Fatigue assessment of an adhesively bonded EV battery enclosure, using LS-DYNA implicit tools

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1 Abstract

Adhesively bonded aluminium structures are becoming increasingly popular within the automotive industry. Bonded connections are continuous, and therefore can avoid the stress concentrations which arise in discrete connections such as spotwelds, rivets or bolts, and thus have the potential to perform better from a fatigue perspective. However, bonded structures have their own challenges to analyse, particularly for predicting fatigue life, where limited data exists in the public domain.

Using a generic electric vehicle (EV) battery enclosure as the case study structure, this paper demonstrates that LS-DYNA implicit solvers can perform simulations for all China regulation GB38031 mechanical vibration tests, which comprise a mixture of random vibration and fixed sine wave load cases. These are durability tests, compromising large numbers of cycles for fatigue assessment.

Using finite element (FE) results from analyses of these vibration load cases, a method developed by *Sousa et al* is adopted, where adhesive fatigue performance is predicted by first calculating an “effective stress” for each element in the model. To obtain a time-history of “effective stress”, a time-domain approach is taken using the LS-DYNA **`*CONTROL_IMPLICIT_MODAL_DYNAMIC`** keyword (a mode-based transient analysis, performed using modal superposition). This “effective stress” is then mapped onto an S-N curve (also derived from tests by Sousa), and the number of fatigue cycles from the test compared to the predicted number of cycles to failure for the adhesive.

For a complete assessment of the battery enclosure, the aluminium fatigue performance is calculated separately using an equivalent LS-DYNA frequency-domain approach, with input from the power spectral density (PSD) of the mechanical vibration load cases and using keyword **`*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE`**. The aluminium fatigue performance is predicted using the Dirlik method, which is embedded within LS-DYNA.

It is shown that these LS-DYNA implicit tools provide a credible prediction of fatigue performance for adhesively bonded structures, and are a valuable design iteration tool, in combination with physical testing. It brings us a step closer to the one-code ideal, where a single LS-DYNA model is used for all implicit and explicit load cases, leading to a more streamlined CAE workflow.

2 Introduction

The driver behind researching adhesively bonded structures for fatigue performance within this paper has been the recent trend for this design approach in EV battery enclosures to be favoured by some manufacturers. The battery enclosure must have sufficient strength and stiffness to protect the batteries during a vehicle crash event, to contribute to overall stiffness of the vehicle, to provide containment in the event of thermal runaway, and to withstand inertial loads from the mass of the batteries (which can be the order of ~0.5-1.0 tonnes – as much as 25% of the vehicle's total mass [1]).

Aluminium structures are a lightweight alternative to steel structures. The connections on such structures can be welded, bolted, or fixed with adhesive bonds. One issue with welding is that it is difficult to achieve without weakening the parent material in the weld region (the heat affected zone, HAZ). Other issues arise from thermomechanical effects, such as crack formation during heating and cooling cycles of the weld region, affecting fatigue life. The aluminium material is not negatively affected in the same ways when connected via adhesive bonds. Stress concentrations occurring around spotwelds would be expected to be more severe than those around large, smeared areas of adhesive bond.

Structural fatigue assessments are crucial for ensuring the safe design of mechanical components that are subject to cyclic loading. Typically, a combination of physical testing and FE analyses are necessary to analyse and improve structural designs, to achieve an acceptable predicted fatigue life for the component. Physical fatigue tests are limited to time-domain cyclic loading, whereas FE can take a time-domain or a frequency-domain approach. The loading towards a fatigue assessment can be applied as constant amplitude (constant frequency) cycles, a sweep of increasing amplitude (or frequency), or a random vibration signal. The comparison in *Table 1* assumes random vibration loading, and describes the process of the fatigue assessment, along with some benefits and shortcomings.

	Time-domain fatigue assessment	**Frequency-domain fatigue assessment**
Physical tests	Random (representative) cyclic loading, until the test specimen fails	Not possible
FE analysis	Random transient input loading	Random input loading from a defined PSD
FE benefits	More flexibility with the fatigue assessment methodology (post-processing on time history results)	Fast analysis method, which outputs element stress PSDs (therefore, can assess all elements and do many studies)
FE shortcomings	Slower analysis than frequency domain approach, producing more data (therefore, need to focus on regions of greatest importance)	Constrained to standard frequency domain fatigue assessment methods
FE fatigue method	Element stress time histories to count cycles at each stress range	Using PSD statistics to obtain cycles at each stress range
	Fatigue damage calculated via comparison to failure cycles (using the relevant material S-N curve, and Miner's rule)	

Table 1: Comparison of time-domain and frequency-domain approaches to random vibration fatigue assessments.

The objective of this paper was to use LS-DYNA implicit solvers to replicate the China regulation GB38031 mechanical vibration tests. These tests involve independent loading in the global Z, Y, and X directions of the vehicle, and a mixture of random vibration and fixed sine wave (constant amplitude, constant frequency) loading – these are shown graphically in *Fig.1* and *Fig.2*. These are durability tests, compromising large numbers of cycles for fatigue assessment.

The random vibration test signals within GB38031 are provided as frequency-domain PSDs (seen in the top half of *Fig.1*). To obtain equivalent time-domain signals (the bottom half of *Fig.1*), a MATLAB script methodology was used to synthesise a unique time history from each PSD, containing the same energy and frequency content as the PSD. It was very important to ensure that the generated time signal was long enough to accurately capture the contents of the original PSD – creating a PSD from the generated time-domain signal should result in a new PSD with very close agreement to the original PSD.

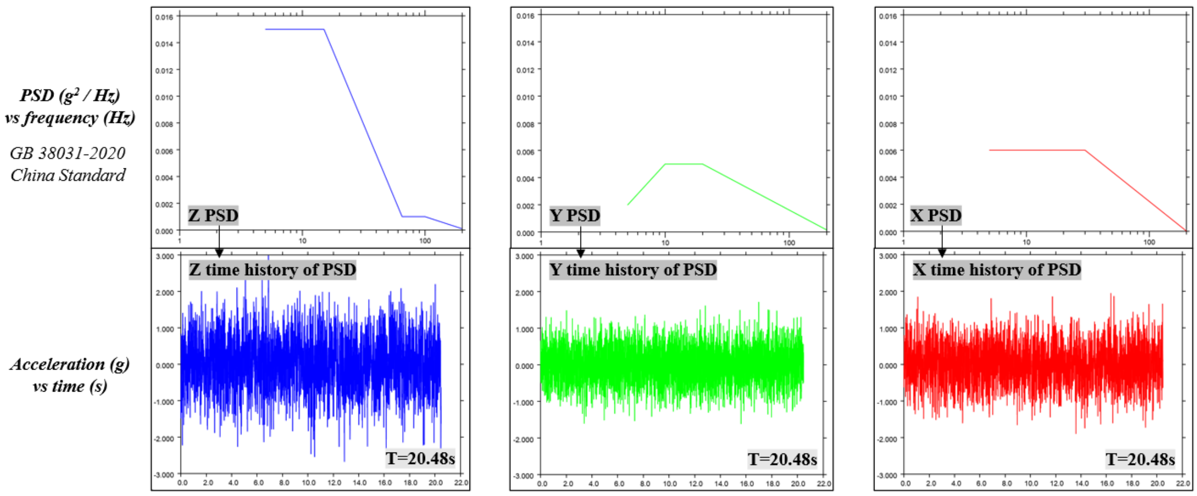

Fig.1: China regulation GB38031 mechanical vibration tests (PSDs and time-domain equivalents).

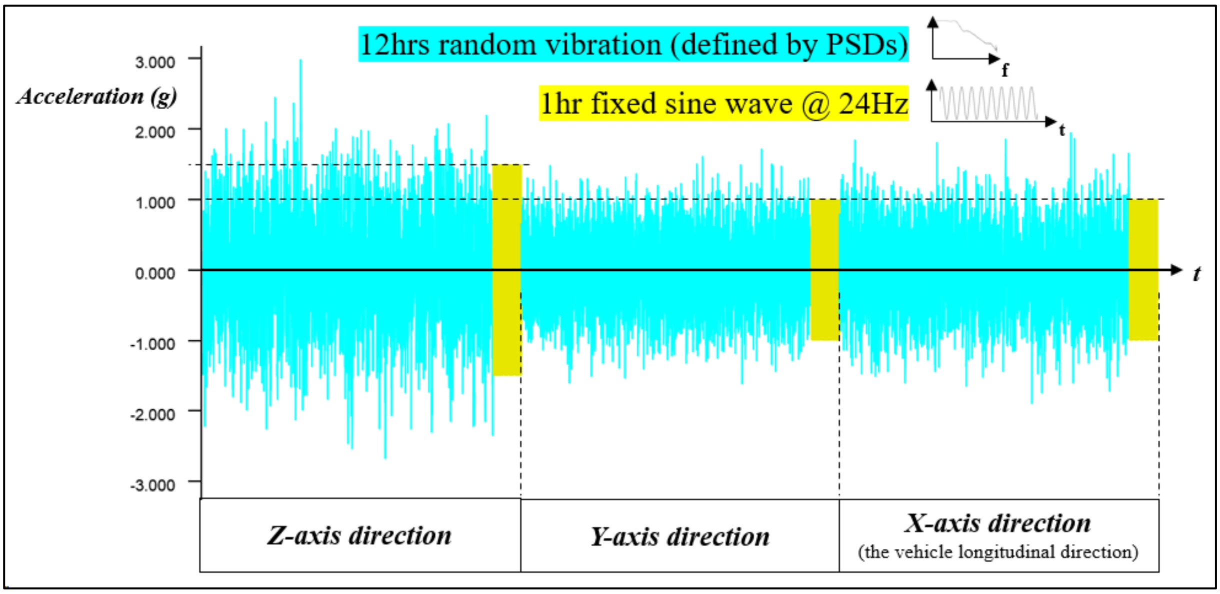

Fig.2: Summary of the China regulation GB38031 mechanical vibration tests (in the time domain).

The material S-N curves (stress range vs cycles to failure) for adhesive (from [2], assuming 23.1 MPa shear strength) and aluminium (from [3], assuming plain members, with 2E6 cycles to failure for a 125 MPa stress range) are shown in *Fig.3*. These are the curves used to calculate fatigue damage from the LS-DYNA results. During a random vibration event, each location in the structure will experience many stress ranges, so a method known as Miner's Linear Damage Rule [4] is applied to calculate a linear summation of fatigue damage caused by each of these stress ranges, where it is known how many occurrences of each stress range occurred during the event. For a steady state (e.g., fixed sine wave) event, there will be only one stress range (which occurs many times), so Miner's Rule is not required.

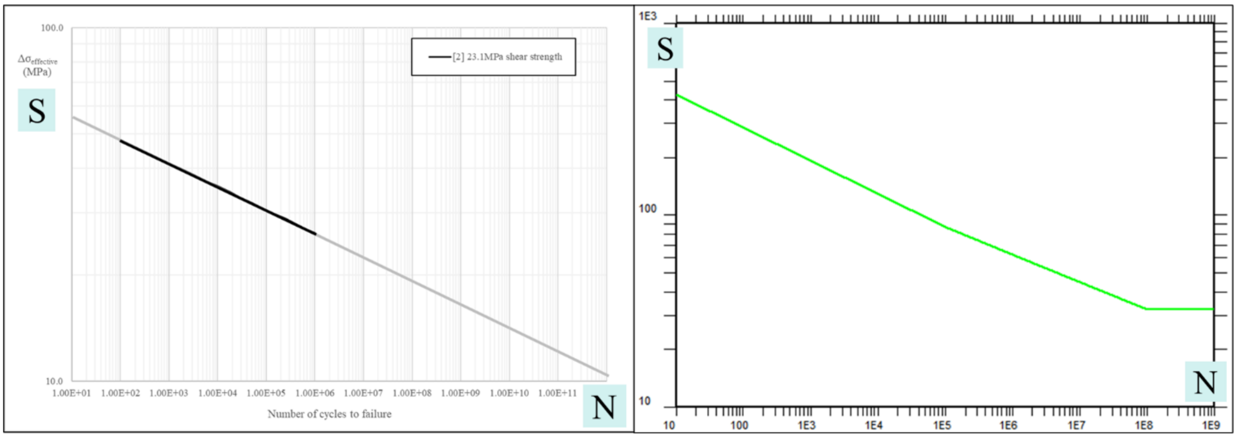

Fig.3: Material S-N curves (stress range vs cycles to failure) for adhesive (left) and aluminium (right).

3 LS-DYNA model

The geometry, connections, and restraints of the LS-DYNA model are shown in *Fig.4* and *Fig.5*. The adhesive elements were modelled from mid-surface to mid-surface of adjacent aluminium plates, connected via **`*CONTACT_TIED_NODES_TO_SURFACE`**, and using **`*MAT_ARUP_ADHESIVE`** defined with 0.3mm bond thickness.

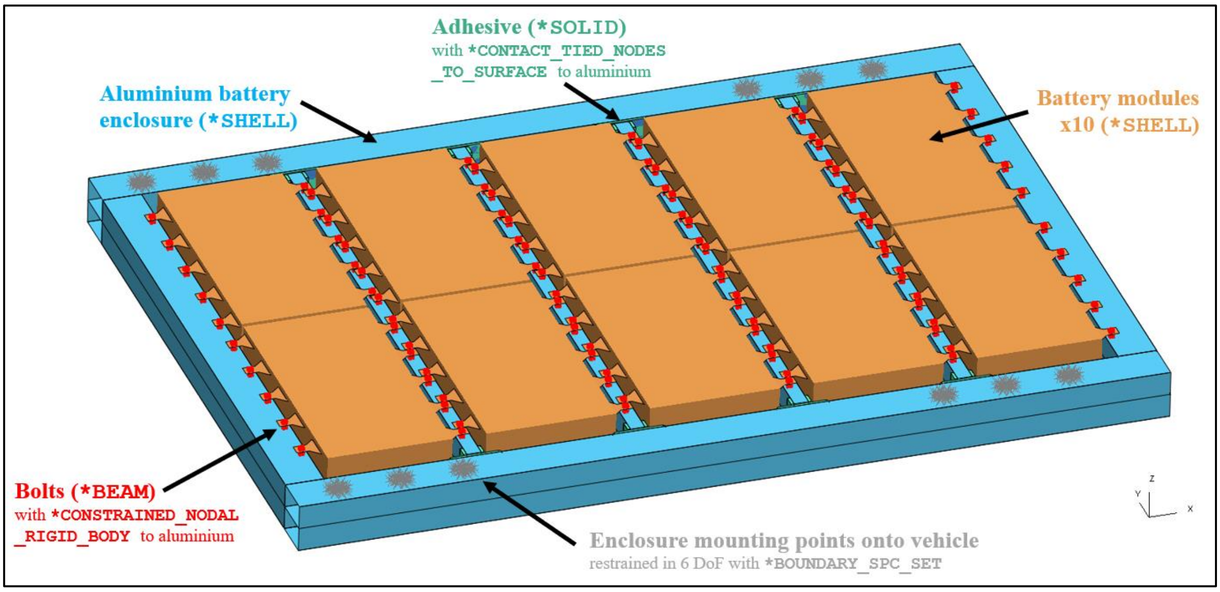

Fig.4: LS-DYNA model, with annotations for each component, connection, and restraint.

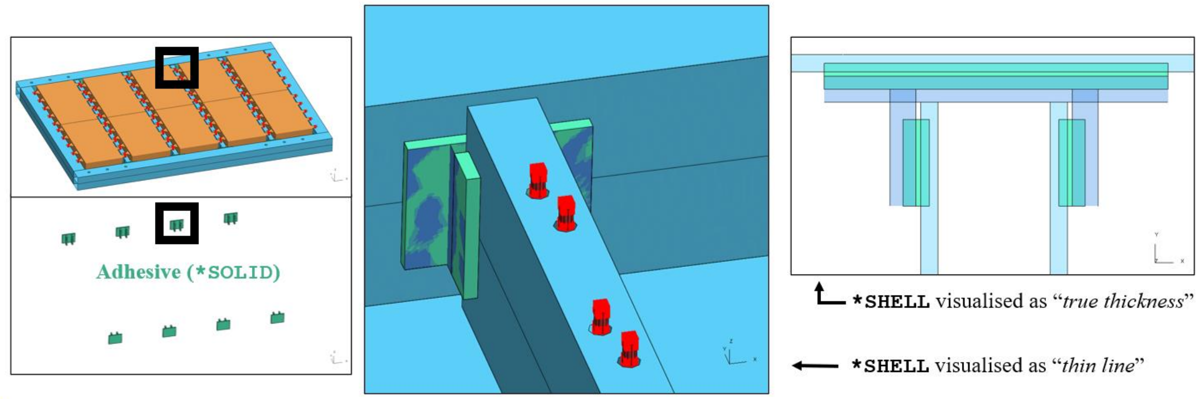

Fig.5: LS-DYNA model, with focus on the adhesively bonded regions.

4 LS-DYNA implicit analyses

With the objective to use LS-DYNA implicit solvers to replicate the China regulation GB38031 mechanical vibration tests, a range of analysis keywords were used, shown in *Table 2*. This range of keywords allowed for fatigue damage to be calculated for the adhesive and the aluminium, in both the random vibration and fixed sine wave tests.

LS-DYNA implicit analysis…	To compute fatigue damage for…
Random vibration time-domain fatigue analysis `*CONTROL_IMPLICIT_MODAL_DYNAMIC`	GB38031 random vibration tests Adhesive only Using Sousa method & Steinberg 3-band method to map to S-N curve
Random vibration frequency-domain fatigue analysis `*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE`	GB38031 random vibration tests Aluminium only Using Dirlik method to map to S-N curve
Steady state frequency-domain fatigue analysis `*FREQUENCY_DOMAIN_SSD_FATIGUE`	GB38031 fixed sine wave tests Adhesive and aluminium One stress range to map to S-N curve

Table 2: Summary of the LS-DYNA implicit analyses used to compute element fatigue damages.

4.1 Random vibration time-domain fatigue analysis

The GB38031 random vibration tests for adhesive elements were analysed in the time domain to allow for fatigue damage to be calculated via the Sousa method [5], requiring time histories of adhesive element stresses. The Sousa method calculates an “effective stress” for each element, from the element time histories of Von Mises stress and hydrostatic stress (pressure), as shown in the following equation:

$$\sigma_{effective} = \sigma_{von\ mises} + \sigma_{hydrostatic}{}^{2} \,/\, \sigma_{von\ mises}$$

The RMS (root mean square) value of this “effective stress” time history then gets mapped onto a Gaussian distribution of stress, which according to the Steinberg 3-band method has the RMS value at one standard deviation (1σ) from the mean for 68.3% of the time, 2σ for 27.1% of the time, and 3σ for 4.3% of the time. By mapping these 1σ, 2σ, and 3σ “effective stress” values onto the adhesive S-N curve, and applying Miner’s rule, the number of cycles to failure $(n_{failure})$ for the adhesive is determined:

$$n_{failure} = 1.0 \,/\, \left(\frac{0.683}{N_1} + \frac{0.271}{N_2} + \frac{0.043}{N_3}\right)$$

The methodology is shown diagrammatically in *Fig.6*. The “effective stress” has been shown to correlate best to overall adhesive fatigue damage, based on tests performed by Sousa.

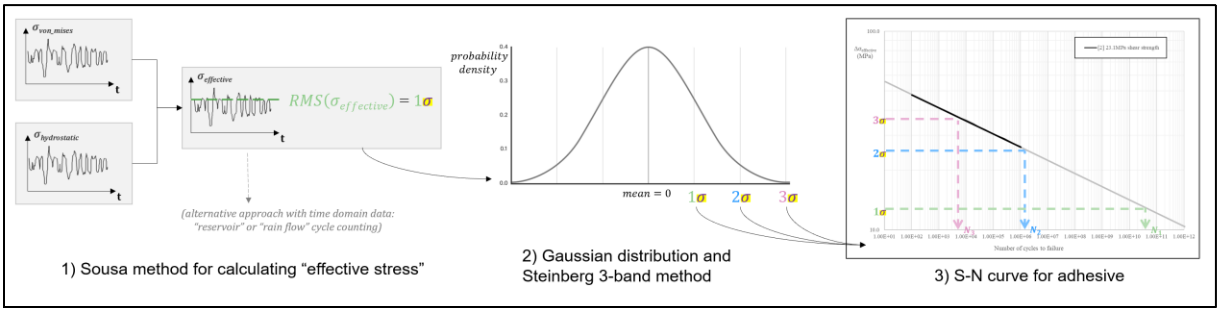

Fig.6: Methodology applying the Sousa method and Steinberg 3-band method for adhesive elements.

The number of cycles within the 12-hour load case $(n_{load\ case})$ was calculated by assuming that vibration occurs purely at the dominant modal frequency of the structure (calculated from the initial ***CONTROL_IMPLICIT_EIGENVALUE** analysis). Finally, fatigue damage for each element was calculated as follows (noting that damage > 1 is a prediction of fatigue failure):

$$Fatigue\ damage = \frac{n_{load\ case}}{n_{failure}} = \frac{\text{\#cycles during the vibration test}}{\text{\#cycles at which the material will fail}}$$

To get the stress time histories required to input into the *Fig.6* methodology, the LS-DYNA implicit sequence of ***CONTROL_IMPLICIT_EIGENVALUE** (to find all structural modes below a certain frequency), followed by ***CONTROL_IMPLICIT_MODAL_DYNAMIC** (to apply the acceleration time history from *Fig.1* to the structure), was implemented. The acceleration time history was applied using ***LOAD_BODY**, separately for X, Y, and Z, as per GB38031. Using implicit time integration, this time history was used to magnify each previously computed mode, and then linearly combined into an overall response using modal superposition. This modal transient approach is more efficient than performing a direct implicit transient analysis because it only considers the response of the computed mode shapes, rather than computing the response of every degree of freedom in the model.

4.2 Random vibration frequency-domain fatigue analysis

The GB38031 random vibration tests for aluminium elements were analysed in the frequency domain using ***FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE**. This approach first computed all structural modes below a certain frequency with ***CONTROL_IMPLICIT_EIGENVALUE**, then applied the relevant acceleration PSD from *Fig.1* to the structure. The duration of the applied loading (the exposure time) was defined as an input for LS-DYNA. This approach is much faster to compute than the time-domain approach, hence can be applied to all aluminium elements in the structure without significant penalty to the runtime or volume of data written by LS-DYNA. The fatigue damage for each element is calculated internally by LS-DYNA using the Dirlik method, which is the industry standard for aluminium. The number of cycles for each stress range was determined using a probability density function within the Dirlik method. The Von Mises stress ranges from the output element PSDs were mapped on to the aluminium S-N curve.

4.3 Steady state frequency-domain fatigue analysis

The GB38031 fixed sine wave vibration tests for both the adhesive and aluminium elements were analysed in the frequency domain using **`*FREQUENCY_DOMAIN_SSD_FATIGUE`**. This approach first computed all structural modes below a certain frequency with **`*CONTROL_IMPLICIT_EIGENVALUE`**, then applied a constant-frequency, constant-amplitude input to the structure (essentially a vertical line on a PSD, with the duration of the applied loading defined as an input for LS-DYNA). The fatigue damage for each element was calculated internally by LS-DYNA, noting that for this scenario there is only one Von Mises stress range to be mapped on to the aluminium's S-N curve.

5 LS-DYNA implicit results

5.1 Combined fatigue assessment results

For each adhesive or aluminium element with output requested, an overall combined fatigue damage value was calculated, as a linear summation of the fatigue damage from each individual load case, as shown in *Table 3*.

<table>
<tr><td></td><td colspan="6">For each adhesive or aluminium element in the LS-DYNA model…</td></tr>
<tr><td rowspan="2">Inputs</td><td colspan="3">Random vibration load case</td><td colspan="3">Fixed sine wave vibration load case</td></tr>
<tr><td>Z PSD</td><td>Y PSD</td><td>X PSD</td><td>Z</td><td>Y</td><td>X</td></tr>
<tr><td rowspan="3">Outputs</td><td colspan="6">For each load case… stress components, Von Mises stress, Hydrostatic stress etc.
(Also, Sousa effective stress, for adhesive elements only)</td></tr>
<tr><td>Fatigue damage A</td><td>Fatigue damage B</td><td>Fatigue damage C</td><td>Fatigue damage D</td><td>Fatigue damage E</td><td>Fatigue damage F</td></tr>
<tr><td colspan="6">Combined fatigue damage summation (A + B + C + D + E + F)</td></tr>
</table>

Table 3: Workflow for calculating overall fatigue damage for each element in the model.

Contours for combined fatigue damage of one of the bonded joints in the structure are shown in *Fig.7*. This joint is towards the middle of the battery enclosure, away from the mounting points onto the vehicle body. The middle of the enclosure is the most mobile part of the structure during the fundamental (lowest) modes; hence this joint does a lot of work, which translates to the largest fatigue damage region on the structure. The peak aluminium fatigue damage occurs in the corner of the T-junction (SHELL 402788) – an element which undergoes the largest amount of in-plane strain. Aluminium fatigue damage has remained below 1 (non-failing), whereas for the same number of loading cycles there are regions of adhesive predicted to fail (peak damage = 8.5). It can be concluded that the adhesive itself (or the bonded interface) is likely to fail sooner than the aluminium, under this regime of cyclic loading.

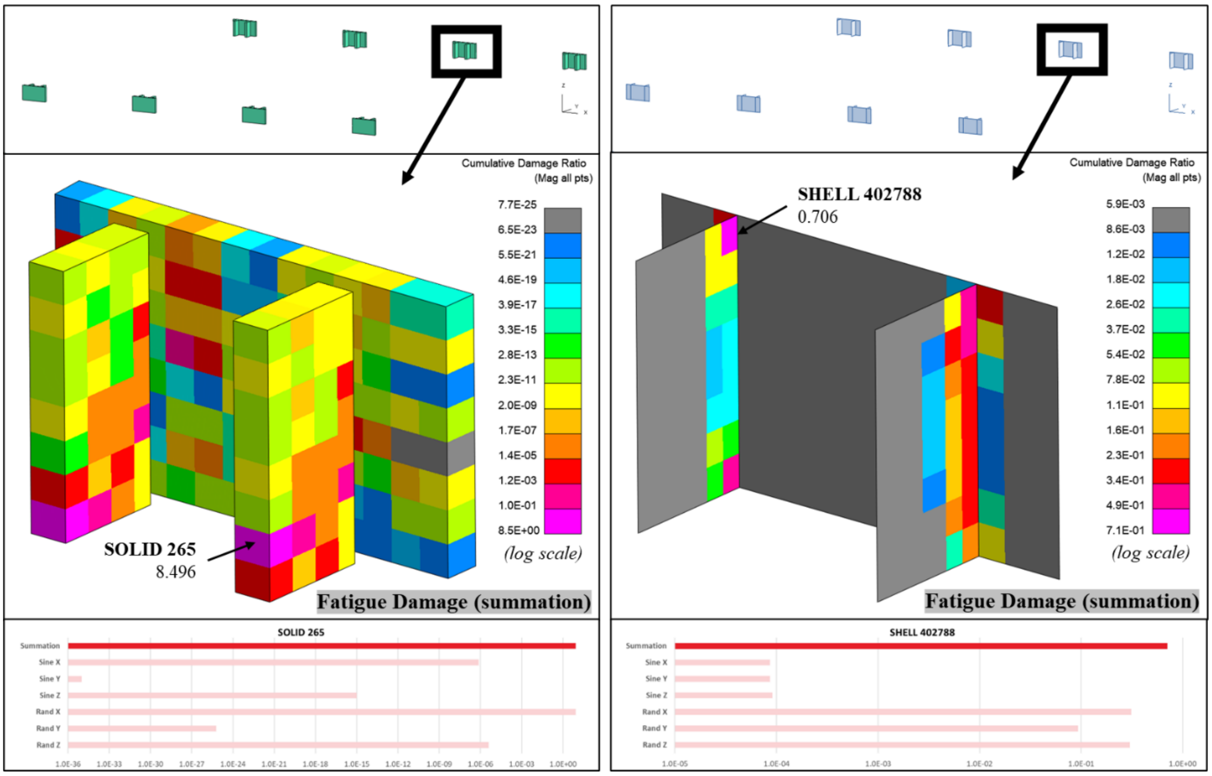

Fig.7: *Combined fatigue damage for one of the bonded joints – adhesive (left), and aluminium (right).*

5.2 Example element stress and fatigue results

Each load case (from *Table 3*) provides the element stress results, with an example shown in *Fig.8*. For frequency-domain analyses, the results can also be plotted as element stress PSD curves. Peak values on such curves should occur at frequencies which correlate with the eigenvalue results for the structure – the element shown in *Fig.8* is at a location which particates in the first mode, hence a peak at 41.5Hz.

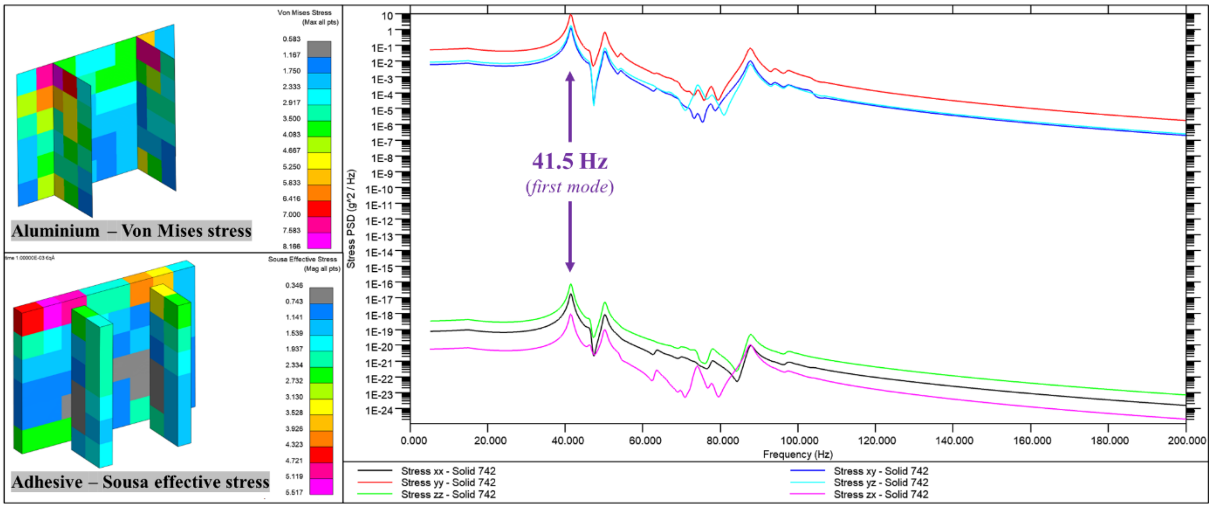

Fig.8: *Stress contours for one load case (frequency-domain von Mises stress for aluminium; time-domain effective stress for adhesive), and a frequency-domain element PSD stress plot (all six stress components, with a peak at the frequency of the first structural mode indicated).*

5.3 Sensitivities and validation of results

Comparisons can be made to demonstrate how modelling input decisions (such as the inclusion of bolt pre-load, accurate battery mass distribution, and mesh size/quality) affect the overall fatigue performance and predicted life of the structure. Errors during assembly of the physical components can also be studied in LS-DYNA, such as the effect of insufficient coverage area of the adhesive, incorrect adhesive material properties, or lack of surface roughness on the bonded interface.

Fatigue damage will also be sensitive to the level of modal damping assumed (a conservatively low 1% was used for this paper, but 2-5% could be appropriate, if justified against results of physical tests). The number of modes used in the modal superposition is also very important – the first 25, 50, 100, or 200 modes may be sufficient for a converged solution – enough modes to have captured 80% accumulated modal mass for the most important degrees of freedom (or modes up to ~300Hz) would likely be sufficient in most cases for this sort of structure.

Fatigue performance results will inform the iterative design process for the structure. If fatigue damage is above target (i.e., damage >1), then local structural modifications can be made to increase the stiffness and/or mass, and perhaps resizing or redistributing specific adhesive bond areas. If local fatigue damage is below target, then there may be scope for removing aluminium mass or having smaller adhesive bonds, whilst remembering that performance must be achieved for all other load cases (crash, NVH, etc), so it is important to understand whether fatigue is critical or not for any given design.

6 Conclusions

The primary conclusion from this paper is that LS-DYNA is capable of performing the range of analyses needed to assess fatigue for adhesively bonded structures (such as an EV battery enclosure), using the methodology demonstrated here. Fatigue methodologies for welded and bolted connections are well established, whereas the behaviour of adhesive bonds under cyclic loading is less well understood. Using a method outlined by Sousa [5], this methodology performs an implicit time-domain LS-DYNA analysis, to then calculate an “effective stress” within each adhesive element, from which fatigue damage can be calculated via the appropriate adhesive S-N curve. The methodology also calculates fatigue damage in the adjacent aluminium plates, so that an assessment of performance for the entire adhesively bonded joint can be made.

For the design engineer, the methodology captured in this paper is very powerful because it exclusively uses LS-DYNA solvers – in the past, a similar approach would more likely have involved converting the LS-DYNA model into an equivalent model to use with a different FE package. This enables a design workflow where the same LS-DYNA model can be used for the implicit load cases (such as modal, static stiffness, fatigue, NVH etc) as for the explicit load cases (non-linear vehicle crash and pedestrian impact etc). This eliminates the need to convert the LS-DYNA model for use with another FE package, resulting in a more streamlined CAE workflow – quicker turnaround times between analyses, easier for engineers to QA the model, and cheaper licensing costs, due to the sole reliance on LS-DYNA.

7 Literature

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[3] BS EN 1999-1-3:2007: “Eurocode 9: Design of aluminium structures – Part 1-3: Structures susceptible to fatigue”, British Standard, 2011, Figure J.1 / Table J.2.

[4] Y.L. Lee, H.T. Kang: “Miner Linear Damage Rule”, Metal Fatigue Analysis Handbook: Vibration Fatigue Testing and Analysis, 2012, 333-382.

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