**Proceedings of the 17th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2013
August 18-23, 2013, San Francisco, CA, USA**

AN EXPERIMENTAL PROCEDURE FOR MEASURING ACCELERATIONS AND STRAINS FROM A TIE DOWN SYSTEM OF A HEAVY NUCLEAR TRANSPORT PACKAGE DURING A RAIL JOURNEY

A.D.Cummings
International Nuclear Services
Warrington, United Kingdom

J.Krywonos
International Nuclear Services
Warrington, United Kingdom

P.Purcell
International Nuclear Services
Warrington
United Kingdom

G.Rothwell
Liverpool J.M University
Liverpool
United Kingdom

R.English
Liverpool J.M University
Liverpool
United Kingdom

ABSTRACT

The transportation of nuclear waste and new nuclear fuel is an important aspect in sustaining the generation of electricity by nuclear power. The design of packages that satisfy regulatory requirements for normal operating and accident conditions is a complex engineering challenge. The ancillary equipment used to constrain the packages to their conveyance, a tie down system, is part of a multi component system used to transport packages. Traditionally, the individual components of the transport system have been designed in isolation. This approach does not account for the interaction between components of the system such as the conveyance, tie down system and package.

The current design process for tie down systems is well established but due to its heuristic development, suffers from uncertainties over which loading conditions should be applied. This paper presents a method for collecting measured acceleration and strain data that can be used to derive customised load cases for the design of tie down systems during rail transportation. The data was collected from a tie down system that restrained an empty package, weighing 99.7 tonnes during a routine rail journey from Barrow-in-Furness to Sellafield. Furthermore, the data can be used to validate modern computer models, allowing for the development of the previously described holistic approach to tie down system design.

The results are unique because an ensemble of acceleration and strain time histories from a transport system laden with a nuclear package is unprecedented. A visual examination indicates that this tie down system was subjected to low magnitude accelerations. The measurement points also show that the general trend of acceleration levels is highest nearest the track and is attenuated by the package.

The implications for the design of tie down systems are that two potential failure modes, fatigue and static strength, have been identified. The data provides scope for customising accurate static strength and fatigue calculations using modern computational techniques. This allows for the safety margins inherent in new designs to be determined and optimised design solutions made possible.

INTRODUCTION

The safe transportation of new fuel and irradiated nuclear waste is an essential part of the nuclear fuel cycle. The short and long term management of nuclear waste is a complex subject with many engineering challenges. For example, the design of transportation packages that satisfy the regulatory demands for normal operating conditions and accident conditions is a major challenge. Another engineering challenge, closely related to package design, is the method of constraining packages to their conveyance during transportation. The constraint mechanism is called a tie down system (**Figure 1**).

There are four modes of transport for packages; road, rail, sea and air. In practice, the most prevalent modes of transport used in the UK, for intermediate and high level waste, are rail and sea. A tie down system can therefore be mounted to the flat-bed of a trailer, to a rail wagon bed or in a ship or airplane cargo hold. The loading conditions depend on the mode of transport.

Figure 1. Typical Tie Down System

The mass of nuclear shipping packages can vary from just a few tonnes to >100 tonnes. Therefore, generic load cases must encompass all different types of packages and each mode of transport.

This paper evaluates the most pertinent points from some of the currently used design codes of practice and standards for tie down systems (in the UK) and focuses on the inconsistent load cases suggested within them. A methodology for obtaining experimental data suitable for design use is then presented.

Tie Down System Design for Rail Transportation

An older design procedure for tie down systems is the Oak Ridge National Laboratory Cask Tie Down Design Manual [1]. Further design guidance is available within the current Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material [2].

The design method is to apply acceleration factors to the centre of gravity of a package, multiplying the package mass by the appropriate acceleration to derive forces to apply to the tie down system. The resulting stresses in the members of the structure are then calculated and compared to allowable stresses. The current IAEA Advisory Material [2] states "the accelerations derived from routine conditions of transport should not cause any component of the package or its retention system to yield"; i.e. the yield stress of the material should be used as the allowable stress.

Table 1. Proof Load Cases

	Longitudinal [g]	Lateral [g]	Vertical [g]
IAEA Regulations Advisory Materials TS-G-1. Radioactive material packages in Europe by rail (UIC) [IV.8]	4	0.5	1±0.3
TCSC 1006 Guide to the Securing/Retention of Radioactive Material Payloads and Packages During Transport, 2012 [1]	4	1	2(D); 1(U)
TCSC 1006 Guide to the Securing/Retention of Radioactive Material Payloads and Packages During Transport, 2012 [2]	1	1	2(D); 1(U)
RSSB - GMGN2589 Guidance on the Structural Design of Rail Freight Wagons including Rail Tank Wagons	2	1	2(D); 1(U)

1.Wagons Subjected to Shunting 2. Combined Transport

Table 2. Fatigue Load Cases

	Longitudinal [g]	Lateral [g]	Vertical [g]
TCSC 1006 & GM/GN 2589 [5]	±0.2	±0.2	±0.4

The current IAEA Advisory Material does not stipulate that the design of a tie down system should prevent failure by fatigue; in contrast, the 2002 revision of the advisory material [3] states "In addition to these quasi-static force considerations, the package designer must also account for the effects of fluctuating loads which could lead to the failure of components of the package and its retention system caused by fatigue". Guidelines also state that suitable acceptance criteria for stresses should be agreed by the relevant competent authorities [2, 3].

In the UK, one relevant competent authority for tie down systems is the Rail Safety Standards Board, who publishes a standard for the structural design of rail freight wagons [4]. A further source of guidance is published by the Transport Container Standardisation Committee (TCSC) [5]. These guidance documents state that the design for prevention against fatigue failure should be considered and provide fatigue load cases to be applied. **Tables 1** and **2** compare the proof and fatigue acceleration factors [2, 4, 5]. These design guides place emphasis on classical hand calculation methods and not finite element analysis (FEA).

Motivation for Experimental Work

Internationally the subject of which acceleration factors should apply and their possible revision has been raised by several authors [6-8]. Fourgeaud *et al* states that some of the acceleration factors in the literature, which are based upon experimental data, should be increased and rounded up to account for lack of data. Purcell suggested that reduced design criteria may be required when considering tie down systems for heavy nuclear packages as the use of the load cases enforced the need to oversize structural members, causing tie down systems to be heavier [7]. Desnoyers recommended that the IAEA Advisory Material should be updated with a current list of rules, standards and guidelines for designers [8].

In the UK the current transportation solutions for moving waste to underground Geological Disposable Facility by rail are easier in practice if the packages can reside with the rail conveyance until they are underground. This poses an optimisation problem were constraints are imposed by the size of the rail gauge specifications and rail vehicle gross laden weight. These constraints limit the maximum size and mass of packages and their tie down systems.

Additional optimisation constraints on a tie down system are imposed by package shielding requirements and impact resistance, which constrain space and allowable mass. Therefore, the structural design of tie down systems requires a thorough understanding of the mechanical loads imposed upon them, as they will have a significant effect on the solution space available to the designer.

Despite the demanding nature of tie down system design, modern computational methods have not yet been fully utilised. With the use of FEA the stresses and strains of an entire tie down system can be accurately calculated. The UK's Office of Nuclear Regulation for Radioactive Materials Transport (ONR-RMT) emphasised the use of FEA for structural assessments of tie down systems as a more robust method than the traditional approach [9].

It appears that defining generic load cases for such a diverse range of transport applications causes significant difficulties. Several authors have presented arguments for revision of guidance documentation; therefore, further experimental work is required.

GENERAL TEST PROCEDURE

Test Plan

The following procedure demonstrates a method for positioning instrumentation and collecting test data that can assist in the understanding and use of acceleration factors for the design of tie down systems for transport by rail.

The measurements were taken during a routine journey by rail from Barrow-in-Furness to Sellafield. The rail vehicle consisted of two locomotives supplied by Direct Rail Services and three rail wagons. Two of the wagons acted as spacer wagons between the locomotives and the central wagon, which transported the 99.7 tonne package and its tie down system. The wagon, having previously been used for only 611 miles, was in excellent running condition, and therefore, a favourable environment for the tie down system was expected.

The first part of the test was the loading of the package onto the tie down system. The strain gauges were fitted to the frame before lifting, but during this operation, no measurements were taken. The package was lifted off the frame, and the strain gauges and accelerometers were calibrated. Strain and acceleration were measured during the reloading of the package onto the frame.

Figure 2. Map of Rail Journey between Barrow-in-Furness and Sellafield

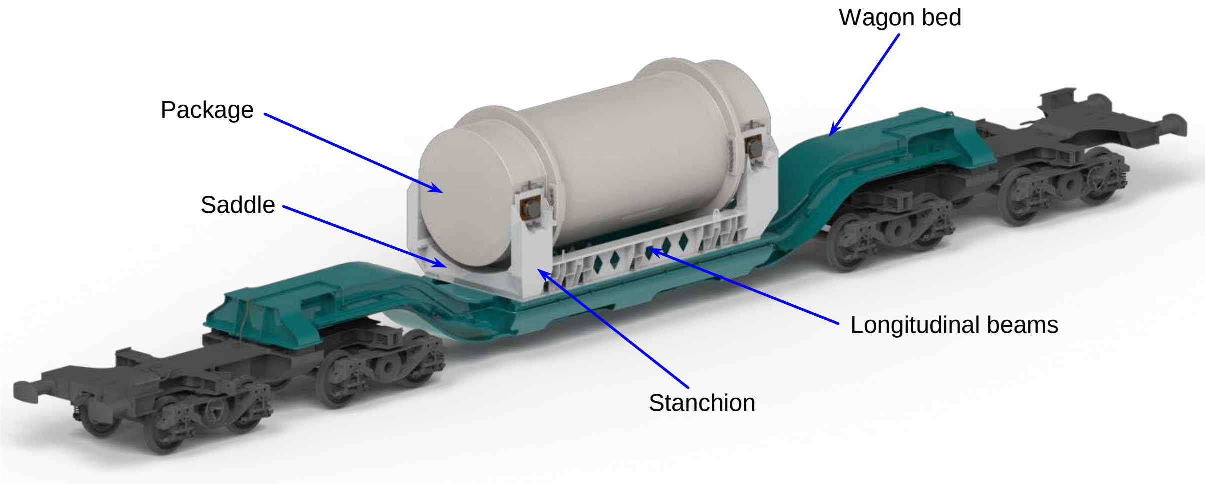

Figure 3. CAD Model of Rail Wagon and Package

The second part of the test was the continuous measurement on all data channels. Owing to unforeseen circumstances, several minutes of data were not collected in the central section of the journey (**Figure 2**).

Figure 3 shows a computer aided model of the rail wagon and package. **Figures 4** and **5** show the positions and labels of each transducer (denoted by red triangles). A total of 10 triaxial accelerometers were used, 8 of which were supplied by Data Acquisition and Testing Services Ltd. One accelerometer was mounted to each stanchion of the tie down system (**Figure 5**).

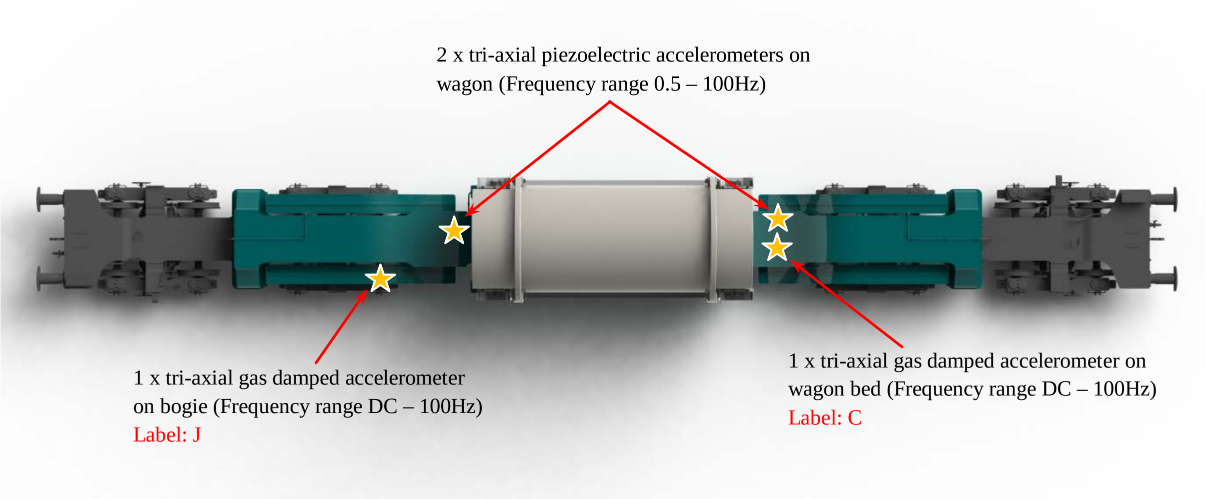

Figure 4. Accelerometers Positions

Two more accelerometers were mounted at the centre of each of the saddles, another on the wagon bed near the frame to wagon interface. The final accelerometer was mounted on the bogie of the rail vehicle. The other two triaxial, piezoelectric accelerometers were mounted onto the wagon bed. These two transducers recorded peak acceleration values at 5 minute intervals.

Twelve strain gauge rosettes were mounted to various locations on the frame as shown in **Figures 6 - 8**. During the loading test, one of the strain gauge rosette legs was found to be faulty, on channel 34, rosette number 6. A new rosette was fitted for the journey measurements.

Positioning of the Accelerometers

Redundancy was built in to the test by using duplicate accelerometers. This ensured that if an instrument failed or suffered malfunction, the test would still produce some data from the other channels. All the accelerometers were mounted on suitably stiff structures.

An ideal scenario would be to position the accelerometer at the centre of gravity of the package; however, at the exact position of the centre of gravity, there was no physical structure to mount an accelerometer. To identify loading on the tie down system two alternative positions were suggested; the four stanchions and the wagon bed.

Mounting the accelerometers to the stanchions meant that they were as close to the centre of gravity of the package as possible. The wagon bed measurement was included to provide a position closest to the base of the tie down system. This gives an insight into what vibration energy is transmitted through the wagon bed into the frame. This is critical to understanding the source of the accelerations that arise during freight transport and also for comparing the relative motion between the wagon bed and stanchions.

Two further accelerometers were mounted to the centre of the saddle sections between the lid stanchions and the base stanchions. These positions enabled valuable analysis when studying the transmission of vibration through the frame.

The final accelerometer was positioned on a bogie of the rail wagon, which was used to understand how much vibration was present from the wheel/track interface and how much energy contained in the signal was filtered out by the suspension. This was used as a point of reference to understand the source of the accelerations.

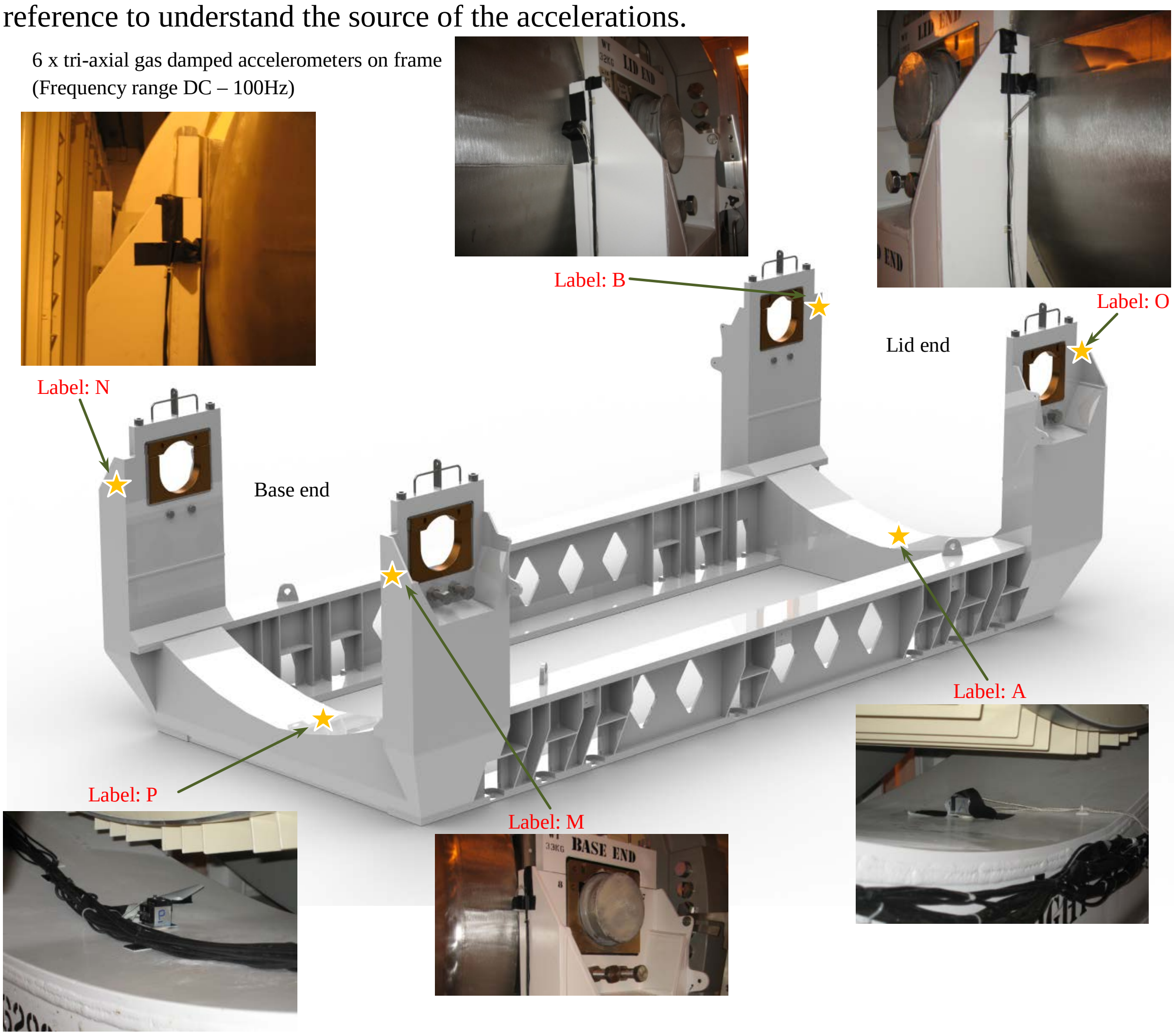
6 x tri-axial gas damped accelerometers on frame
(Frequency range DC – 100Hz)

Figure 5. Accelerometer Positions

Positioning of the Strain Gauges

A mixture of nominal and local stress positions were selected for strain gauging (**Figure 6**). Eight strain gauges were positioned to monitor nominal stresses on the stanchions and saddles of the tie down system.

Four strain gauge positions were determined by FEA, which typically highlights welded joints as more highly stressed than other parts of the structure (**Figures 7 and 8**). From the analysis results, the strain gauges were positioned to monitor local stresses on three welded joints on a stanchion and one on a saddle (**Figures 6**).

Numbers in red are strain gauge rosette numbers. Individual legs of rosettes are numbered in purple

Figure 6. Strain Gauge Rosettes Labels and Locations

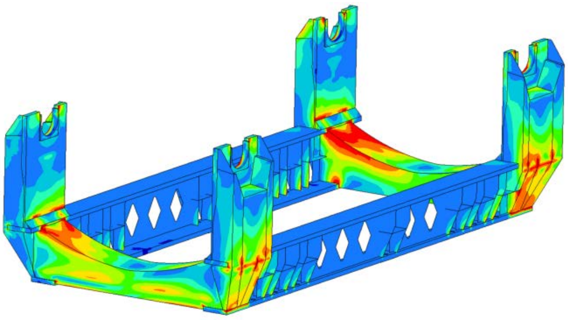

Figure 7. Principal Stress Contour Plots

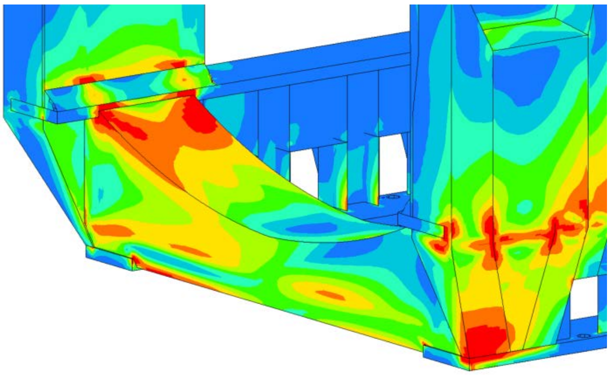

Figure 8. Principal Stress Contour Plots of Welded Joint Hot Spots

Data Acquisition System and Transducers

The data acquisition system used was a multichannel, HBM MGCplus ML801B (DAQ). The frequency range of interest was 0 – 100Hz [10]. Sampling at 1000Hz to avoiding aliasing and truncation of peaks, a sampling frequency of 1000Hz was initially selected, but due to limitations of the DAQ, this was increased to 1200Hz. The signal was passed through an analogue Butterworth anti alias filter, with a cut off frequency of 100Hz, before digitisation.

RESULTS

The results of the loading test are shown in **Table 3** and **4**. The principal stresses are shown in **Table 3**. The absolute maximum values of acceleration are shown in **Table 4.**

An example of the journey measurements are shown in **Figures 9 and 10**. The time histories of strains in **Figure 9** have been converted into maximum and minimum principal stresses. The absolute maximum principal stresses recorded are shown in **Table 5**. The absolute maximum values of acceleration are shown in **Table 6**. **Figure 11** shows time histories of GPS coordinates and vehicle running speed. This allows identification of events in the acceleration and strain time histories to be compared to vehicle running speed and location i.e. additional information on extreme or rarely occurring events can be extracted.

Table 3. Maximum Principal Stresses Measured during Loading Test

Rosette Number	Minimum Principal Stress [MPa]	Maximum Principal Stress [MPa]
1	-3.79	-1.28
2	-4.70	1.99
3	-2.81	-1.43
4	-2.16	1.91
5	-2.16	0.52
6	N/A	N/A
7	-1.29	0.49
8	-1.73	1.85
9	-10.26	-0.87
10	-1.77	2.45
11	3.71	4.46
12	1.92	3.27

Table 4. Absolute Maximum Accelerations Measured During Loading Test

Accelerometer Label	Longitudinal Accel [g]	Lateral Accel [g]	Vertical Accel [g]
A	0.04	0.06	0.08
P	0.04	0.12	0.04
B	0.07	0.08	0.12
M	0.07	0.15	0.16
N	0.18	0.07	0.18
O	0.16	0.14	0.14
C	0.02	0.03	0.02
J	0.10	0.32	0.21

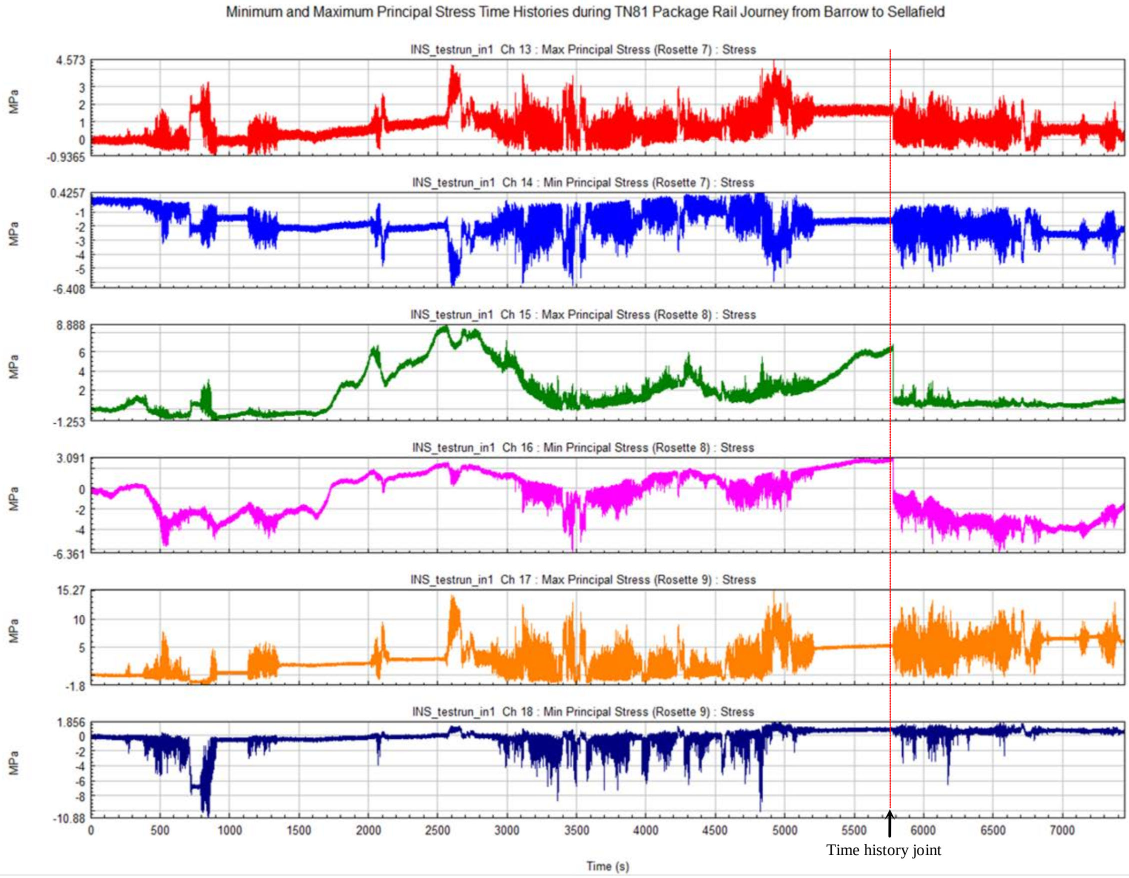

Figure 9. An Example of Principal Stress Time Histories

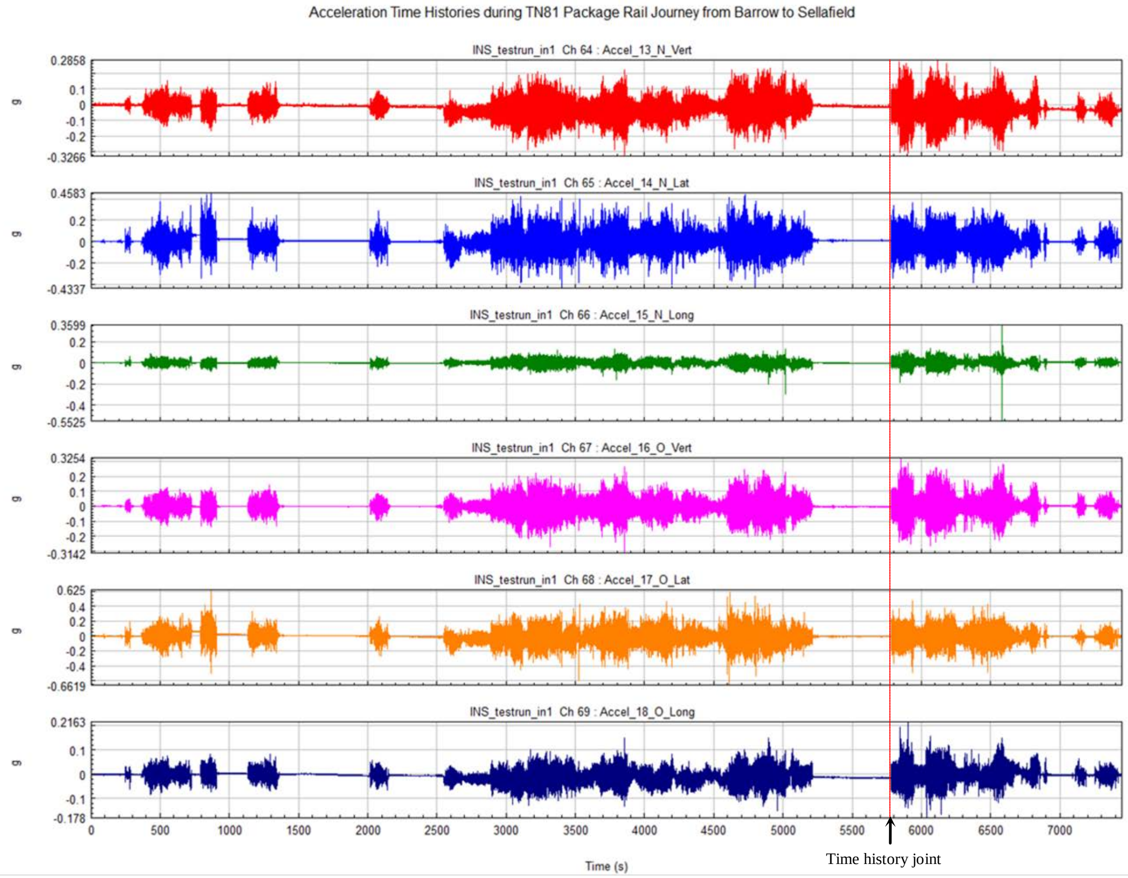

Figure 10. An Example of Acceleration Time Histories

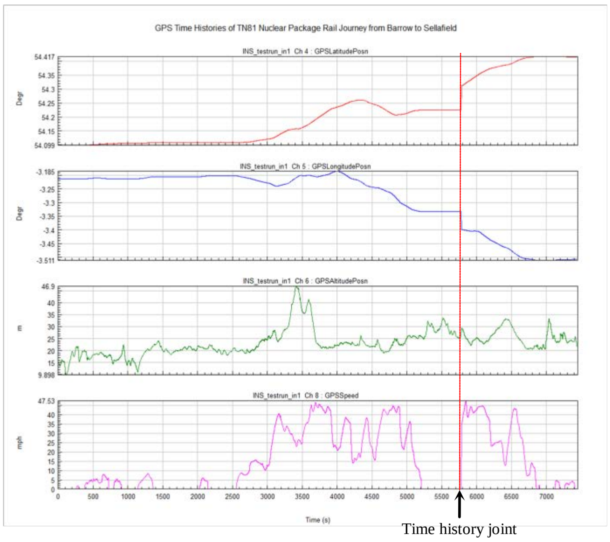

Figure 11. Latitude, Longitude, Altitude and Vehicle Speed Time Histories

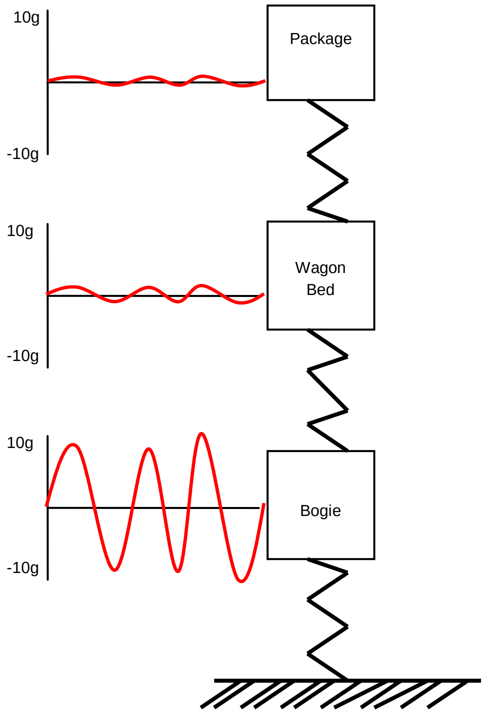

Figure 12. Schematic of Acceleration Field in the Conveyance, Tie Down System and Package

DISCUSSION

The largest amplitude accelerations in all three axes were measured on the bogie (Label J); vertical 8g, lateral 4.8g and longitudinal 6.7g. These are typical values of acceleration for a rail bogie [10]. On the tie down system, the lateral and vertical accelerations were generally of a similar order of magnitude to those shown in **Tables 1** and **2**. The measured longitudinal accelerations where found to be an order of magnitude lower than some of those recommended in the literature [2, 4, 5]. This can be attributed to the documented accelerations accounting for shunting operations, which were not permitted during this transportation.

The measurements show that the acceleration field arises from the wheel-track interface and is attenuated by the suspension system. This is evident by the magnitude of the acceleration levels, which are highest at the bogie and attenuate upwards through the structure (**Figure 12**). It is also evident that the nature of the accelerations and stresses is highly cyclic. Therefore, an under designed tie down system may fail due to two possible failure modes: gross yielding or fatigue. However, in this experiment, the stresses at the measured locations were very low and the methodology created indicates that this tie down system will not fail in this environment.

It is imperative that appropriate signals processing techniques and statistical methods are used for deriving load cases and that the maximum values reported here are not used as design parameters. The main reasons for this are that the peak values are the raw measurements that require further signals processing. A digital filter may be used to remove content in the signal which is not appropriate for design use.

Table 5. Principal Stresses Measured During Journey

Rosette Number	Minimum Principal Stress [MPa]	Maximum Principal Stress [MPa]
1	11.79	12.81
2	7.54	11.95
3	-13.41	13.52
4	-8.89	9.69
5	-6.04	6.21
6	-5.14	8.46
7	-6.41	4.57
8	-6.36	8.88
9	-10.88	15.27
10	-5.57	6.05
11	-12.04	9.45
12	-12.66	10.04

Table 6. Absolute Maximum Accelerations Measured During Journey

Accelerometer Label	Longitudinal Accel [g]	Lateral Accel [g]	Vertical Accel [g]
A	0.38	0.48	0.62
P	0.43	0.61	0.65
B	0.16	0.48	0.29
M	0.14	0.42	0.32
N	0.55	0.46	0.33
O	0.22	0.66	0.33
C	0.43	0.58	0.87
J	6.73	4.76	8.03

CONCLUSIONS

A review of current design practices, as prescribed by relevant regulations, standards and competent authorities, has been conducted. It is evident that there is little agreement between all parties, and further experimental work is required. Further motivation for experimental work has also been presented, and its benefit for producing optimised transport solutions has been emphasised. The ONR-RMT stated the benefits of the use of FEA for structural assessments of tie down systems as a more robust method [9].

An experimental procedure has been created that will provide data sufficient for characterising the loading environment supplemented by computational methods. The data can also be used to customise tie down system design for particular applications, verify existing designs and benchmark FEA.

The results show that strains in the tie down system are very low. Strain occurs as a consequence of the relative motion between the conveyance and package. Since the magnitude of accelerations varies, a “relative” acceleration maybe more applicable than the current design load cases, which are absolute values. This is critical for static strength and fatigue design considerations. It is evident that the careful selection of loads and boundary conditions is required during design of tie down systems.

The highest accelerations were measured at the bogie and are brought about by the harsh wheel/track interface. It is therefore overly conservative to apply the entire content of the acceleration signal to the centre of gravity of a package. The signals should be filtered to ensure that only accelerations acting at the centre of gravity of a package are considered.

The nature of the signals is highly cyclic; therefore, there are two important failure modes to consider during tie down system design: gross yielding and fatigue.

FUTURE WORK

Computational Design Work

An important next step is to model the rail wagon and track profile using rigid body dynamics (RBD) and calibrate the model with this test data. This will increase confidence in the method and any derived load cases.

RBD is a computational method that can approximate the full range of complex kinematic and dynamic behaviour particular to rail vehicles and accurately model the influences of undulating, random track profiles, something difficult to achieve with FEA. Although not capable of reproducing stresses within a tie down system, a calibrated RBD model can be used for sensitivity studies of the mechanical loads experienced during transportation.

Similarly, an FEA model that is calibrated with test data can provide valuable insight into the behaviour of tie down systems and a sound basis for a design by analysis methodology.

Experimental Work

More studies of this kind are needed to understand the other transport environments, particularly in a ships hold. There is more uncertainty in the loads experienced at sea than any other transportation mode and for this reason; experimental data would be an invaluable acquisition.

REFERENCE

---

[1] Oak Ridge National Laboratory, Structure Analysis of Shipping Casks. Volume 7. Cask Tie-down Design Manual, Technical Report, Rep. ORNL-TM-1312, Oak Ridge Natl Lab., TN (1969).

[2] TS-G-1, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, 2008, Rev1

[3] TS-G-1 (ST.2), Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, 2002, Rev1

[4] RSSB, 2010, GMGN2589, “Guidance on the Structural Design of Rail Freight Wagons including Rail Tank Wagons”, Issue 4

[5] TCSC 1006, Transport of Radioactive Material Code of Practice, “Guide to the Securing/Retention of Radioactive Material Payloads and Packages During Transport”

[6] Fourgeaud, S., Sert, G., Ben Ouaghrem, K., Le Bars, I., 2011 “External Loads Applied to Packages during Routine Transport”, Packaging, Transport, Storage and Security of Radioactive Material, Vol 22, No 2, pp99 – 103, Maney Publishing

[7] P.Purcell: “Designing tie-down system for heavy RAM packages – should revised design criteria apply?”; 2010, INS, PATRAM

[8] Desnoyers, B., 2012, “Stowage and Retention of Radioactive Packages during Transport: Which rules should be acceptable?”, TN International, AREVA Logistics Business Unit – Transport Oversight Division, RAMTRANS

[9] Davidson, I., 2010, “A Discussion on the Secure Stowage of Packages”, Department for Transport, Patram

[10] RSSB, “Engineering Vibration Environment for Rail Vehicle Mounted Equipment”