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TCSC 1087: GOOD PRACTICE GUIDE - THE APPLICATION OF FINITE ELEMENT ANALYSIS TO DEMONSTRATE IMPACT PERFORMANCE OF TRANSPORT PACKAGE DESIGNS

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ABSTRACT
The Transport Container Standardisation Committee (TCSC) is a UK nuclear industry committee whose main function is to maintain and develop codes of practice relating to radioactive materials transport. Its role 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 Committee comprises of the Atomic Weapons Establishment plc, British Nuclear Group (Sellafield) Limited, British Energy Generation Ltd, GE Healthcare Ltd, Magnox Generation Business Group, Reviss Services (UK) Ltd, Rolls-Royce plc - Submarines, United Kingdom Atomic Energy Agency and United Kingdom Nirex Limited.
To raise the standard of Finite Element analyses in order to improve confidence in their use, the TCSC and Arup have developed a good practice guide, TCSC 1087: "Good Practice Guide - The Application of Finite Element Analysis to Demonstrate Impact Performance of Transport Package Designs".

The Finite Element Method (FEM) is a powerful tool for the simulation of mechanical and thermal behaviour of structures. The implicit method has been used for many decades to simulate the behaviour of structures under static loading and is now well established in that role. The explicit method is relatively novel and best suited for simulating non-linear, time dependent, dynamic problems. Over the years, it has been demonstrated by many users that when FEM is used properly, it can produce results that replicate test results faithfully, even for complex geometries under complex loadings, and can provide a sound basis for demonstrating regulatory compliance.

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

of packages. The Guide sets out current ‘good practice’ in using explicit FEM for the analysis of impact behaviour of transport packages, and specifically for demonstrating compliance with the regulations for public domain transport in the UK. This approach is particularly recommended for use in support of applications for transport approvals containers with the UK Competent Authority.

This paper presents a summary of the Good Practice Guide.

INTRODUCTION

Testing and analysis are the two methods specified in the IAEA Regulations for the Safe Transport of Radioactive Material [1] for demonstrating the structural and thermal performance of a transport package against the requirements of the Transport Regulations.

The roles of testing and 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, the Department for Transport (DfT), currently has no prescriptive requirements in this regard; it is the applicant’s responsibility to justify the combination of test results and ‘reasoned argument’ (including computer analysis) used in each submission [2].

The Finite Element Method (FEM) is a powerful tool for the simulation of mechanical and thermal behaviour of structures. The implicit method has been used for many decades to simulate the static behaviour of structures and is well established. The explicit method is relatively novel and best suited for simulating dynamic non-linear problems in the time domain. FEM allows the simulation of mechanical 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 variable 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.

The Guide sets out current ‘good practice’ in using 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 Department for Transport. 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, so that FE analyses can take a more central role in demonstrating regulatory compliance.

It is a “Good Practice Guide”, and not strictly a “Code of Practice”. Neither is it a primer of FE analysis nor a training manual of any specific FE analysis code.

Although the context of this guide is the application for approval from the UK Department for Transport for public domain transport, the good practices are equally relevant in the application of licences from other authorities for on-site transport.

The Guide is structured into seven sections:

- Introduction
- Managing the FE Analysis Process
- Planning
- Modelling
- Checking and Evaluation of Results
- Documentation
- References

The following sections of this paper summarises the key points from the Guide.

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:

1. Planning
2. Modelling
3. Analysis
4. Checking and results evaluation
5. Evaluation of the transport package
6. Post-processing and reporting
7. Documentation
8. Review

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 stake-holders
- Stringent quality assurance procedures

Advice from the DfT on the analyses programme should be sought at the earliest opportunity.

PLANNING

Careful planning of the analysis campaign must precede any modelling and 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. The plan should also be presented to the Competent Authority for comment at the earliest opportunity.

The Guide recommends the following headings in the analysis plan and discussed the details that need to be defined. They are summarised as follows:

Objectives and purposes of the analyses

- 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.

Impact scenarios, drop orientations, punch impact locations, order of the analyses, inter-relationship between the analyses and with the thermal analyses

Input to the analysis – define the design drawings and source of material data

Choice of mechanical properties

- what properties to use in the analysis, e.g. minimum properties, maximum properties, code defined properties or as-built properties, depending on the purpose of the analyses
- material modelling assumptions – e.g. for steel materials, modelling the stress strain behaviour as bi-linear elastic plastic with strain hardening, or bi-linear elastic perfectly plastic, or with real stress strain curve from tensile tests
- temperature at which material properties should be used
- whether strain rate dependent behaviour should be modeled and if so, how

Choice of dimensions

- the type of dimensions that should be used in the analyses, e.g. nominal dimensions, as-built dimensions, dimensions at extremes of dimensional and geometric tolerances, or dimensions taking into account thermal expansion and contraction.

Loadings and initial conditions

- internal pressure, bolt pre-stress, seal load, fabrication stress, thermal stresses.

FE analysis code, pre-processor and post-processor (including the version and the platform),

Design Code

- e.g. ASME Boiler and Pressure Vessel Code Section 3 Division 3

Analysis methodology and modelling assumptions

- How is the transport package to be modeled, including the extent of the models, how are the components to be modeled, how are the interfaces to be modeled, how are the initial conditions and loading are to be applied, what are the boundary conditions and how are they to be applied, what output are required and at what frequency.

Analysis team

Checking and review regime

- including the names of the persons who will be responsible for the verification, the timing of the checking, the extent of the verification at these times, and the procedures/check list etc, that are to be used.

Programme

- including the timing of individual activities, interdependence of these activities, personnel for these activities, milestones and hold points.

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. The Guide gives the criteria for selecting a suitable FE code and an analysis team for the analyses.

MODELLING

The basis of good modelling is a good understanding of:

- The design of the package that is to be analysed
- The dynamic behaviour of transport packages
- The expected behaviour of the package under the load cases analysed
- The criteria of performance
- The objectives of the analyses
- The analysis plan
- The FE code

And there must be a good grasp of these before proceeding to the next stages of the analysis process.

The Guide then presented and discussed the following principles of mesh design:

- 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
- The mesh should be coarser at areas of lower stress gradients and deformation gradients since a fine mesh is not required
- The mesh should be refined at locations where a higher level of accuracy is required
- The mesh design must take account of the element type used
- The mesh should be designed taking into account computing resources and project timescale
- Element quality in terms of aspect ratio, warpage and internal angle must be taken into account and the code-specific recommendations adhered to

The Guide recommends:

- 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

The Guide then gave examples of good practice in the modelling of welded connections, components that buckle and bolted connections.

CHECKING AND EVALUATION OF RESULTS

With the increasing power and capabilities of computers it is easy to be lulled into accepting all results without question. The truth is that the opportunities for bad engineering increase as the complexity of the computer model increases. Computer models sometimes produce surprising results because the initial expectation was wrong, and sometimes because it is behaving incorrectly. Either way, it is necessary for an engineer to have a good idea of what to expect from an analysis and be able to judge whether the results produced are reasonable or not. It is vital for the engineer to work from a sound and thorough understanding of the problem being analysed.

The validity of and reliability of an analysis depends on:

- Validity and reliability of the analysis software (as mounted on the hardware on which the analyses are carried out) and any pre- and post-processing software
- Validity of the analysis methodology, i.e. the approach (with its assumptions) by which a problem is analysed
- Validity, sufficiency and correctness of the analysis model – the mesh, the input data, the application of loading, the boundary conditions, the material properties and so on

Checking is vital. With the increasing complexity of analysis models, this is increasingly important.

The model and the analysis should be checked at different stages in the modelling/analysis process, and not only at the end. This is especially important for complex models, modelling processes that are time-consuming, and models that will be used in multiple analyses.

Checking and verification should also be carried out at different levels in terms of checker's expertise:

- Self-checking by the analyst
- Checking by the team manager or lead analyst in the team
- Checking by an expert in the organisation who is not directly involved with the project

The level of checking required will depend on the expertise of the analysts.
Checking should also be carried out at different "levels" of an analysis:

- Pre-analysis – of the input deck and using the pre-processor
- Post-analysis – standard checks
- Examination of results

Checking should be carried out during the analysis - especially if the analysis has a long run-time.

If the work consists of a number of analyses forming a complete campaign, then the analyses should also be checked on the campaign level, i.e. the analyses should be checked together for consistency of results between the different analyses.

The analyses must be checked and the results interrogated. Questions to ask include:

1. Pre-analysis check
   - 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 design drawings.
   - Have material properties and section properties been input correctly?
   - Are consistent units used throughout?
   - 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.
2. Post-analysis checks
   - Has the analysis reached termination time?
   - Are there errors or warnings in the output file? Are they significant?
   - Are the total energy, the exchange of energies and energy absorbed by individual parts sensible? Is energy loss and hourglass energy acceptable?
   - Are the contact surfaces performing properly (e.g. penetration, contact forces) and is the extent of contact surfaces sufficient?
   - Is the deceleration sensible and as expected?
   - Is the deformed shape (globally and locally) realistic?
   - Has any element suffered extreme distortion? Will this affect overall results? Is this acceptable?
   - Is the mesh sufficiently refined to simulate the deformation modes with sufficient accuracy?
   - Is the added mass due to mass-scaling acceptable?
   - Would any of the areas/connections have failed and would they need to be re-analysed with failure?
   - Have boundary conditions, restraints, constraints, loadings etc been applied correctly?
3. Examination of results
   - Does the predicted behaviour "make sense"? Is it as expected?
   - 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?
   - What are the load paths? How is the structure behaving – bending, axial loading, tension, compression, shear, etc? What dominates the behaviour?
   - Are the choice of material model and boundary conditions sensible?
   - 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?
   - Are there uncertainties in any aspect of the input and should sensitivity analyses be carried out to bound the uncertainties?
   - 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?
   - How does the behaviour compare with similar packages in similar scenarios, and the same package in different scenarios?
   - Having evaluated the adequacy of individual analysis, the adequacy of the overall analyses campaign should be evaluated.

Checking must be documented. The record must include the name and location of the analysis that has been checked, the person who carried out the checking, check list indicating items that have been checked and items that have not been checked, evidence of checking, findings, improvements and corrections required.

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

DOCUMENTATION

All details of models, analyses and checking 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 (e.g. on CD) 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 including evidence of checking

REFERENCES

1. International Atomic Energy Agency, Regulations for the Safe Transport of Radioactive Material – 1996 Edition (As amended 2003). IAEA Safety Standard Series No. TS-R-1.
2. Department for Transport, Guide to an Application for UK Competent Authority Approval of Radioactive Material in Transport. DETR/RMTD/0003, 2001.