of transport, these drop tests should also take into account the need to inflict impact damage likely to result in maximum damage in the fire accident which follows [1, 2]. The maximum damage resulting from both the drop tests and the fire test will vary depending on the design of the package. It should be noted that for some package designs, maximum deceleration could also be a design criteria. Careful consideration needs to be given to the choice of scenarios to be analysed and the inter-relationship of these analyses.

Besides impact velocity, impact orientation, impact location in the case of drop onto a punch scenarios, and initial damage from previous tests, other initial loadings could also be acting on the package and will need to be considered:

- Internal and external pressure.
- Pre-stress in the bolts and stresses in the vicinity of the bolt due to the pre-stress.
- Seal load and stresses in the vicinity of the seals due to seal load.
- Fabrication stresses.
- Thermal stresses and deflections, i.e. stresses and deflections caused by different combination of extreme ambient temperatures, insolation and decay heat from the contents.

Although some of these loadings may not be present or significant, they, nonetheless, need to be addressed and taken into account if necessary.

Temperature is an important parameter that needs to be taken into consideration and defined in the analysis matrix. Besides pressure, which could be dependent on the temperature, the properties of most materials vary with temperature and especially so in certain energy absorbing materials used in impact limiters.

Sensitivity analyses, if required, should be defined in the analysis matrix.

5. Choice of FE Analysis Code

The quality of the FE analysis code is paramount in achieving quality of analysis. To select a suitable FE code for the analyses, the following criteria should be addressed:

- Does it have adequate element formulations, material models, contact algorithms and other necessary capabilities to simulate the transport package structure?
- Are QA procedures in place to manage the continuous development and ongoing support of the code and are they adequate?
- Has testing been carried out on the code at different levels - element level, component level, full-scale model level – and are the results acceptable?

- What steps were taken for QA verification, and are they sufficient?
- Has the code been audited by users, and what was the outcome?
- Is the code widely used in the packaging and transport industry?
- Has the code been used to demonstrate impact performance of similar packages in applications for Competent Authority approval? Is the Competent Authority familiar with the code? Using a code that is unfamiliar to the Competent Authority may significantly delay the licensing process while the Competent Authority gains the expertise that is necessary before it can make informed judgements.

The FE code and the analysts are the two key ingredients of good FE analyses. While the analysts should be chosen considering their familiarity with the FE code, a suitable FE code should be chosen taking into account the analyst's expertise with the code.

While FE codes are the software which carry out the calculations, post-processing software are software which interfaces with the output from an analysis so that the model and the results can be viewed and interrogated. Accuracy and reliability of post-processors are therefore extremely important. A post-processor should ideally be bespoke for the FE code that is being used. It should have good three dimensional viewing facilities as well as graphical output facilities. It should have facilities to view and interrogate the model, and facilities to plot and extract results. As with FE codes, wide use in the industry, and an adequate QA regime in its continuous development and ongoing support, are essential.

6. Modelling

The foundation of good modelling is a good understanding of:

- The design of the package that is to be analysed.
- The expected behaviour of the package under the initial conditions and impact scenarios analysed.
- The criteria of performance.
- The objectives of the analyses.
- The analysis plan.
- The FE code.

The following sub-sections outline the considerations for dimensions to be used in the modelling, basic principles of mesh design, good practice in the modelling of a number of specific features, the choice of material properties, the modelling of interfaces, the modelling of package contents, the modelling of impact target, initial conditions, and analysis duration.

6.1. Extent of the Model

For impact analyses to demonstrate impact performance for competent authority approval, it is recommended the model should be three dimensional to represent the three dimensional nature of the package and the impact scenarios. If the geometry of the package and the impact scenario being analysed consist of plane or planes of symmetry, cut-down models consisting of half or quarter of the package could be used to take advantage of symmetry. If cut-down models are used, care must be exercised such that potential non-symmetric behaviour is not suppressed.

Although axi-symmetric models and two-dimensional slice models could be useful in impact analyses to support package developing or to assess alternative modelling methodologies, they should not be used unless it can be justified that the simplifications associated with using such models is acceptable.

6.2. Dimensions for Modelling

In deciding on the dimensions to use in the analyses, the following need to be considered:

- It is common to use nominal dimensions in the modelling ignoring variation in dimensions and geometries at extremes of dimensional and geometrical tolerances. However, it should be noted that behaviour could be sensitive to these variations, in certain circumstances, and should be taken into account.
- For FE analysis to correlate with drop test results, as-built dimensions of the drop test package should be evaluated, and if necessary, used in the modelling.
- Interference and variation of gap size between adjacent components due to thermal expansion or contraction could be significant in certain circumstances and in some package designs. The effects of this should be evaluated and taken into account in the modelling if necessary.

6.3. Mesh Design

6.3.1. Basic Principles

A finite element mesh is a discretisation of the geometry of the structure to be analysed into “elements” (hence, “finite element method”), and each element is defined in turn by nodes. Key quantities - stresses, strains, displacements, accelerations and forces – are calculated at “integration point(s)” in each element. The key feature of the finite element method then, is that these key quantities are calculated at discrete points in the structure rather than continuously throughout the structure. The number and location of such discrete points - in other words, the design of the mesh – should therefore be defined depending on the way the key quantities vary under the loadings it is subjected to. Taking stress variation as an example:

- For a stress field that is constant over the geometry, a very coarse mesh will suffice
- For a stress field that is linearly varying only a few elements is required through the thickness of the beam to model the stress variation properly
- For a stress field that varies non-linearly over the geometry, a more refined mesh is required in order to better approximate the non-linear distribution

The design of the FE mesh is of primary importance in order to obtain robust results from an FE analysis.

The following principles should be taken into account in designing the mesh:

- Mesh coarseness or fineness must be appropriate for the purpose of the analysis.
- The mesh should be refined in areas where the quantity to be calculated is undergoing rapid change. Examples include areas of high stress gradients (e.g. adjacent to a bolted connection) and areas of large deformation gradients (e.g. in buckling behaviour).
- The mesh should be coarser at areas of lower stress gradients and deformation gradients since a fine mesh is not required. This is to economise on the number of elements so that the number of elements at areas where a fine mesh is needed can be maximised.
- The mesh should be refined at locations where a higher level of accuracy is required (e.g. at a lid-body interface if prediction of gap sizes is required).

- The mesh design must take account of the type of element used.
- The mesh should be designed taking into account computing resources and project timescale – the larger the number of elements, the longer the analysis; the smaller the elements, the smaller the time step, and hence a longer run time.
- Element quality in terms of aspect ratio, warpage and internal angle must be taken into account when designing a finite element mesh. Different FE codes may have their own recommendations for these values. If these limits are exceeded, reliability of the results will be compromised.
- For solid element meshing, hexahedral (brick) elements should be used wherever possible while tetrahedron and pentahedron (wedge) elements should only be used sparingly, as a last resort, and when it is not possible to use hexahedral elements.
- If shell elements need to be used, thin shell elements should be used while thick shell elements should be avoided. Four noded thin shell elements should be used and excessive use of triangular elements should be avoided.
- Sensitivity analysis should be carried out if required to demonstrate that the mesh used is adequate in that further refinement would not significantly alter the results.

6.3.2. Examples of Good Practice in Mesh Design

Some examples of good practice in mesh design, relevant to the analysis of transport packages, include:

- Identical mesh for all the lid bolts, so that the same accuracy can be attributed to the results for all bolts,
- Identical mesh for each repeating geometry in the body flange between adjacent lid bolts, and similarly in the lid flange between adjacent bolt holes, so that the same ‘accuracy’ can be attributed to the lid-body gap calculated all along the seal,
- Identical mesh for similar components that undergo large deformations, e.g. using identical mesh for all the similar internal partitions in an impact limiter.

6.4. Good Practice in the Modelling of Specific Features

6.4.1. Modelling of Welded Connections

In general, components connected by full penetration butt welds could be modelled as continuous with each other with full moment transfer.

Modelling of other common weld types in transport packages - e.g. fillet welds, partial penetration butt welds, and plug welds – is less straightforward. The appropriate way to model will depend on the significance of its behaviour on the overall behaviour, and the amount of deformation it is expected to experience. Often, it is sufficient to model the components joined by these welds also as continuous. In some cases - e.g. with single sided fillet welds - modelling the connecting components as continuous but with no moment transfer may be the most appropriate. If the size of the weld allows, modelling the weld explicitly with solids is often a good option.

Weld failure is also difficult to predict with certainty. Although there are facilities in FE codes to model welds including weld failure, they are often difficult to define and post-process. If the welds in question could fail in the impact and are important to the overall behaviour, e.g. weld seams in impact limiters or weld at the root of fins, the behaviour should be bound by two analyses – one analysis with the welds remaining intact throughout, and in another analysis, with the welds modelled with a pessimistic lower bound failure strain. If the welds are required to maintain integrity with good margin, e.g.

when the weld is part of the containment, then the integrity of the weld should be assessed by appropriate well established design codes using output from the analysis.

Stresses and strains in the vicinity of the weld in the analysis should be monitored to evaluate the adequacy of the modelling assumption.

6.4.2. Modelling of Components That Buckles

Fins on the side of flasks and steel housing in impact limiters are two typical components that deform by buckling in certain drop scenarios. In order to model the buckling behaviour correctly, there should be at least three or four elements on the buckling half-wavelength. If there are an insufficient number of elements, the buckling mode will not be represented and the behaviour will be too stiff. If the number of elements is insufficient, increasing the order of the elements (e.g. increasing the number of integration points) will not improve the simulation. Impact limiter housings could be responsible for absorbing a significant proportion of the impact energy and it is recommended that a realistic refinement is employed to obtain a correct buckling behaviour. Too stiff a behaviour may mean the simulation is conservative in terms of deceleration, but it will be unconservative in terms of deformation.

The appropriate refinement should be judged on an individual basis and depends, not least, on the significance of the contribution of the buckling component to the overall behaviour. Component test in which a single component – e.g. a single fin – is crushed in a manner that is representative of the loading in the full model, is often useful in evaluating the merit of different mesh refinement, element type and element formulation in the modelling of these components, and to demonstrate that the chosen model design is sufficient.

The way the stress strain behaviour are modelled – e.g. using bilinear elastic plastic curve or realistic elastic plastic curve - may have a significant influence on the component's behaviour and must be considered.

6.4.3. Modelling of Bolted Connections

There are different ways to model bolts. The most appropriate method will depend on a number of factors, for example:

- The size of the bolt.
- The location and function of the bolts.
- The accuracy required in predicting their performance.
- The role of the bolts in the overall performance of the package.
- The expected behaviour of the bolts.
- The design code requirements for assessing the bolts performance.

At its simplest, bolts could be modelled as “discrete beams” - a short beam element connects two end nodes – or using spring elements. They could also be modelled with a combination of beams and solids – beams to represent the shank and solids to represent the head. However, for bolted connections where accurate and detailed prediction of their behaviour is required and where their behaviour has a significant influence on the adjacent components, e.g. the bolts connecting the lid and the body of a transport package, the whole bolt must be modelled explicitly with solid elements, with a matching mesh on the connected components. The mesh must be designed and adequately refined to capture the stress variations due to bending, shear and axial loading on the bolt as well as due to its interface with the lid and the body.

Bolt pre-stress could have a significant effect on the behaviour of the bolted connection and it should be modelled, unless not modelling it could be justified.

6.5. Choice of Mechanical Properties

There are a number of key considerations in the choice of mechanical properties (e.g. Young's modulus, yield stress, tensile strength, failure strain) as input to analyses.

1. Mechanical properties of materials as defined in the respective standard of the material are often used as the basis of input to analyses. However, these properties are often minimum properties and using them does not necessarily produce conservative analysis results. For example, using minimum properties in modelling steel components in impact limiter structures will lead to maximum deformations but using realistic or maximum properties will result in higher decelerations which could also be a limiting performance criteria.
2. If the analyses are intended for comparison with drop test results, it will not be sufficient to use standard mechanical properties as input to the analyses. Mechanical properties of the actual materials of the drop test package should be used. That is, mechanical properties should be based on mechanical properties as stated in the material test certificates of the material used in manufacturing the drop test package, or they should be obtained from material tests carried out on samples of the material used in manufacturing the drop test package.
3. Stress strain behaviour of metallic components in transport packages are often modelled as bi-linear elastic-plastic with strain hardening. Although this is sufficient for areas that remain elastic during the drop event and areas that suffer little plastic deformation, this will under-predict energy absorption in components that undergo large plastic deformations, e.g. bolts that stretch significantly and impact limiter housings that buckle. Depending on the situation and the material, the under-prediction could have a significant implication on the accuracy of the analysis. Where they are available, realistic stress strain curves should be used for all components, and especially for components that undergo large deformations. In the absence of such realistic stress strain curves, bounding analyses with bi-linear stress-strain curves representing upper bound properties and lower bound properties, should be carried out.
4. Full stress strain curves could be generated using methodologies such as that described in ASME Boiler and Pressure Vessel Code Section VIII Division 2 Annex 3-D [4] and the standard Ramberg-Osgood method although the adequacy of the resulting stress strain curves must be justified.
5. Material properties vary with temperature and especially so in some non-metallic materials that are often used in transport packages. Temperature dependent properties together with an appropriate temperature distribution should be defined in the model so that mechanical properties for the relevant temperature is used for each location of the model.
6. Stress strain behaviour of most materials is strain rate dependent. The significance of this should be addressed and appropriate values chosen for the analyses.
7. If the transport package is to be designed to structural design codes, e.g. ASME Boiler and Pressure Vessel Code Section III Division 3 [3], mechanical properties and assumptions regarding stress-strain curves as specified in the codes need to be adhered to.

6.6. Modelling of Interfaces

Typical explicit FE codes offer a wide range of contact surface facilities to simulate interface between components. What is the most appropriate definition depends on the specific interface and interaction that is being modelled, and it would be specific to the FE code being used. Checking must be carefully and thoroughly carried out to ensure that the behaviour is correct. Typical areas that should be checked include: Initial contact penetration, contact over-penetration, incorrect contact energy and contact instability. Output from contact surfaces, including contact energy and contact forces, as well as stresses in the contacting components and position of the nodes of the surfaces that came into contact during the interaction should be used to evaluate the performance of the contact surface.

Friction at interfaces could have a significant effect on the behaviour of the interface. For interfaces that are sensitive to the level of friction at the interface, analyses should be carried out with upper bound and lower bound coefficient of friction to bound the behaviour.

For some packages and impact scenarios, the level of friction between the package and the target, including flat target and punch target, could have a significant influence on the behaviour of the package. In case of uncertainty, analyses with upper bound and lower bound coefficient of friction should be carried out.

6.7. Modelling of Packages Contents

Package contents in terms of spent fuel or waste items, does not normally need to be modelled in detail unless it is necessary to predict their behaviour during the impact in detail, e.g. if the structure of the fuel assemblies contribute to the containment justification of the package. However, it may not be adequate to model them with extreme simplifications (e.g. as completely rigid, or with no stiffness at all while its mass is distributed on the supporting surfaces) as their impact response could have an influence on the response of the container and hence the response of the overall package. For complex structures like spent fuel assemblies, some form of homogenized/simplified model which captures their global flexural behaviour, local stiffness behaviour, size of footprint and mass distribution could be used. There should be robust justification of the modelling methodology.

Package contents in terms of structures like spent fuel basket and waste container, or any furniture to locate any waste item, should typically be modelled with similar level of details as the transport container, as the behaviour of these components are often integral to the performance of the package as a whole.

6.8. Modelling of the Target

IAEA Transport Regulations has defined the drop test target as “a flat, horizontal surface of such a character that any increase in its resistance to displacement or deformation upon impact by the specimen would not significantly increase damage to the specimen”. In FE analysis to demonstrate the performance of a package, it is often adequate to model this as completely undeformable and unmoveable. This can be done either by using “stonewall” or “rigidwall” type facility in FE codes, or by modelling it with solid elements and assigning “rigid” material properties. However, if the purpose of the analysis is to benchmark it against drop test results, then it is not adequate to assume a rigid target - the target must be modelled as like-for-like with the actual target in the drop test. Friction between the package and the target (including flat target and puncture bar target) can have a significant effect on impact response in some impact orientations. Sensitivity analyses should be carried out to demonstrate that the package design is robust to such variations.

6.9. Initial Conditions

At the start of an analysis of an impact following a free drop, the package should be located close to the target, be it the flat target or a puncture bar target, in the required orientation, and be given the initial velocity due to free fall from the drop height of the impact event. However, this should be preceded by applying the other applicable initial conditions, e.g. temperature, thermal stresses, internal pressure, damage from a previous impact, gravity, and bolt pre-stress. Depending on the nature of these initial conditions, they may be applied by “dynamic relaxation”, deformation and strains from a previous analysis, a quasi-static analysis before the impact analysis, or an implicit analysis before the impact analysis.

The choice of impact orientation in the case of drops onto a flat target and the choice of impact orientation and impact position in the case of drops onto a puncture bar target are discussed in detail in TCSC 1086 [5] in the context of drop test design. The same decisions should be made in the choice of such parameters in impact analyses and TCSC 1086 [5] should be consulted.

There are two main classes of impact orientations in the drop onto a flat target event – orientations in which the centre of gravity is over point of impact and orientations in which the centre of gravity is off-set from the point of impact, commonly called oblique drops. It should be noted that the orientations of maximum damage/deceleration will depend on the design of the package and specific features of the design may mean orientations other than centre of gravity over point of impact orientations could also produce significant or even bounding damage/deceleration. In oblique drops, the impact velocity at second impact can be significantly higher than the impact velocity at the first impact and could be more damaging than the first impact. However, the behaviour during the first impact should not be dismissed. Long slender packages are especially prone to bending/flexure deformation during the first impact in an oblique drop, and this behaviour must be considered in the choice of oblique drop orientations.

In most packages, there would be clearance between different items in the content – e.g. between the basket and the container, between the spent fuel and the basket. In reality, at the time of impact in a drop test or a real drop event, the content could be anywhere in the cavity of the package where the clearance allows. It may not always be conservative in terms of performance of the transport container to assume that the content rests on the surfaces as under gravity at the start of the impact. This is especially so in impact orientations in which the content impacts the lid of the container. The stresses in the lid bolts could be much higher if the contents is located furthest from the lid as allowed by clearance, then if it is resting on the lid at the start of the event. Therefore, the location of the contents in the analysis of transport packages in impact events need to be careful considered and justified.

6.10. Analysis Duration

The duration of the analysis of impact events should be chosen such that at the end of the analysis:

- the change in global energies should be negligible.
- the change in internal energy of the components of the package should be negligible.
- all significant impacts between the components of the package – e.g. between contents, between the contents and the container, between the lids of the container – have taken place.
- the displacements of key components have passed their maximum value.

- the largest relative displacement between components that are structurally connected (e.g., between lid and body) has taken place.

7. Typical Example of Structural Design Criteria and Associated Stress-strain Modelling and Evaluation Methodology for Performance in Impact Scenarios Under the Accident Conditions of Transport

The requirements for package performance in impact accident scenarios is “performance based”, in that the Transport Regulations define the performance criteria – e.g. retain sufficient shielding, restrict loss of radioactive contents, maintaining sub-criticality – but not “code based”, with design codes specified against which the packages need to be designed. While design codes for the overall design of transport packages do not exist, there are structural design codes including ones that have been specifically developed for transport packages, that are suitable for evaluating the structural performance of packages in impact scenarios (noting that the FE method being discussed in this guide is a computational method to simulate the structural response of packages in impact scenarios).

The advantage of using a structural design code is that they provide a framework for the analyses and evaluation, a degree of assurance that the structural behaviour is evaluated appropriately, and a suitable margin of safety is obtained.

This section outlines the selection of criteria to evaluate the integrity of the structure of typical Type B packages in impact scenarios of the accident conditions of transport, and the associated stress-strain modelling and evaluation methodology.

- While this section sets out a typical choice of evaluation criteria and the associated stress-strain modelling/evaluation methodology in the FE analyses of Type B packages in impact accident scenarios, it must be recognised that:
- They are presented as examples and there are equally valid alternative approaches.
- The evaluation criteria and associated stress-strain modelling/evaluation methodology are presented for specific package designs as noted below, and is not meant to be exhaustive in terms of package design or materials.
- Whatever the approach adopted, the details and the assumptions of the approach must be justified for the specific package, depending on how the package is designed to perform in the impact scenarios.

Type B packages are typically classified into two broad categories in terms of impact behaviour in accordance with how the impact energy is absorbed:

- Packages in which the energy is absorbed predominantly by bolt-on impact limiters.
- Packages in which the energy is absorbed by the cask structure itself.

A typical example of the former is GNS’ CASTOR family of casks, and a typical example of the latter are Magnox flasks. It is also common for packages to have a combination of energy absorbing features that are integral with the packaging itself and features that are bolt-on, to control deceleration in different impact orientations. For example, a package with integral impact limiters may also have bolt-on impact limiters to control deceleration in the base edge and side drop orientations. The guidelines are presented for the two broad types of packages under its main constituent components.

Typical examples of evaluation criteria and associated stress-strain modelling/evaluation methodology for evaluating the structural performance of packages with bolt-on impact limiters are presented in Section 7.1 and for packages with integral impact limiters, in Section 7.2. Sub-sections under Sections 7.1 and 7.2 present the evaluation criteria and associated stress-strain modelling/evaluation methodology for constituent components of these two types of packages.

Although the examples are generic within the two broad types of packages, different package designs within each broad type may require different approaches where different approaches will be more appropriate. The package envisioned in drawing up Section 7.1 is a spent fuel transport flask with impact limiters attached to each end of a thick-walled containment structure. The package envisioned in drawing up Section 7.2 is a transport flask, with a thick-walled containment structure with specific areas shaped to absorb energy by solid metal flow, which has additional fins and impact limiters with energy absorbing materials attached to it.

7.1. Packages with Bolt-on Impact Limiters

7.1.1. Impact Limiters – Energy Absorbing Materials Contained in a Steel Housing

Structural performance evaluation criteria

There is typically no stress or strain evaluation criteria for impact limiter structures. Their function is to absorb impact energy at a suitable rate and to control deceleration to below suitable limits. However, depending on the design, there may be a requirement on the integrity of the steel housing (e.g. such that the energy absorbing material is not subjected to fire in the thermal test that is to follow the drop tests) and of the bolts connecting the impact limiters to the body of the transport package (e.g. they should not fail, such that the impact limiters will protect the ends of the transport package during the thermal test)

Stress-strain modelling methodology

<u>Steel housing:</u>

- Stress-strain behaviour could be modelled as bi-linear with strain hardening based on steel specification properties, or preferably, as a realistic stress-strain curve based on tensile test results.
- Stress-strain properties should be those at the relevant temperatures.
- If there is uncertainty about differences in the stress-strain properties in the analyses and in the eventual package, analyses with typical/mid-range properties and sensitivity analyses with upper bound properties to obtain upper bound deceleration and with lower bound properties to obtain upper bound knockback deformation should be carried out.
- Variation of stress-strain properties due to strain rate effects should be taken into account.
- Weld failure should be modelled if the welds cannot be assumed to have similar or better ductility than the parent metal. If weld failure cannot be predicted with confidence, an analysis which optimistically assumes that no welds fail and an analysis which models failure pessimistically are required to bound the solution.

<u>Energy absorbing material:</u>

Synthetic material (e.g. closed-cell polyethylene foam) and honeycomb:

- Stress-strain behaviour should be modelled based on stress-crush data at the appropriate strain rates, grain/cell orientation and temperatures provided by the material's manufacturer, although preferably, stress-crush data obtained by bespoke crush tests at appropriate strain rates, grain/cell alignments and temperatures should be used,
- Stress-strain behaviour must take into account the orthotropic stress-strain characteristics of the material with respect to the impact direction.
- To account for uncertainties with respect to the stress-strain properties of the energy absorbing material in the eventual transport package, analysis with mid-range/typical properties and sensitivity analyses with upper bound and lower bound properties should be carried out.

Wood:

- Stress-strain behaviour should be based on stress-crush data obtained from crush test on the wood at the appropriate confinement, strain rate, grain orientation and temperature.
- Stress-strain behaviour must take into account the orthotropic stress-strain characteristics of wood with respect to the impact direction.
- To account for uncertainties with respect to the stress-strain properties of the wood in the eventual transport package, analysis with mid-range/typical properties and sensitivity analyses with upper bound and lower bound properties should be carried out.
- Behaviour of wood is strongly dependent on confinement conditions and this must be modelled realistically.

7.1.2. Containment (Excluding Bolts, See Section 7.13 for Bolts)

7.1.2.1. Stress Based Criteria

Structural performance evaluation criteria

Level D Service Limits, as defined in WB-3224 of ASME Boiler and Pressure Vessel Code Section III Division 3 [3]

Stress-strain modelling methodology

Plastic Analysis, as defined in WB-3224.2 of ASME Boiler and Pressure Vessel Code Section III Division 3 [3], which in turn refers to plastic analysis rules as defined in ASME Boiler and Pressure Vessel Code Section III Non-mandatory Appendix F [6] and more specifically F-1341.2 Plastic Analysis.

Stress-strain behaviour could be modelled as bi-linear elastic-plastic with strain hardening, but preferably, as a realistic stress strain curve, at temperatures relevant to the scenario being analysed. F-1322.3 specifies that mechanical properties shall be taken from ASME Boiler and Pressure Vessel Code Section II Part D [7] Subparts 1 and 2 at the actual temperature of the material. Effect of strain rate on the stress-strain behaviour could be included in the stress-strain modelling.

Stress limits

Primary stress shall be evaluated against the limits as defined in F-1341.2:

- For ferritic steel materials included in ASME Boiler and Pressure Vessel Code Section II Part D [7] Subpart 1 Table 2A: the general primary membrane stress intensity Pm shall not exceed 0.7Su.

For austenitic steel, high nickel alloy, and copper-nickel alloy materials included in ASME Boiler and Pressure Vessel Code Section II Part D [7] Subpart 1 Table 2A and 2B: the general primary membrane stress intensity Pm shall not exceed the greater of 0.7Su and Sy+(1/3)(Su-Sy).

- The maximum primary stress intensity at any location shall not exceed 0.9Su.
- The average primary shear stress across a section loaded in pure shear shall not exceed 0.42Su.

Deformation limits

WB 3224 and F-1322.5 requires that any deformation limits prescribed for the design, such as those to limit leakage, shall be satisfied.

7.1.2.2. Strain-based Criteria

Structural performance evaluation criteria

ASME Strain-based acceptance criteria as defined in Non-mandatory Appendix EE and FF of ASME Boiler and Pressure Vessel Code Section III Appendices [6]

Strain limits

Locations away from a gross or local structural discontinuity

For material at least 3 x [nominal wall thickness] away from a gross or local discontinuity, the following limits must be satisfied at any time:

- [TF x εpeq]average through the section ≤ (0.67 εuniform)
- [TF x εpeq]max value ≤ [εuniform + 0.25 (εfracture - εuniform)]

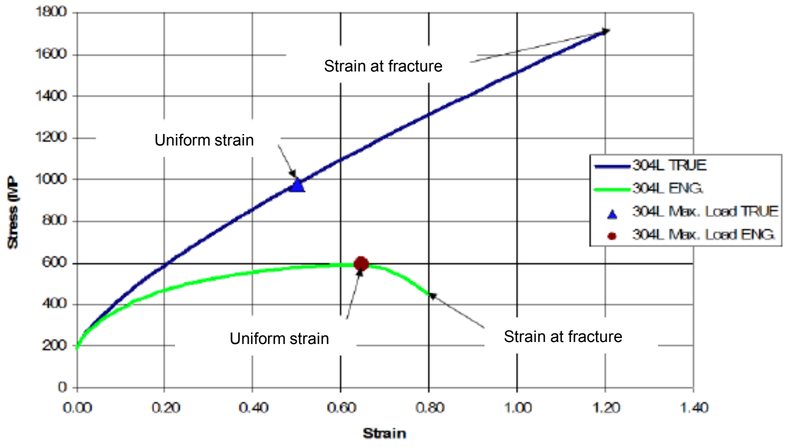
Locations at a gross or local structural discontinuity

At a gross or local structural discontinuity, the following must be satisfied at any time:

- [TF x εpeq]average through the section ≤ (0.85 εuniform)
- [TF x εpeq]max value ≤ [εuniform + 0.25 (εfracture - εuniform)]

Where:

- εuniform is the true uniform strain just prior to the onset of necking in a uniaxial tension test
- εfracture is the true strain at fracture in a uniaxial tension test:



- εpeq is equivalent (true) plastic strain and is defined as:

$$\varepsilon_{eq}^{p} = \int_{0}^{t} \left(\frac{2}{3} \dot{\varepsilon}_{ij}^{p} \, \dot{\varepsilon}_{ij}^{p} \right)^{1/2} dt$$

It is a cumulative, positive, scalar, non-decreasing strain measure that takes into account the entire deformation history.

- TF is triaxiality factor, defined as:

$$TF = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{\sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}}$$

It is the first stress invariant divided by the von Mises' effective stress, where σ1, σ2, σ3 are principal stresses at a location. Typical TF value of 1 represents uniaxial tension, 2 represents biaxial tension, >2 indicates triaxial tension, and <1 due to compressive principal stresses in one or more directions. (Note: some FE softwares define TF differently.)

ASME Boiler and Pressure Vessel Code has specified that the strain-based acceptance criteria must not be applied to:

- Regions of the containment where strain deformations are detrimental to maintaining the desired leakage rate (e.g., the sealing region of a bolted closure),
- Structural or non-structural attachments to the containment,
- Containment boundary fillet welds or partial penetration welds and their heat affected zones, including such welds of attachments to the containment boundary
- Threaded connections to the containment.

It has also specified that the strain-based criteria is only applicable to

- Grade 304/304L, 316/316L stainless steels
- Temperature range from -40°C to 425°C
- Welded joints that are full penetration welds

Modelling requirements

FF-1130 of Appendix FF specifies that "The strain-based acceptance criteria shall be implemented using strains calculated from Quality Models." EE-1240 of Appendix EE defines Quality Model as follows: "A Quality Model is a model that adheres to the guidance set forth in the ASME Computational Modelling Guidance Document for Explicit Dynamics Software (currently being developed by the Special Working Group on Computational Modelling for Explicit Dynamics), or using a model with suitable convergence and sensitivity studies already completed."

Stress-strain modelling requirements

Accurate inelastic response of materials is vital for accurate prediction of strains and proper implementation of the strain based criteria. Appendix EE requires that in the choice of material properties, the following shall be considered:

- Aged condition – potential material degradation throughout the design life
- Temperature effects on material properties
- Variation of material properties between manufacturer production batches

Appendix EE states two options for determining appropriate material properties for the analyses:

- Using ASME specified material strength properties ASME is developing true stress-strain curves, εuniform and εfracture for design, although this is still under development by ASME.
- Using actual material properties from tensile test data reflecting the specific material properties from the actual material heats used in the containment fabrication

7.1.3. Bolts

Structural performance evaluation criteria

Level D Service Limits for bolts as defined in WB-3234 of ASME Boiler and Pressure Vessel Code Section III Division 3 [3].

Stress-strain modelling methodology

Stress-strain behaviour shall be modelled as linear elastic.

Stress limits

For closure with no leak tightness requirement, stresses should be evaluated against the limits of F-1335 of Sec III Non-mandatory Appendix F as follows:

- Allowable tensile stress

  The average tensile stress computed on the basis of the available tensile stress area shall not exceed the smaller of 0.7Su and Sy. When higher strength bolts or threaded parts having an ultimate tensile strength greater than 700MPa at operating temperature are used in component applications, the maximum value of the stress at the periphery of the bolt cross section resulting from direct tension plus bending and excluding stress concentration shall not exceed Su.

- Allowable shear stress

  For bearing type joints, the average bolt shear stress expressed in terms of available shear stress area shall not exceed the smaller of 0.42Su and 0.6Sy.

- Combined tensile and shear stress

  For bearing type joints, combined shear and tension stresses shall satisfy the following equation:

  (ft2/Ftb2) + (fv2/Fvb2) ≤ 1

  where

  ft = computed tensile stress

  fv = computed shear stress

  Ftb = allowable tensile stress at relevant temperature as per i above

  Fvb = allowable shear stress at relevant temperature as per ii above

For closure with a leak tightness requirement, stresses should be evaluated against the limits of WB-3232 Level A Service Limits for Bolts as follows:

- Average Stress.

  The maximum value of stress, averaged across the bolt cross section and neglecting stress concentrations, shall not exceed two times the stress values of Section 2 Part D Subpart 1 table 4

- Shear Stress.

  The average bolt shear stress expressed in terms of available shear stress area shall not exceed 1.2Sm from Section 2 Part D Subpart 1 Table 4

- Maximum Stress.

  The maximum value of stress, except for high strength alloy steel bolting, at the periphery of the bolt cross section resulting from direct tension plus bending and neglecting stress concentrations shall not exceed three times the stress values of Section 2 Part D Subpart 1 Table 4. Stress intensity, rather than maximum stress, shall be limited to this value when the bolts are tightened by methods other than heaters, stretchers, or other means which minimise residual torsion.

7.1.4. Spent Fuel Basket

Structural performance evaluation criteria

Level D Service Limits as defined in NG-3225 of ASME Boiler and Pressure Vessel Code Section III Division 1 NG [8].

Stress-strain modelling methodology

- Using Appendix F, as allowed in NG-3225, and using Plastic Analysis specifically.
- Stress-strain behaviour could be modelled as bi-linear elastic-plastic with strain hardening, although preferably, a realistic stress-strain curve, at temperature relevant to the scenario being analysed. F-1322.3 specifies that mechanical properties shall be taken from Section 2 Part D Subparts 1 and 2 at the actual temperature of the material. Effect of strain rate on the stress-strain behaviour could be included in the stress-strain modelling.

Stress limits

Primary stress shall be evaluated against the limits as defined in F-1341.2:

- For ferritic steel materials included in ASME Boiler and Pressure Vessel Code Section II Part D [7] Subpart 1 Table 2A: the general primary membrane stress intensity Pm shall not exceed 0.7Su.

  For austenitic steel, high nickel alloy, and copper-nickel alloy materials included in ASME Boiler and Pressure Vessel Code Section II Part D [7] Subpart 1 Table 2A and 2B: the general primary membrane stress intensity Pm shall not exceed the greater of 0.7Su and Sy+(1/3)(Su-Sy).
- The maximum primary stress intensity at any location shall not exceed 0.9Su.
- The average primary shear across a section loaded in pure shear shall not exceed 0.42Su.

Deformation limits

WB 3224 and F-1322.5 requires that any deformation limits prescribed for the design shall be satisfied.

7.2. Packages with Integral Impact Limiters

7.2.1. Containment Which Has Integral Parts Used as Impact Limiters

Structural performance evaluation criteria

- There is no relevant structural design code that specifies the structural performance criteria. The structure needs to maintain integrity in terms of containment and it also needs to plastically deform in order to absorb the impact energy.

Stress-strain modelling methodology

- Model stress-strain behaviour as bi-linear with strain hardening based on steel specification properties, or preferably, as realistic stress-strain curve where data is available.
- Stress-strain properties should be those at the relevant temperatures.
- To account for potential variation in impact response due to variation in stress-strain properties, bounding analyses with upper bound properties to obtain upper bound deceleration and with lower bound properties to obtain upper bound knockback should be carried out.
- Variation of stress-strain properties due to strain rate effects should be taken into account.

Strain and deflection limits

- Plastic strains, principal stress directions and triaxiality should be tracked throughout the analysis. If plastic strains are above the allowable true strain which is determined taking into account triaxiality of the location, and triaxiality and principal stresses indicate that stresses are predominantly tensile at that location, additional analyses should be carried out in which those elements deemed at risk of tearing should be allowed to be deleted when their plastic strains exceed the allowable true strain. The mesh should be adequately refined and continuously refined in successive iterative analyses such that such tearing can be modelled realistically. Reduction of allowable true strain with triaxaility should be based on a validated methodology that is suitable for the material. One such methodology is the R3 [9].
- Deformations and deflections, including relative displacement between components (e.g. gap between lid and body at seal location), during and after the impact event, should be assessed against limits prescribed for the design.

7.2.2. Impact Limiters – Metal Component Welded to Cask (e.g. Fins Used for Absorbing energy)

Structural performance evaluation criteria

- There is no structural design code that specifies their performance criteria. They are required to absorb impact energy at a suitable rate and to control deceleration to below suitable limits.

Stress-strain modelling methodology

- Stress-strain behaviour could be modelled as bi-linear with strain hardening based on steel specification properties, or preferably, as a realistic stress-strain curve based on tensile test stress-strain data.
- Stress-strain properties should be those at the relevant temperatures.
- To account for uncertainty in stress-strain properties of the eventual package, the analyses should be carried out with upper bound properties to obtain upper bound deceleration and with lower bound properties to obtain upper bound deformation.
- Variation of stress-strain properties due to strain rate effects should be taken into account.
- Weld failure should be modelled if the welds cannot be assumed to have similar or better ductility than the parent metal. If weld failure cannot be predicted with confidence, an analysis which optimistically assumes that no welds fail and an analysis which models failure pessimistically are required to bound the solution.

8. Model and Analysis Checking

In any analysis campaign, the models, analyses, evaluations and reports must be checked thoroughly when they are complete. The following is a typical check list for checking a model and the analysis of the model:

Have the input values (e.g. material properties, section properties, mass, loadings, etc) been derived appropriately? Check and confirm calculations and assumptions.

Has the geometry been correctly represented? Check geometry in the model against drawings.

Have material properties and section properties been input correctly?

Are consistent units used throughout?

Are correct units used?

Have the loadings been correctly applied?

Have the contacts, boundary conditions, constraint conditions, etc been correctly defined?

Is element quality (e.g. warpage, angles, aspect ratio etc) acceptable? Is the mesh properly connected? Check, using built-in checking function in pre-processors.

Are the modelling assumptions reasonable within the context of the purpose and objectives of the analysis?

1. Has the analysis reached termination time?
2. Are there errors or warnings in the output file? Are they significant?
3. Are the total energy, the exchange of energies and energy absorbed by individual parts sensible? Is energy loss and hourglass energy acceptable?
4. Are the contact surfaces performing properly (e.g. penetration, contact forces) and is the extent of contact surfaces sufficient?
5. Is the deceleration sensible and as expected?
6. Is the deformed shape (globally and locally) realistic?
7. Has any element suffered extreme distortion? Will this affect overall results? Is this acceptable?
8. Is the mesh sufficiently refined to simulate the deformation modes with sufficient accuracy?
9. Is the added mass due to mass-scaling acceptable?
10. Is the mass correct?
11. Would any of the areas/connections have failed and would they need to be re-analysed with failure?
12. Have boundary conditions, restraints, constraints, loadings etc been applied correctly?
13. Does the predicted behaviour “make sense”? Is it as expected?
14. Examine stresses and strains and their development with time. Are they as expected? Do they tie in with each other, and with analyses of other drop scenarios?
15. What are the load paths? How is the structure behaving – bending, axial loading, tension, compression, shear, etc? What dominates the behaviour?
16. Are the contact surfaces performing as expected?

17. Are the choice of material model and boundary conditions sensible?
18. Is the model – with its mesh design, material properties, material models, analysis assumptions, initial conditions, boundary conditions, contact definition, etc - sufficient to produce realistic and conservative results?
19. Are there uncertainties in any aspect of the input and should sensitivity analyses be carried out to bound the uncertainties?
20. Are there stress, strain or deformation gradients that are significantly larger than originally envisaged such that the mesh may not be sufficient to capture the variation? Should mesh refinement be carried out?
21. How does the behaviour compare with similar packages in similar scenarios, and the same package in different scenarios?

Although the models and analyses of an analysis campaign obviously need to be checked when the modelling and analyses are complete, checking should also be carried out at suitable stages of the analysis campaign. The purpose of this is to catch errors and anomalies as soon as they arise, and so to minimise the time that may otherwise be wasted. This is especially important for models that are particularly complicated, modelling processes that are time-consuming and models that will be used in multiple analyses. Typically, checking could be carried out at the following stages of an analysis:

- After completion of the modelling and before the model is analysed - Pre-analysis check.
- During an analysis, as the analysis is in progress, if the analysis time is significant.
- After completion of the analysis.
- When examining the behaviour of the transport package obtained from the analysis.

Items 1 to 9 of the above check list could be used for the pre-analysis check. Items 10 to 21 of the above check list could be used to check the analysis during the analysis and after completion of the analysis. Items 22 to 30 of the above check list would be most suitable when examining the behaviour of the transport package obtained from the analysis.

Checking should also be carried out by different persons - self-checking by the analyst, checking by the lead analyst in the team, and checking by an expert in the organisation who is not directly involved with the project.

After individual models and analyses have been checked, the models and analyses should also be checked on the campaign level, i.e. the models should be checked together for consistency, and analyses should be checked together for consistency of results between the different analyses.

Results of the checking should be thoroughly documented.

It should be noted that explicit FE codes are complex softwares. Where necessary, FE code developers who know the internal workings of the FE code should be consulted to advise on appropriate use and limitations of the FE code and to audit the analyses

9. Reporting

Submissions for Competent Authority approval in the UK normally consists of a design safety report supported by a set of reports dealing with individual aspects of a package’s performance – e.g. structural performance, impact performance, thermal performance, shielding performance. While the supporting reports present the details of the analyses and tests that have been carried out to demonstrate the performance of the package, the design safety report draws out the safety implications from the supporting reports and presents the argument for the safety of the package.

Impact performance of a package is often demonstrated by a combination of analyses, tests and reasoned argument although the relative emphasis on each varies depending on the package. The supporting reports for the impact performance aspect of packages therefore often consist of a drop test report or an FE analysis report, or both. Depending on the background of the package, and the role of the FE analyses in the submission, the supporting reports for impact performance could also include a benchmarking report in which the validation of the FE analyses against the drop tests is presented.

Whether the analyses are the primary demonstration of impact performance, or whether they are supplementary to the drop tests, the analysis report should present the information clearly and succinctly, in good English.

Typical structure and contents of an analysis report to demonstrate the impact performance of a package should consist of the following components:

1. **Introduction**

   This section should discuss the purpose of the analyses and their relationship with drop tests (if any), and state their corresponding sections in the design safety report.

2. **Design criteria and performance criteria**

   This section should present and discuss the performance criteria (e.g. reduction of shielding, opening of lid-gap interface, displacement between spent fuel elements) against which the package is designed, and/or the design criteria (e.g. ASME Boiler and Pressure Vessel code) against which the package is designed and provide justification that the criteria is adequate for the performance required. Limits - e.g. stress limit, strain limits, gap size limits - should be stated.

3. **Analysis methodology**

   This section should present and discuss the approach to demonstrating the performance.

   This section should also state the FE code(s) (including version number) used for the analysis, pre-processing and post-processing, and hardware they are mounted on.

4. **Analysis matrix**

   This section should present and discuss the analysis matrix, including analysis sequence, and initial conditions such as impact orientation, drop height, impact position (in the case of punch drops), bolt pre-stress, pressure conditions, temperature conditions (as assumed for material properties and calculation of pressure), initial deformations (e.g. damage from previous drop) etc. This section should also provide justification that this is a sufficient matrix that adequately bounds the performance.

5. **Modelling**

   a. **Modelling of the package**

   b. **Basis of the geometry**

      This section should state the basis of the geometry, the drawings and their status.

   c. **Design of the model**

      This section should present, discuss and justify the design of the model, including the design of the mesh, the choice of dimensions (e.g. nominal, maximum, minimum within allowable tolerance), the choice of element type (shell, solid, beams, springs etc), choice of order of element (e.g. number of integration point, type of shell), the choice of material model and modelling of interfaces. This section should also state, discuss and justify the simplifications and omissions to the geometry in the model.

d. **Material properties**

This section should present and discuss the material properties used as input to the model, including the source of the material properties and the derivation of the input. Justification should be given as to the adequacy and appropriateness of the input.

e. **Mass**

This section should state the mass of the package in the model and in reality, including the mass of component (and sub-components where appropriate). The mass in the model and in reality should be compared in percentage terms and differences justified.

f. **Modelling of the target and the puncture bar**

This section should present, discuss and justify the modelling of the flat unyielding target and the puncture bar, including geometry, mesh design, choice of element, choice of material model and derivation of material properties.

g. **Initial conditions**

This section should present, discuss and justify initial conditions applied to the model, how they were derived and how they were applied. This should include initial velocity, orientation, bolt pre-stress, internal/external pressure, temperature distribution, thermal stresses and deflections, deformation and stresses from other analyses.

6. **Results**

Vast amounts of data in terms of stresses, strains, displacements, forces and bending moments, can be generated from each time step of an FE analysis. In this section of the report, a selection of the results of each analysis should be presented, discussed and explained in order to show that the analysis is well behaved, the model and the analysis are adequate, and that the behaviour of the package has been understood. The results should present a coherent explanation of the behaviour of the package, and should consist of relevant combination of energy time histories, acceleration time histories, velocity time histories, displacement time histories, plots of deformed geometry, plots of stress and strain contours, at relevant times during the impact event.

7. **Evaluation**

This section of the report should present the evaluation of specific parameters from the analyses against the performance criteria.

8. **Conclusions**

This section should summarise the work that has been carried out.

9. **References**

This section should list the references.

10. Documentation

All details of models and analyses should be traceable and documented.

Each finalised analysis (including all the input files and output files) should be archived and the archive should be backed up and stored separately.

If the analyses are stored in some central computer archive, it would be useful to store a copy of the input file with the project files for ease of access.

For each finalised analysis, there should be an accompanying record including at least the following items:

- Date of analysis.
- Identification of analysis within the analysis campaign.
- Analyst, checker, approver.
- Source of geometry, including detail reference of the source.
- Sources of material data, including detail reference of the source.
- Supporting calculations, including reference to the location of the calculations.
- FE analysis code, pre-processor, post-processor used including their version and the platform on which they were mounted.
- Record of checking.

11. References

1. International Atomic Energy Agency, *Regulations for the Safe Transport of Radioactive Material – 2012 Edition.* IAEA Safety Standards, Specific Safety Requirements No. SSR-6.
2. Department for Transport, *Guide to an Application for UK Competent Authority Approval of Radioactive Material in Transport*. DETR/RMTD/0003, 2001.
3. American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code, Section III Rules for Construction of Nuclear Facility Components, Division 3 – Containment for Transportation and Storage of Spent Nuclear Fuel and High Level Radioactive Material and Waste, 2013* Edition.
4. American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code, Section VIII - Rules for Construction of Pressure Vessels, Division 2 - Alternative Rules*, 2013 Edition.
5. TCSC, *Transport of Radioactive Material Code of Practice - Good Practice Guide to Drop Testing of Type B Transport Packages*, TCSC 1086, 2009.
6. American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code, Section III Rules for Construction of Nuclear Facility Components, Appendices, 2013* Edition.
7. American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code, Section II Materials, Part D Properties (Metric), 2013* Edition.
8. American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code, Section III Rules for Construction of Nuclear Facility Components, Division 1 – Subsection NG Core Support Structures, 2013* Edition.
9. Magnox Electric Ltd & British Energy Generation Ltd*, R3 Impact Assessment Procedure,* 2008.