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# Substantiation of a Type B(M)F Radioactive Material Transportation Package by Finite Element Analysis

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## Abstract

The approval of nuclear transport packages requires the demonstration of performance against regulatory tests. This has typically required a significant amount of physical testing with concomitant time and cost implications. The capability of analysis techniques used in the nuclear industry for the substantiation of package designs has advanced significantly in recent years to the point where it has become feasible that little or no physical testing could be required in the assessment of a transport package against the regulatory tests.

A paper presented by Rolls-Royce plc at PATRAM2007 described the use of the explicit non-linear Finite Element (FE) code LS-DYNA in the substantiation of a new package for the transport of new nuclear fuel. The paper concluded that explicit analysis codes were so reliable for package impact calculations that minimal test work, limited to key confirmatory impact scenarios, should be pursued.

This paper describes the analysis approach adopted to substantiate the performance of a Type B(M)F package using Finite Element Analysis (FEA) without validation provided by physical testing of a full or scale model. The paper also discusses the key areas of investigation, the methods used and how the substantiation of previous packages has been used in support of the assessment.

## Introduction

The basis of the four possible approaches for design approval of Radioactive Materials (RAM) transport packages with respect to impact is described in the regulations (Reference 1):

a) Comparison to similar packages: demonstration by discussion and reference to drawings and/or sketches that the package is, in all respects, better than or equal to, a previously approved package.

b) Prototype testing: direct testing with reliance on the results of the test to demonstrate compliance.

c) Model Testing: testing that validates an FEA, in turn demonstrating compliance.

d) Analysis: compliance demonstrated entirely in FE environment with limited physical testing.

For a new package that is dissimilar to any existing design, approaches b) and c) are those normally followed to demonstrate compliance with the regulations. However, these approaches require prototypic packages to be manufactured in support of physical testing. These are usually costly and time consuming, especially in the scenario where the total number of packages to be manufactured is low.

Following the successful approval of an Industrial Package Type 2 Fissile (IP2-F) package using the model testing approach, confidence that an analysis-only approach could be used was such that it was advocated by Rolls-Royce plc at PATRAM in 2007 (Reference 2).

This paper details the approach taken in successfully achieving a competent authority design approval for a Type B(M)F package using an FEA based approach as the primary method for demonstration of compliance. The FEA was also supported by verification and validation from previous Rolls-Royce plc package substantiation.

# Package Description

The SMF is a packaging designed for use between nuclear licensed sites. It accommodates both vertical and horizontal loading and unloading, in either dry or submerged environments. The package is transported dry.

The package (see Figure 1) is constructed of a bolted body, base flange and lid assembly, with these items forged from stainless steel. To facilitate dry loading and unloading, a stainless steel rotating ‘gamma gate’ has been incorporated. Two valves are positioned at either end of the cavity to facilitate submerged loading and unloading.

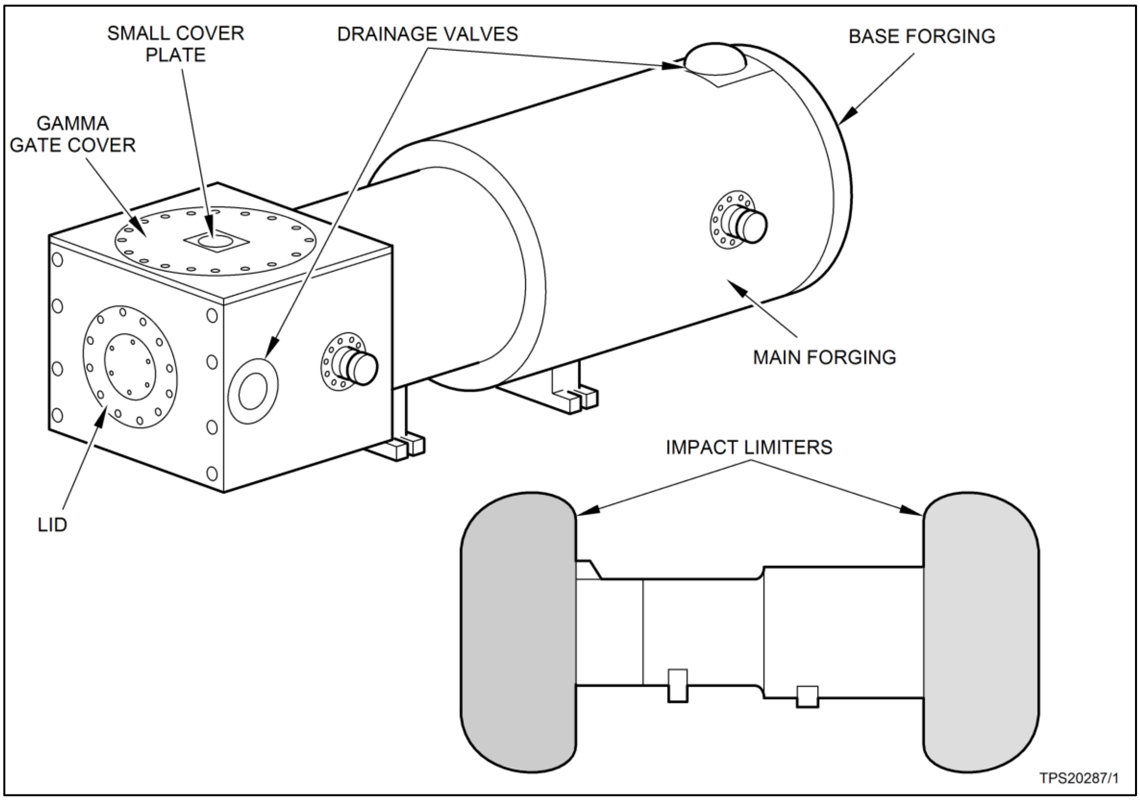


**Figure 1 Package General Arrangement**

To control the deceleration of the package in an impact scenario, two impact limiters are bolted onto the ends of the package; one at the lid end and one at the base forging end. These impact limiters are manufactured from a spun stainless-steel skin filled with energy absorbing polyurethane foam that is assembled in block form and glued together.

Shielding is provided by means of the bulk of the body wall. Containment between the smaller forgings and the main body forging is maintained by O-ring seals compressed by the bolting arrangements.

Horizontal and vertical lifting out of a transport or turning frame is achieved using four-point or two-point lifting beams. Transport can be by road or rail modes.

## Assessment Approach

The approach to the assessment can be broken down into the following areas:

a) IAEA requirements.

b) Governance.

c) Design optimisation.

d) Finite Element Analysis of the package.

e) Justification.

f) Key variable sensitivity.

g) Manufacturing variability.

h) Validation and verification.

## IAEA Requirements

For a competent authority to approve a package that is substantiated for impact integrity using FEA as its primary justification without a full/scale test, confidence in the design and the company QA systems must be demonstrated. This is necessary to ensure that the design not only meets the IAEA regulations (Reference 1), but also demonstrates that the design is robust against the requirements. This must also be supported by robust and in-depth validation and verification.

## Governance

Rolls-Royce plc has a governance structure that supports consistency and drives an appropriate level of review throughout an analysis. This includes:

a) A gated review process. A panel of internal experts and independents are used to review the modelling techniques.

b) A Suitably Qualified and Experience Persons (SQEP) development and assessment programme, to ensure engineers are capable of assessing and reviewing the work undertaken.

c) Technical checking procedures.

## Design Optimisation

In the design stage of the package, the material and size of the impact limiters were selected using a simplified FEA model representation of the package and impact limiters. The design optimisation study was based on a small sub-group of well-defined limiting drop scenarios that encompassed a range of different drop angles. The investigations used an initial estimate of the impact limiter size and then investigated the following:

a) Two different foam definitions.

b) Upper and lower temperature effects for the impact limiter.

c) Initial design plus incremental changes on radius of 50 mm.

The study focused on finding an impact limiter size and material that improved the deceleration of the forgings while operating within the allowable limits of the impact limiter foam performance at the lower and upper operating temperatures. This study also provided an insight into the robustness of the impact limiter design to ensure that there were no cliff-edge effects associated with the level of crush of the impact limiters and the ultimate deceleration of the package.

# Finite Element Analysis of the Package

A full three-dimensional model of the package was developed using LS-DYNA (Reference 3). It was not possible to use a partial model because the package is asymmetric.

The package forgings were modelled with solid brick elements, with a refinement of mesh in the locations of impact and in other areas of interest, such as around bolt holes.

The bolted joints between the main forging and the four smaller forgings have been modelled in detail using solid elements for each bolt. Each bolt is tied onto the main forging surface and preload is applied across the central part of the bolt shank. The thread on each bolt has not been modelled, but the associated strain concentration is accounted for in the assessment.

The double seals located between each of the smaller forgings and the main forging are not modelled in this analysis, but the gap between the forgings has been monitored to determine how much compression remains in the seal during and following the drop scenario. These gaps are monitored at multiple radial positions in the locations of the seals.

The impact limiters are modelled using solid elements, excluding the outer impact limiter skin which is modelled using shell elements. Each impact limiter is tied onto the main forging in the location of the bolts and the shear features designed to hold the impact limiters in place. These forces are monitored throughout the impact scenario for each bolt location and hand calculations are conducted to ensure that the impact limiters remain attached.

A simplified model of the contents of the package, representing its mass and stiffness, is included in the model. Velocity time histories of the internal furniture were then extracted so that a more detailed sub-model assessment of the contents can be conducted to assess payload integrity.

# Justification

To demonstrate that the IAEA regulatory requirements are met, the FEA assessments focused on:

a) Drop Attitudes and operating temperatures.

b) Forging integrity.

c) Bolted joint containment.

d) Minor valve integrity (e.g. drainage valves).

 

e) Retention of the impact limiter.

f) Payload integrity.

Drop Attitudes and Operating Temperatures

Typically, it will not be clear which drop attitude or temperature will produce the most severe damage to the package or highest risk of compromising the structural integrity of the package during the regulatory tests, especially given the asymmetrical nature of the package design. For example, the drop scenario that produces the greatest damage to the gamma gate cover may not necessarily be the same as that which causes greatest damage to the base forging. It is also not evident which initial 'slapdown angle' will also produce the greatest load on the contents.

To provide confidence that all regions of the package are assessed, a total of three Normal Condition of Transport (NCT) and 17 Accident Conditions of Transport (ACT) for different drop angles were analysed for an impact onto a flat rigid target. Additionally, eight ACT impacts onto a punch were assessed. These assessments aimed to maximise the load and damage in key locations of the package.

At the extremes of temperature of the expected package performance, only the foam experiences significant variation in properties, in particular its force-deflection properties. Heat transfer analyses identified that the bulk impact limiter should consider foam material properties in the range of -18°C to +60°C.

To determine the initial slapdown angle that would lead to the greatest load, in particular into the payload, a simplified model of the package was generated. This simplified model (see Figure 2) consisted of the foam impact limiter tied onto inertia properties of the package. Multiple angles were then investigated to maximise the perpendicular velocity at slapdown. The velocity conditions immediately prior to the secondary impact were extracted from the simplified model and then applied to the detailed model of the package. The slapdown with the greatest perpendicular velocity at one end of the forging was selected for the detailed assessment.

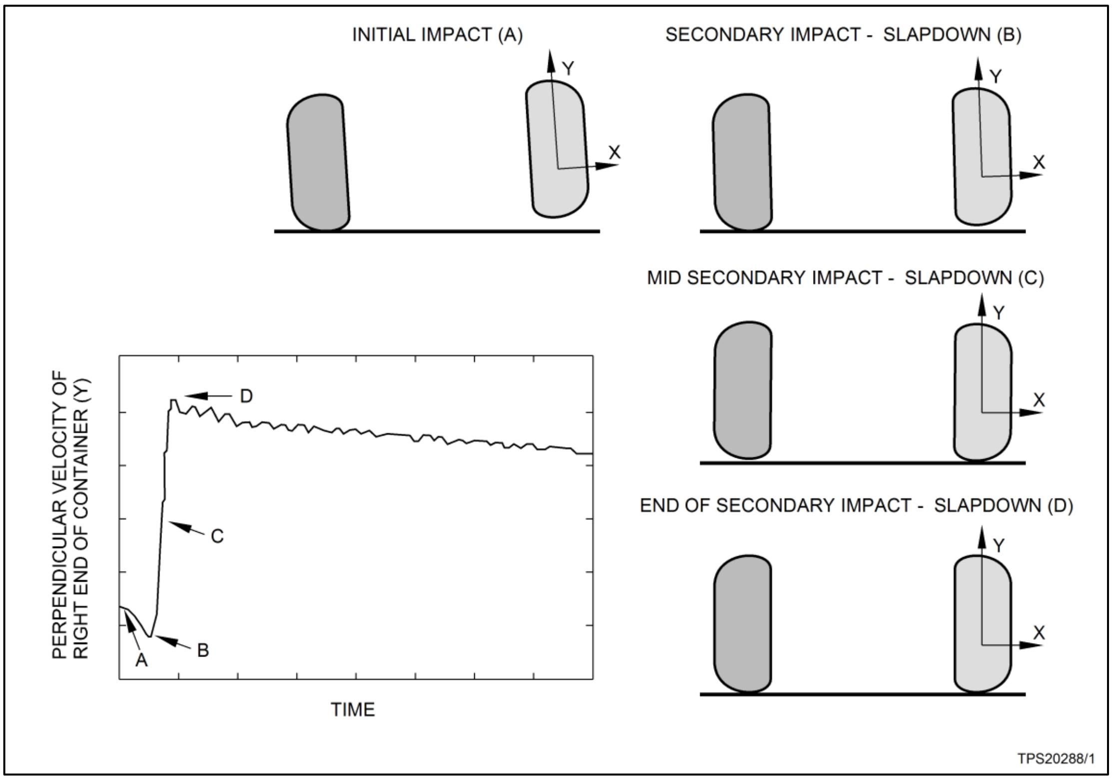


**Figure 2 Stages of Package Slapdown**

The objective of the critical drop angles assessment was to:

a) Establish the critical drop orientations for oblique package drops where the centre of gravity is not directly above the point of impact. For example, in a corner drop, a secondary impact (slapdown) of the package occurs after the initial primary impact due to rotation of the package.

b) Identify the worst case orientations of the package, such that the impacts maximise the damage to the package and/or the package payload. In general, there is not a single impact scenario which represents a worst case for all damage criteria.

A range of methods were used to assess for required slapdown scenarios to establish critical drop orientations for oblique drops. These were:

a) BAM analysis of the slapdown kinematics, where the package is assumed to behave like a rigid rod (T. Quercetti et al, PATRAM 2001, Reference 4).

b) MATLAB coding of the BAM rigid body equations.

c) LS-DYNA explicit FEA rigid body model representation of the BAM model.

d) Oblique drops of the FEA model of the package with, and without, impact limiters.

The assessment of critical drop angles for package slapdown conditions concluded that:

a) The BAM equations are a useful early design tool for establishing the governing package dynamics for a slapdown scenario.

b) However, for package justifications (particularly with impact limiters incorporated in the design), detailed models of the package are required to establish the precise slap-down dynamics. This is as described in Scenario d).

## Forging Integrity

The package forgings are substantial and, for most drop scenarios, the plastic deformation is limited to small surface deformations. A few limited drops, such as corner drops and the punch test, resulted in a small amount of plasticity that is more extensive than small surface deformations. The through-section investigations demonstrated that the plastic region had progressed through a small percentage of the wall thickness only, and that the majority of the forging had remained elastic.

## Bolted Joint Containment Capability

The bolted joints have been modelled explicitly, excluding the seals and bolt threads. The bolted joints essentially have three failure modes which could lead to loss of containment:

a) Failure of the bolts which retain the cover plates and are therefore required to maintain seal compression.

b) Loss of pre-load across the seal, resulting in a leak path.

c) Failure of the cover plates (investigated in the ‘Forging Integrity’ section of this paper).

Modelling of threads within FEA is prohibitive and, therefore, an equivalent assessment is adopted in which a relationship was derived between the plastic strains on the surface of an un-threaded bolt and the strains experienced at the root of the thread. The failure strain of this bolt material was then scaled-down accordingly and compared against the predicted strains experienced in the un-threaded FEA representation of the bolts as a failure criterion.

 

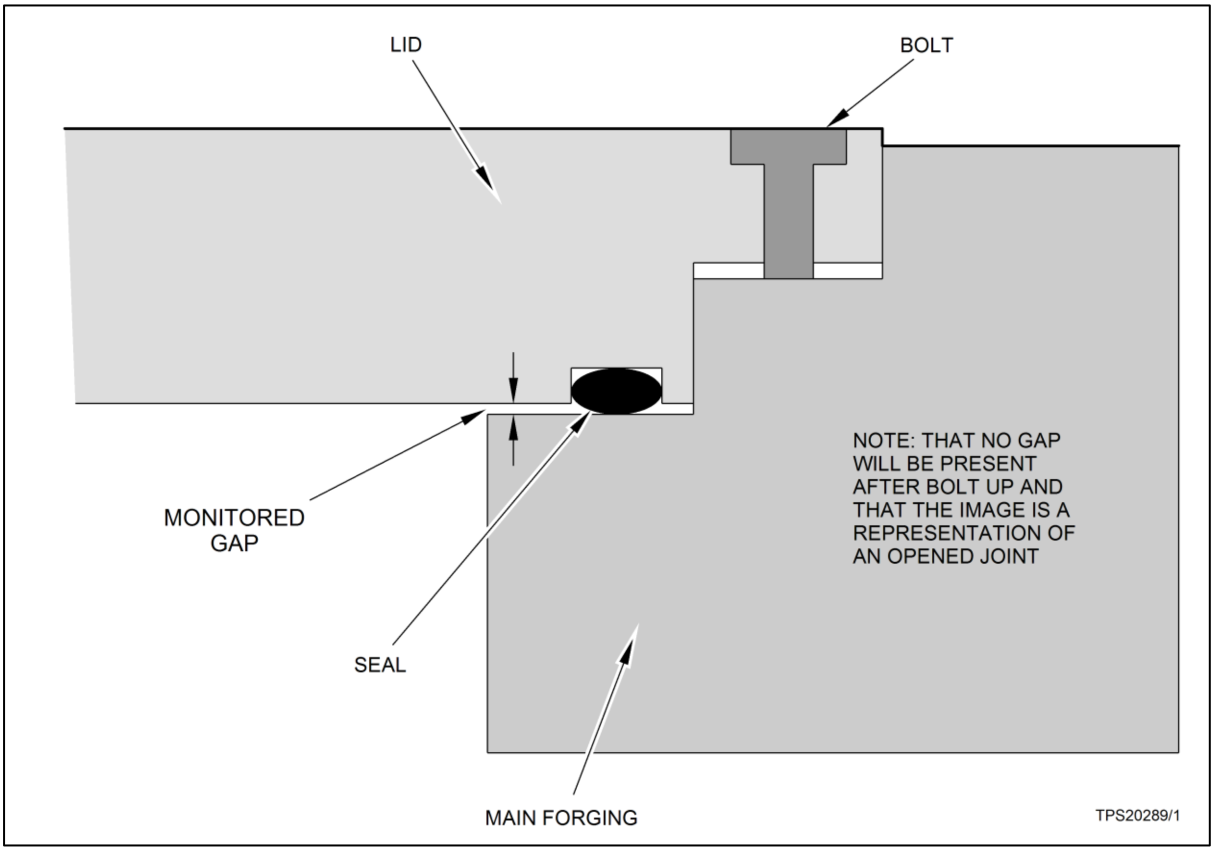


**Figure 3 Modelled Bolted Joint**

The seals in the package were not explicitly modelled in any of the analyses; instead, the gaps between the main forging and the lids were monitored (see Figure 3) throughout the drop scenario at different radial positions. The requirement for any containment seal is that compression should not fall below 10% of the as-fitted seal compression. Based on this allowable reduction in seal compression, an allowable gap between the main forging and the lids was derived. The maximum gap monitored between the main forging and the lid for each of the drop scenarios does not fall below the limit and so sufficient seal compression is maintained. The gap developed across the joint is 15% of the allowable gap, resulting in an acceptable reduction in preload across the seal.

## Minor Valve Integrity

The drainage valves were not explicitly modelled in the FEA; peak accelerations were, therefore, extracted from each of the locations of these features for all of the drop scenarios. Conservative hand calculations using British Standards were used to justify these bolted and welded regions, along with calculations to confirm that preload across the steel mating faces were not lost, thus maintaining preload in the seals.

## Retention of the Impact Limiters

Bolts and localised shear features are used in multiple locations to ensure that the impact limiters remain attached to the main forgings. Rather than model these features explicitly, which would dramatically increase the run times of the analyses, ties were used in the location of each attachment feature and forces were extracted from these connections for each attachment location throughout each drop scenario. These forces were resolved into tensile and shear loads. Conservative hand calculations using the bounding tensile/shear loads demonstrated that the attachment features would be retained.

 

Payload Integrity

Velocity time histories were extracted from the FEA model of the internal features for use in sub-models of the contents. Various gaps between the internal features and the payload were investigated to assess the integrity of the contents following each of the drop scenarios. Only limiting drop scenarios were investigated, though this did include the key variable sensitivity analyses discussed later in this paper.

These assessments were only possible because of the knowledge library generated for similar contents in the preparation of previous package assessments.

# Key Variable Sensitivity

For this assessment the following two were assessed as being the most significant:

a) Foam stiffness.

b) Bolt preload.

Foam Stiffness

Due to the large stiffness difference between the impact limiters and the steel main forging, it is clear that the impact limiter material properties will control the deceleration of the package.

By altering the stiffness of the impact limiter foam, the variation in the response of the package and its contents can be determined. Using a 1.5 factor applied to the foam stiffness, the robustness of the package response can be investigated. This 1.5 factor is used to increase the stiffness by multiplying the stress component of the lower temperature foam stress stain curve and is also used to reduce the stiffness of the foam by dividing the same stress component of the higher temperature curve (Figure 4). A similar sensitivity study can be found in Reference 5.

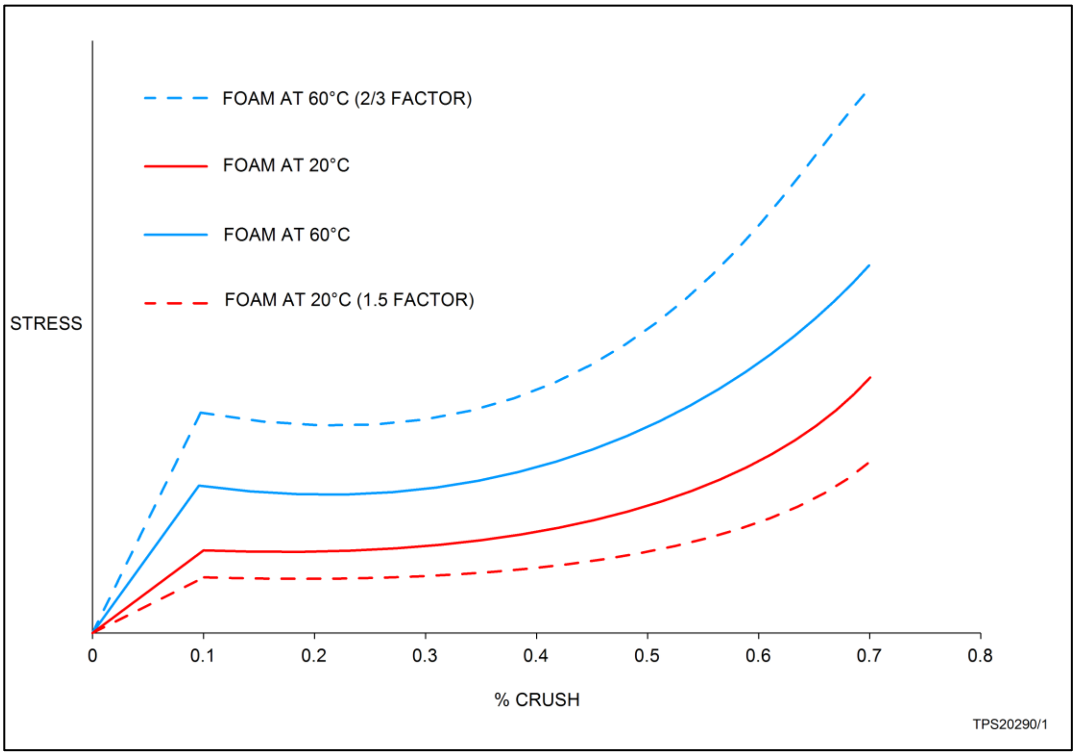


**Figure 4 Variation in Foam Stiffness**

Bolt Preload

Following the initial assessments, it was found that the lid bolted joint would be the most likely cause for a loss of containment, in particular at the seal. To investigate the sensitivity of the seal compression, a further analysis was undertaken that used half the design preload across each bolt. This study showed that there was only minimal change in the gap between the two steel faces during an impact scenario and thus a satisfactory compression across the seal was maintained.

# Manufacturing Variability

The manufacture of a large-scale impact limiter can be complicated and requires large tolerances. These impact limiters are a novel design that required new specialised manufacturing capability and it was therefore considered likely that:

a) There would be gaps between the internal foam and the outer skin.

b) The outer skin dimensions would vary.

c) The glue used between each individual foam block in the impact limiters may not remain integral with the foam following manufacture.

An investigation was conducted to determine the effects of the following variations in the manufacture of the impact limiters:

a) Tolerance on the impact limiter outer dimension.

b) Variation in skin thickness of impact limiter outer skin.

c) Tolerance of the foam within the impact limiter outer skin.

d) Absence of a glue bond between the internal foam blocks fitted within the impact limiters.

This assessment selected one drop scenario and analysed the velocity profile at one end of the package, located on the forging, for a number of the key manufacturing variables. This shows that none of the manufacturing investigations produce a significant change to the velocity profile and are therefore demonstrated to have a secondary sensitivity to the package response.

# Validation and Verification (V&V)

This section provides a brief overview of the approach to V&V used for the assessment submission.

FEA codes, such as LS-DYNA (Reference 3) have been verified and validated for a particular application. For the V&V to be relevant, validation evidence needs to test the physical responses of interest for a similar or bounding loading environment. Each contributing component, feature and material in the package was reviewed against previous physical testing to determine what level of validation confidence could be attributed to the particular section of the FEA model. This relied on a library of physical testing conducted by Rolls-Royce plc, not only of full-scale drop tests, but also for on-site safety justifications. The following is a list of some of the physical testing previously conducted by Rolls-Royce plc:

a) Extant full-scale radioactive materials transport package drop tests versus analysis. Reference 2 shows a test previously commissioned by Rolls-Royce plc that supported bolted joints, the use of foam as the primary impact material and other relevant features.

 

b) Static and dynamic testing of crush tubes. The impact limiter skins closely matched the material and thickness of previous crush tube tests conducted by Rolls-Royce plc.

c) Testing of specific impact limiter foam. Testing of the specific foam used within the impact limiters was commissioned at appropriate temperatures, forces and strain rates.

# Conclusions

This paper discusses the approach used by Rolls-Royce plc in the successful application and licencing of a package, in which the impact assessments were conducted using FEA as the primary mode of demonstration of compliance. This was the first time that this approach was used and has demonstrably removed time and cost from the programme for the delivery of a key customer capability.

In summary, this was achieved by:

a) A methodical approach to the assessment of the package, to demonstrate that containment was maintained.

b) Design optimisation of the key impact controlling features, i.e. the impact limiters, to ensure a robust design.

c) Understanding key variable sensitivity, by factoring the key deceleration material by a factor of 1.5 and by halving the applied preload in the bolted joints.

d) Testing the implications of the manufacturing tolerances on the response of the package.

e) A robust itemised approach to V&V, assessing the level of confidence for each individual component, feature and material.

# References


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