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The Design of Nuclear Transport Frames For Fatigue Loadings Utilising Finite Element Analysis

Robert Belsom
CEng MIMechE
Design Engineer, Roll-Royce

David Patrick
CEng MIMechE
Dynamic Stress Engineer, Rolls-Royce

ABSTRACT

Nuclear transport packages are typically attached to transport trailers through the use of a transport frame. The International Atomic Energy Agency (IAEA) transport regulations do not provide guidance on the design of the tie-down system or transport frame during Routine Conditions of Transport (RCT). There is a requirement to demonstrate that the design is appropriate and able to withstand the loadings experienced during transport. The Transport Container Standardisation Committee (TCSC) code of practice TCSC 1006 provides some guidance on the design of such items for transport. The use of Finite Element Analysis (FEA) to analyse the response of these structures is increasingly prevalent.

Transport frames typically have complex load paths and are subject to a variety of loading conditions (such as normal and accident conditions of transport). These can cause premature failure if the correct design considerations are not implemented. As they are typically steel structures, there is potential for fatigue failure to occur due to RCT; especially through design features such as welds.

This paper discusses an approach for assessing a nuclear transport frame for fatigue loadings that would typically be experienced during RCT. The paper discusses the cyclic loadings caused by RCT, their provenance and how these are assessed using an FEA model to determine stresses within the system.

The paper describes the application of BS 7608 to the analysis of such structures and includes recommendations whereby the designer can improve fatigue life of the product. This is achieved through the application of various weld parameters and design features to provide a robust solution for fatigue loading of the transport frame structure. In addition, the methodology includes a discussion of the strength assessment of the frame fabrication.

The use of the methods discussed in the paper has allowed Rolls-Royce plc to substantiate the frame-to-trailer tie-down system within the public domain, with a good understanding and knowledge of the estimated fatigue life. Prior to the detailed analysis, through the use of BS 7608, it was predicted (through the use of more conservative design techniques) that the tie-down system may need to be replaced after each transport journey.

INTRODUCTION

Rolls-Royce plc is responsible for the design and manufacture of a transport container that shall be used for the transportation of high mass Radioactive Material (RAM) assemblies. The transport package is rated as an IP-2 (F) package in accordance with the IAEA regulations (Reference 1). During road-transport between sites (on public roads) the package is supported on a handling frame. The package and handling frame is supported on a tie-down system that consists of a sub-frame fabrication and a number of ancillary components. The ancillary components ensure that the loads are distributed appropriately throughout the sub-frame fabrication. The tie-down system, handling frame and trailer bed is shown in Figure 1.

The sub-frame fabrication is attached to a hydraulic flat top modular trailer which is typically used in the heavy transport industry. The sub-frame fabrication has a number of constraints placed upon it:

1. It must not exceed a height that would raise the entire package above 4.9m; this being the UK limit on normal transport routes for bridge height.
2. The mass must also be minimised to prevent the overall mass of the transported assembly exceeding the road mass limits.
3. It must provide features in the appropriate locations to enable securing to standard attachment points on the trailer.
4. S355 structural steel must be used as the main material of manufacture to minimise the cost associated with high strength steels, such as S690.

These constraints have driven an optimised sub-frame design that is manufactured from steel plate to provide the appropriate sectional properties that allow the load to be supported whilst minimising the mass. The use of steel plate allows for the section thickness to be optimised in the appropriate regions. This approach produces a complicated structure that is difficult to analyse through simple beam theory (ie hand calculations), driving an FEA analysis route.

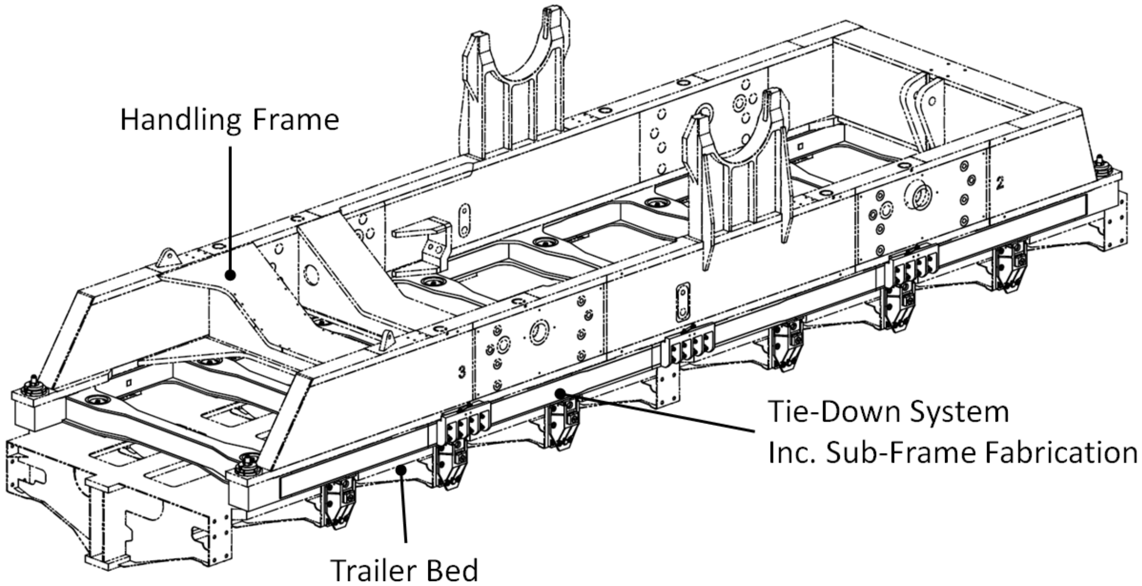

Figure 1. Tie-Down System and Interfacing Components

DESIGN APPROACH

In order to obtain the optimum design for the fabrication, a three-stage design process was adopted, incorporating progressive governance gates at each stage.

Stage 1 – Simple Beam Theory (Hand calculations)

The first stage of the design process involved the sizing of the various cross members and longitudinal members that were required for the design of the fabrication. At this stage, the preference was to use standard box and I-sections where possible but it was soon realised that, due to the constraints placed on the design, a bespoke approach would be required. The simple beam theory method of analysis consisted of two-dimensional analyses of simple beams appropriately representative of a plate structure. Typically, this involved analysing one load at a time rather than combining the loads into orthogonal loading orientations to allow for approximate sizing.

Stage 2 – Simple Finite Element Analysis

Following Stage 1, an integrated design FEA package was used to further optimise the design. The design FEA package used was Siemens NX with Nastran used as the solver. A coarse tetrahedral mesh was developed which showed areas in which the design could be further optimised prior to the full analysis, carried out by the Dynamics Group within Rolls-Royce plc, in Stage 3. A limited amount of load cases were considered for this optimised design solution, with some modification made prior to the detailed FEA.

Stage 3 – Detailed Finite Element Analysis

The Dynamics Group completed a detailed FEA of the transport assembly, and structural integrity assessments of the sub-frame fabrication; this is the focus of this paper.

Ancillary Components and Threads

There were a number of structural connections bolted to the sub-frame fabrication that formed part of the tie-down system. Due to the simplicity of these attachments, the decision was taken to complete analysis of these components through beam theory for both RCT and Normal Conditions of Transport (NCT). The loads at these connections were extracted from the detailed FEA of the transport assembly.

LOADING CONDITIONS

The detailed FEA model was used to assess the sub-frame fabrication in both RCT and NCT. In accordance with the guidance published in TCSC 1006 (Reference 2) the fabrication was assessed against BS 2573 (Reference 3) for strength assessment (typical loads in NCT) and BS 7608 (Reference 4) for fatigue assessment (typical loads in RCT).

Note: BS 2573 (Reference 3) has now been superseded by BS EN 13001 (Reference 5). However, it remains applicable and is widely used within the UK nuclear industry.

Normal Conditions of Transport (NCT)

For NCT, the acceleration factors in TCSC 1006 (Reference 2) were utilised for transport via road. Note: This tie-down system is only used for transport via road. The acceleration factors are shown below. The accelerations are applied in two directions at any one time i.e. it is not anticipated that the load would simultaneously hit a bump or pothole, decelerate and experience harsh cornering.

Table 1. Strength Assessment Acceleration Factors

Mode of Transport	**Acceleration Factors Applied to the Package (Strength)**		
	Longitudinal	**Lateral**	**Vertical**
Road	1g	-	1g down ± 0.3g
	-	0.7g	1g down ± 0.3g

Routine Conditions of Transport (RCT)

For RCT, the acceleration factors in TCSC 1006 (Reference 2) were utilised for transport via road. The acceleration factors are shown in Table 2. The accelerations are applied in all three directions simultaneously.

Table 2. Fatigue Assessment Acceleration Factors

Mode of Transport	**Acceleration Factors Applied to the Package (Fatigue)**		
	Longitudinal	**Lateral**	**Vertical**
Road	± 0.2g	± 0.2g	1g down ± 0.3g

BS 7608 FATIGUE ASSESSMENT APPLICATION

The sub-frame fabrication was assessed in accordance with BS 7608 (Reference 4). To provide the minimum number of cycles for the analysis, a calculation was undertaken where:

$$Number\ of\ cycles = \frac{Distance}{Speed} \times Suspension\ Natural\ Frequency$$

The suspension natural frequency used was 1.5 Hz, as defined in TCSC 1006 (Reference 2), as a hydraulic flat top modular trailer was to be used for transport. These trailers are considered to perform as well as, if not better than, a traditional suspension system. Considering the significant large mass of the package, the natural frequency is considered to be lower than 1.5 Hz; the number of cycles used for the fatigue assessment is considered, therefore, to be conservative.

Due to the high mass being transported, and to improve the estimated design life, stress ranges were assessed for the system configured in both laden and unladen conditions. This had a large impact on the final fatigue life of the sub-frame fabrication. Fatigue Utilisation Factors (FUFs) were a combination of the laden and unladen cycles.

Table 18 of BS 7608 (Reference 4) was used to develop S-N curves for various classes within Mathcad. The FEA software was used to extract stresses and to provide fatigue stress ranges at all weld positions. This is discussed in further detail in the fatigue assessment section. Mathcad was then used to analyse the stress ranges against the S-N curves, and to provide FUFs for various key locations on the sub-frame fabrication.

FE MODELLING AND ANALYSIS

Analysis Method

The FEA for this study used the ANSYS software (Reference 6). A non-linear static analysis approach was adopted, in which the loading is applied in the form of equivalent-static accelerations. Each permutation of the specified road transport acceleration loadcases (see Tables 3 and 4) was analysed as a separate load case. An initial load case captured the solution for self-weight under gravity only. The loadcases analysed in Table 4 were completed for the transport solution with a laden package and then repeated in the unladen configuration.

Table 3. Strength Analysis Load Cases

Load Case	Applied Strength Acceleration (g)		
	Longitudinal (X)	Lateral (Y)	Vertical (Z)
LC1	-	-	1.0
LC2	1.0	-	1.3
LC3	1.0	-	0.7
LC4	-1.0	-	1.3
LC5	-1.0	-	0.7
LC6	-	0.7	1.3
LC7	-	0.7	0.7

Table 4. Fatigue Analysis Load Cases

Load Case	Applied Strength Acceleration (g)		
	Longitudinal (X)	Lateral (Y)	Vertical (Z)
LC1	-	-	1.0
LC2	0.2	0.2	1.3
LC3	-0.2	0.2	1.3
LC4	0.2	-0.2	1.3
LC5	-0.2	-0.2	1.3
LC6	0.2	0.2	0.7
LC7	-0.2	0.2	0.7
LC8	0.2	-0.2	0.7
LC9	-0.2	-0.2	0.7

Modelling Method

In addition to the sub-frame fabrication, both the trailer bed and handling frame were included within the FEA model so that the load distribution between interfaces could be captured correctly.

The FEA mesh primarily comprised eight-noded shell elements and was generated using HyperMesh software (Reference 7) from a CAD parasolid model. The connections to interfacing components were generated using ANSYS Parametric Design Language (APDL) and used a combination of 1D linear and non-linear spring elements, and link compression only elements. The complete model consisted of approximately 330,000 elements.

Due to the performance of the trailer suspension system, rigid boundary constraints were applied to the FEA model at the approximate location of the attachment point of the trailer suspension blocks. The container and payload was modelled as a single mass element with a centre of gravity, mass and mass moments of inertia equivalent to that of the actual package.

Sensitivity Studies

A number of sensitivity studies were undertaken to ensure that variations in key areas of the design were captured. These sensitivities studies included variations in resilient interface stiffness properties (due to temperature and/or variation in batch chemistry) and gaps between interfaces. The results demonstrated a degree of sensitivity and, therefore, this resulted in stress scaling factors being applied to the results of both the strength and fatigue analyses to account for these postulated variations in the manufacturing process.

Scripting Methods

Scripting methods were developed to reduce the time and cost associated with repeating the analyses, post-processing and assessments. The APDL input decks included several parametric features so that the modelled configuration of the interface connections could be easily modified (useful for the sensitivity studies). Calculation spreadsheets were set up such that weld make-up (and the associated weld classification) could be easily modified to optimise the design of the welds. Methods were developed to automatically generate master input decks with little user input, thereby reducing time, cost and risk of user input error (and therefore re-analysis).

STRENGTH ASSESSMENT

The strength assessment was undertaken in accordance with BS 2573 Part 1 (Reference 3). BS 2573 (Reference 3) was developed to assess structures using beam theory (e.g. axial and bending stresses). However, the FEA model adopts a shell element mesh; stresses extracted from the shell model had, therefore, to be linearised to obtain section axial and bending stresses appropriate for use with this design code. Figure 2 shows the limits adopted within the BS 2573 (Reference 3) assessment methodology.

Stress Classification Lines (SCLs) were used in order to extract characteristic linearised stresses from the FEA shell model. These were located at key positions for the strength assessment, identified through analysis of the contour plots. There are areas of the sub-frame fabrication that are affected by discontinuities due to geometric simplifications in the FEA model and therefore SCLs have been placed at least one element away from these positions to ensure that they do not excessively influence the results.

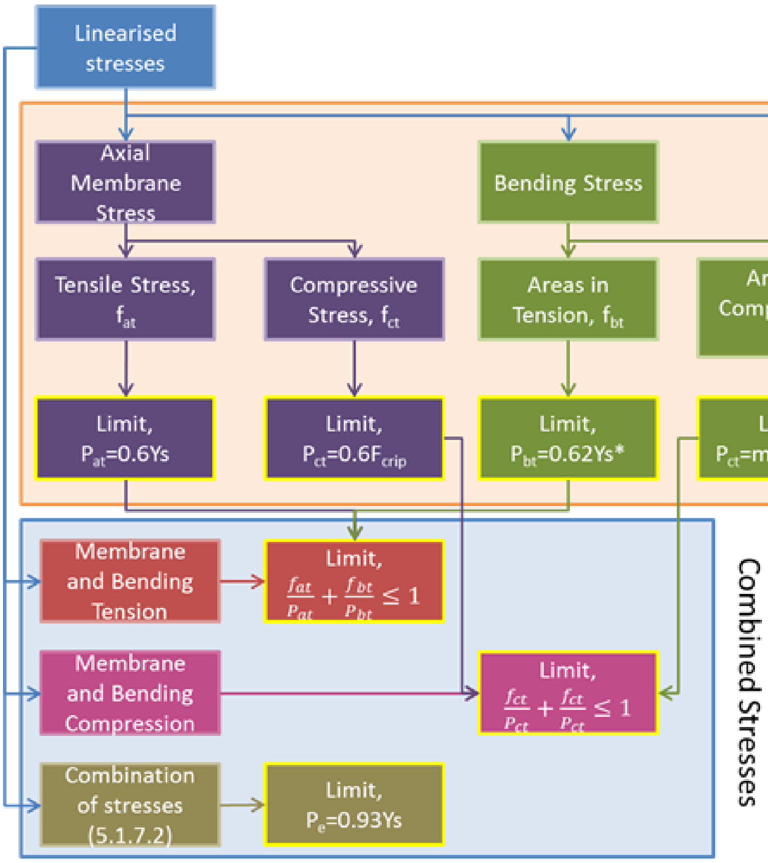

Figure 2. BS 2573 Assessment Methodology

FATIGUE ASSESSMENT

The configuration of the transport package (either laden or unladen) is known for each journey and therefore the use of this transport solution is prescriptive. Therefore, benefit can be taken from order dependence by pairing peak and trough stresses associated for the journey only, in order to calculate a Partial Usage Factor (PUF) for a specific journey. Therefore, a cumulative FUF can be calculated from multiple uses in the laden and un-laden transport configurations.

Weld Classification

Each weld on the sub-frame fabrication was categorised in accordance with BS 7608 (Reference 4). This was based on the weld geometry and load direction. It was necessary to account for all potential fracture modes and potential variations in principal stress direction. It is a complex and cumbersome process to understand the nature of loading at each fatigue site. Therefore for simplicity, two assessments were performed for each fatigue site with differing weld detail classifications assuming:

a. Mode I fracture, and combined in-phase and direct shear stresses.
b. Combined fracture Mode I and II or III, with combined out of phase stresses.

Derivation of Stress Ranges

The standard fatigue assessment procedure was used in BS 7608 (Reference 4) where it states that nominal stresses should be used. BS 7608 (Reference 4) defines a nominal stress as the stress that would exist in the absence of the structural discontinuity being considered. It would be a fairly complex and cumbersome process to extract nominal stresses from the FEA shell model or to use the hot-spot methods described in BS 7608 (Reference 4); therefore stress ranges were conservatively extracted at node positions that are coincident with a given weld. The following procedure was taken:

a. Each of the fatigue load conditions are paired together to calculate component stress ranges and the associated principal stress range for each pair.
b. The stress range to be assessed is taken to be the maximum principal stress across all load condition pairs.

It was necessary to calculate and apply Stress Concentration Factors (SCFs) for the following:

a. Specific standard detail categories where BS 7608 (Reference 4) had placed a requirement.
b. Geometrical discontinuities that are not a natural characteristic of the standard detail categories presented in BS 7608 (Reference 4).

Due to the high loads, further refinement of the estimated fatigue life of certain individual welds was required. For these locations, as described in BS7608 (Reference 4) further post-processing was performed to beneficially scale the compressive portion of the stress range by 60% as the sub-frame fabrication is Post Weld Heat Treated (PWHT). For simplicity, these were conservatively considered for those PUFs for the laden configuration only.

Allowable Fatigue Stresses

The standard basic S-N curves were used for the assessments. These curves represent two standard deviations below the mean line curves with a probability of weld failure of 2.3%. This was judged as appropriate, and conservative, as a single weld failure will not result in collapse of the structure. The maximum stress amplitude varies between the laden and unladen conditions, so the fluctuating stress has varying amplitude; the S-N curves are, therefore, modified to bound the requirements as outlined in Clause 16.4 of BS 7608 (Reference 4).

The S-N curves were modified to consider the effect of material thickness and, for simplicity, the parameters used to calculate this factor are conservatively selected to minimise fatigue strength. Further to this, the application of a weld toe improvement technique has been beneficially utilised.

DESIGN AND ANALYSIS RECCOMENDATIONS

Due to the limits placed on the design of the tie-down system, it was necessary that assessment went through an iterative process to obtain a solution that met the design life requirements. A number of observations and recommendations were generated during the process of the design, analysis and assessment of the sub-frame fabrication.

Design and Analysis Recommendations for Transport Frames

Where possible, the designer should minimise the use of load-bearing welds. This can be achieved as follows:

1. Specific load bearing features could be machined from solid material – particularly in highly stressed regions. This would apply to features to which other components are attached such as threaded regions
2. Offsetting joints so that the load path is not directly through the weld. This can mean either staggering plate joints or through the use of machined features which support joints.

PWHT provide benefits for stress analysis; however the designer should consider different materials that may be used on a fabrication and the interface between them following PWHT. Different materials may have different cooling rates and temperature gradient profiles for heat treatment so a compromise may be required to balance the required material properties and the heat treatment.

For fabrications, full penetration welds should be the preferred method; weld toe improvement techniques should be used, in accordance with BS 7308 (Reference 4), if structural loads are expected to be severe. These allow the designer to take benefit of various weld enhancements for the fatigue analysis specified within BS 7608 (Reference 4).

Time and associated costs were reduced by using parametric FEA modelling and advanced scripting methods. This benefit is only applicable where it is anticipated that an iterative design process is required when severe loading is expected in a regime of highly constrained requirements. Parametric definitions of the weld classifications have also proved useful in dealing with manufacturing concessions where weld make-up has changed during the manufacturing process.

It is also possible to revisit the fatigue assessment following the initial journey in order to improve the estimated fatigue life of the structure. Data loggers will be used to record time-varying accelerations and, therefore, derive actual frequency and acceleration content for the specific transport application. Modifying the fatigue cycles (from revised frequency content) will be relatively simple to do within the Mathcad calculation, providing a quick and simple improvement to the estimated design life. Changing the acceleration values requires the analyses to be re-run and so is more time consuming and expensive; but still a better option than re-manufacture.

CONCLUSION

This paper has discussed the application of BS 7608 to fatigue assessment of a sub-frame fabrication used in the transport of a package. It has also covered the strength assessment of the same frame. This paper presents one method that could be adopted to allow the design and stress engineers to design and analyse a complicated fabrication.

The use of the methods discussed in the paper have allowed Rolls-Royce to substantiate the frame to trailer tie-down system within the public domain, with a good understanding and knowledge of the estimated fatigue life. Prior to the detailed analysis through the use of BS 7608 it was believed (through the use of more conservative design techniques) the tie-down system may need to be replaced after each transport journey.

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