Application of the LS-DYNA Implicit Solver for Battery Regulatory Load Cases

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The automotive industry is shifting from internal combustion engines to electrified powertrains. The battery system has become an integrated part of the vehicle structure and must be included in safety and durability assessments. While some of the global regulatory requirements for battery pack safety fall neatly within LS-DYNA's core explicit capabilities, its implicit capabilities are often overlooked for cases such as vibration fatigue or thermal shock. Clearly, maximising the number of requirements that are assessed with a single solver will result in a more efficient analysis workflow. This paper describes how Arup's engineers have benefitted from using the LS-DYNA explicit and implicit solvers and Oasys software tools to provide efficient outcomes for their clients.

1 Introduction

The global automotive industry is transitioning from the internal combustion engine as a prime mover to battery-electric powertrains. This change has been driven primarily by environmental concerns, with road transport accounting for around 15% of total global CO_2 emissions [1]. In response to the environmental crisis, several countries have introduced targets and deadlines for reduced CO_2 emissions for new vehicles. In the European Union (EU), the target for zero CO_2 emission from new passenger cars and light commercial vehicles is 2035 [2]. In the United Kingdom (UK), the legally binding Zero Emission Vehicle (ZEV) Mandate also requires that 100% of new cars and vans must be zero emission by 2035 [3]. Other regions of the world have adopted similar legislation.

Simultaneously, the rapid development of Lithium-ion battery cells in recent decades has enabled new and established manufacturers to offer a wide choice of battery-electric and hybrid vehicles that are overcoming the long-standing limitations of range and performance. Cell technologies such as Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) offer high energy densities, allowing vehicles to travel further between recharging. Cell technology is an active research area, with new developments on the horizon such as solid-state electrolytes and next generation anode and cathode materials promising dramatic improvements in performance.

The transition to battery-electric power has brought challenges and opportunities to vehicle design engineers. At the forefront is the integration of the battery pack, often large and with significant mass. Current methodology is to arrange groups of cells into modules, which are in turn assembled into a larger pack, which is attached to the vehicle. The pack and module structures (also the cells themselves) can contribute to the stiffness and impact resistance of the whole vehicle structure, however duplication of structure is a downside, addressed recently with cell-to-pack strategies that eliminate intermediate structures [4]. Cleary there are opportunities to optimise the design and integration of the battery pack to satisfy mass, stiffness, strength and thermal requirements.

Simulation is a key enabler in the design of battery-electric vehicles and a holistic approach is required to find optimal solutions. In addition to traditional load cases such as crashworthiness, NVH and durability, the body simulation engineer must now also consider the battery and its associated regulatory requirements. Akin to crash safety regulations, the battery regulations ensure that the battery system meets a minimum standard of safety with respect to its integrity under a variety of loadings. Two such regulations are UN Regulation 100 [5] and GB38031-2020 [6], for the European and Chinese markets respectively. Similar standards exist for other regions. The regulations are broadly similar in their requirements and a comparison is shown in Table 1 for selected mechanical and thermal tests for M1 and N1 vehicles.

Test Type	UN R100 Rev.3	GB 38031-2020
Vibration Test	Sinusoidal sweep: 7–50-7 Hz in 15 min, repeat 12 times. Max 1g sine amplitude 3 hours vertical axis only.	Multi-axis random and sinusoidal vibration. Duration: 39 hours Frequency: 5–200 Hz Max 0.65g RMS / 1.6g sine amplitude.
Mechanical Shock	Max acceleration: up to 28g Direction: longitudinal and transverse	Max acceleration: up to 28g Direction: longitudinal and transverse Max acceleration ±8g. Direction: vertical, repeated 6 times.
Mechanical Integrity	Crush force: 100 kN Platen radius: 75 mm No fire, explosion, or leakage	Crush force: 100 kN Platen radius: 75 mm No fire, explosion, or leakage
Thermal Shock & Cycling	Temperature range: −40°C to +60°C 5 cycles 6 hours per extreme	Temperature range: −40°C to +85°C 5 cycles 8 hours per extreme
Fire Resistance	Open flame exposure in 4 phases Duration: ~2 minutes No explosion or leakage	Direct flame exposure for 2 hours No fire, explosion, or toxic gas release

Table 1: Selected Mechanical & Thermal Test Comparison: UN R100 Rev.3 vs GB 38031-2020

Inspection of Table 1 reveals that a range of analysis types are required to simulate all cases. For mechanical integrity and shock, which may involve large deflections and plasticity, a non-linear dynamic solver is required, whereas for the vibration tests which are much longer duration at lower levels of acceleration, a linear dynamic solution in the frequency domain may be more appropriate. The thermal shock and cycling tests are also long duration and require a thermo-mechanical solver to evaluate both the transient temperature field and the mechanical response. Finally, the thermal propagation simulation requires a multi-physics solution that combines thermal, mechanical and fluid predictive capability to accurately simulate the interaction of vented gases and the structure.

2 Application of LS-DYNA for Battery Regulatory Load Cases

Ansys LS-DYNA is a powerful multi-physics solver that offers coupled mechanical, thermal, fluid and electromagnetics solvers [7]. It is used widely in the automotive industry for prediction of vehicle crash performance, which is highly non-linear and involves large deformations and contact. It has an implicit solver for static problems and frequency domain calculations such as modal analysis and forced response vibrations. It has a thermal solver and an electromagnetic solver, with features developed specifically for the analysis of battery cells. It is therefore an ideal solver for the analysis of battery systems and their integration into vehicle structures.

It is the authors' experience that often LS-DYNA is used for explicit non-linear calculations such as shock and crushing, while frequency domain and thermal calculations are completed in alternative solvers. This requires the model to be translated from one format to another which takes time and requires verification, compounded when multiple design iterations are required. For battery analysis projects undertaken in Arup, the approach is to complete all analysis in LS-DYNA. This leads to a more efficient workflow and consistently high-quality results. Furthermore, model preparation, inspection of results and automated reporting can be seamlessly executed through the Oasys LS-DYNA Environment, developed by Arup [8].

This paper will discuss the application of LS-DYNA for the analysis of typical regulatory load cases, with an emphasis on the use of the implicit solver for vibration and thermal analysis. A simplified example model has been used to illustrate the workflows.

3 Battery system modelling considerations

Any finite element model must be an adequate discretisation of the physical entity so that a reasonable approximation of its performance can be predicted. For a battery pack, it is likely that the components in the following list will be modelled in adequate detail:

- Pack structural frame, including all components such as extrusions, castings, pressed panels and their connections, e.g. welds, rivets, bolts and adhesives
- Battery modules
- Battery cells
- Cooling plates or cooling system, coolant transport pipes
- Busbars and high-voltage conductors
- Battery Management System (BMS) and related components, e.g. fuses, relays
- Foam spacers, Mica barriers which may contribute to mechanical or thermal performance

It is likely that the chosen mesh size for these components will be similar or smaller than the mesh size used for the model of the intended vehicle, if known, since the major dimensions are similar and the requirement for resolution of local damage will be similar. However, many components within the battery pack may be smaller than items of interest in a vehicle crash model and a smaller mesh size may be required. If the battery model is intended for use in a vehicle crash simulation, there may be constraints on minimum mesh size for compatibility. If the battery pack will be analysed as a stand-alone model, then it may be possible to add more detail in areas of interest and remain within the practical constraints of computing resources.

One area where modelling approximations are most likely are the cells themselves. Cells are typically either cylindrical, prismatic or pouch type and consist of layered electrodes and separators that are rolled up (cylindrical) or lie flat within the cell (prismatic, pouch). In a typical cell, the thickness of the coated electrodes is in the order of 0.1mm and they are repeatedly folded or coiled with the separator so that dozens of layers exist through the thickness of the cell [9]. Modelling of this detail is impractical given the number of cells in the pack, which may be in the thousands in a large pack of cylindrical cells.

A suggested approach is to approximate the cell with a coarser homogenised mesh that ignores the individual layers but can reproduce the mechanical response of the cell to external forces such as compression and bending. The cell characteristics can be obtained from component testing which the model can be tuned to match [13]. Furthermore, the cell testing can be used to measure the amount of load or deformation the cell can withstand before a thermal event is triggered. This information can be used as an aid to interpret subsequent analysis results.

LS-DYNA has a wide range of available material models for modelling linear and non-linear phenomena, temperature and strain rate dependence. Representation of failure can be added to most material models. For the majority of the loadcases listed above, adequate material models exist to describe the behaviour of the materials typically found in battery systems.

4 Use of LS-DYNA explicit solver for mechanical shock and integrity cases

It is assumed that the reader is familiar with LS-DYNA's explicit solver and this section will briefly touch on its use for battery system analysis, for completeness.

The shock and integrity requirements of UN Reg 100 and GB 38031-2020 are representative of global standards and require the battery structure to withstand mechanical abuse. Both standards prescribe shock tests where an acceleration of magnitude 28g is applied in the vehicle forward direction of travel over a duration of approximately 0.1s. The test is repeated in the transverse direction with an acceleration amplitude of 15g [5][6]. These acceleration levels may cause relatively large deflections within the battery system, plastic strains and contact between components. Therefore, the explicit solver is suitable for these cases, given the duration of loading and possible non-linear response.

The time dependent acceleration can be applied as a boundary condition via the keyword **`*BOUNDARY_PRESCRIBED_MOTION`** to the battery mounting locations. This replicates the test method, where the acceleration is applied by attaching the battery to a sled or shaker table using the same mounting locations that would attach it to the vehicle.

GB 38031-2020 also prescribes shock loading in the vertical direction at acceleration magnitude of up to 8g, which is consistent with large suspension loads. Unlike the horizontal cases, the loading must be applied six times in both positive and negative vertical directions. The shocks must be spaced apart so that the transient response of the structure to one shock does not interfere with subsequent shocks. To speed up the analysis of this procedure, intermittent damping can be applied to the model after the peak response of the structure to each shock, via the keyword **`*DAMPING_GLOBAL`** and a load curve to control its application in time. The amount of damping will depend on the dynamics of the structure and the predicted damage from each shock. Clearly if no permanent damage is predicted after the first cycle, then continued analysis of subsequent shocks may not be required. Figure 1 shows a simplified example model and acceleration time history.

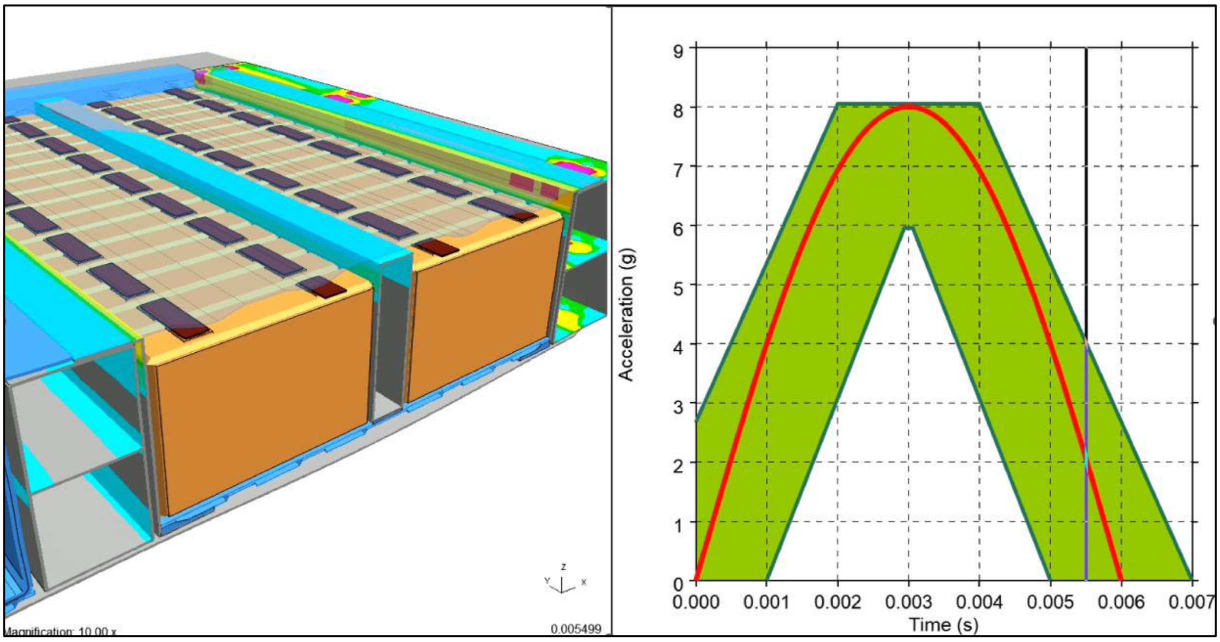

Fig.1: Example of vertical shock loading applied to a simplified battery pack model

The mechanical integrity requirements of both standards require the battery pack to be crushed mechanically in a horizontal direction with a defined impactor up to a maximum force of 100kN. This loading is likely to cause large deformation and plasticity at least in the exterior structure of the pack, if not internally. Therefore, the explicit solver is appropriate, however care should be taken with the rate of loading because the real test is quasi-static in nature. The rate of loading in the analysis should be chosen so that dynamic effects do not become significant. Arguably, this load case is suitable for analysis using the non-linear implicit solver in LS-DYNA, although convergence of solutions with large amounts of buckling and contact may require more time. Figure 2 shows an example of the integrity analysis.

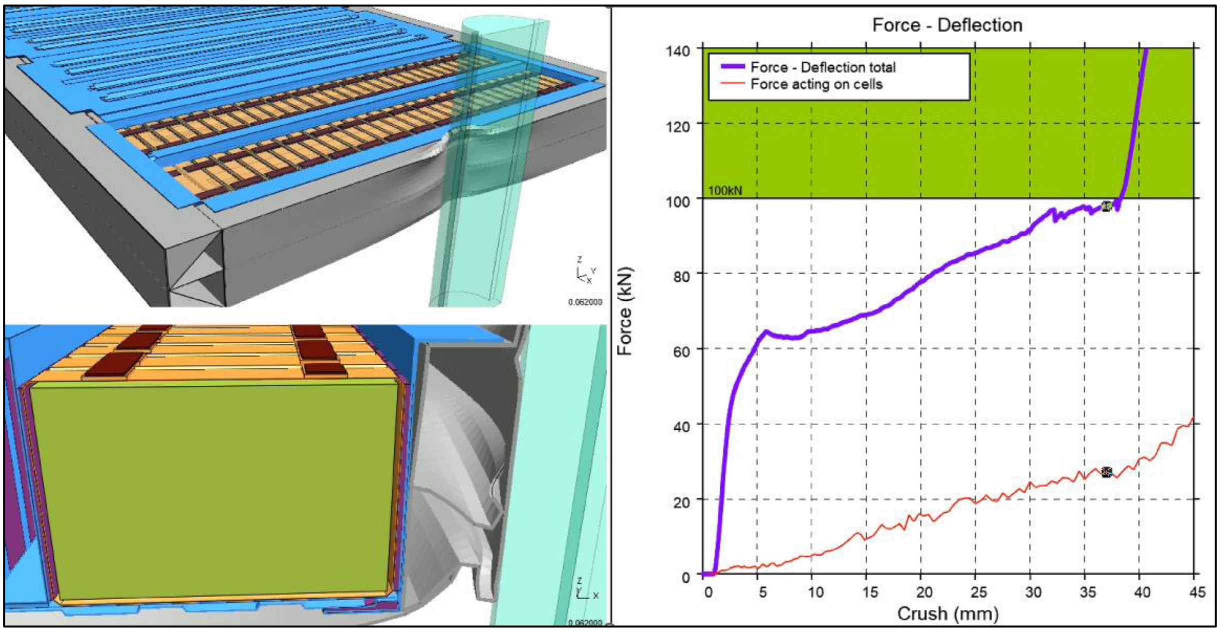

Fig.2: Mechanical integrity analysis using a simplified pack model

For both shock and integrity tests, the standards require that post testing, the battery pack should not exhibit leakage, fire or explosions. Generally, the performance of the battery must be inferred from the results. Damage or erosion of the cell casing in the model may indicate electrolyte leakage. If testing has been performed on the cells, it may be possible to compare the predicted cell deformations with test deformations that caused thermal events. If conductors are included in the model, such as busbars and high-voltage connectors, the predicted deflections and damage can be inspected and the risk of short-circuit inferred from proximity to each other and neighbouring structures. Section 7 of this paper describes the advanced features in LS-DYNA for the prediction of short circuits that could lead to thermal runaway.

5 Use of LS-DYNA implicit solver for vibration cases

The vibration tests prescribed in UN R100 and GB38031-2020 are intended to subject the battery pack to vibrations that are representative of normal operation, albeit in a condensed format to assess the performance in a reasonable amount of time. In both standards, the battery pack is attached to a shaking device which imposes a prescribed sequence of vibrations to the battery. In the case of UN R100, the vibration is a sinusoidal acceleration that sweeps logarithmically from 7Hz to 50Hz to 7Hz in 15 minutes. The amplitude of acceleration varies between 0.2g and 1.0g as a function of frequency. The sweep is repeated 12 times in the vertical direction so that the total test time is 3 hours.

In GB38031-2020, vibration is applied in all three directions sequentially and the vibration consists of random vibration for 12 hours followed by a constant amplitude sinusoidal acceleration for 1 hour, in each direction (for N1 and M1 category vehicles). The total vibration time is therefore 39 hours. The random content is defined by Power Spectral Density (PSD) spectra in each direction, with Root Mean Square (RMS) values of acceleration in the order of 0.5g. The constant sine portion is at a fixed frequency of 24Hz and amplitude 1.5g in the vertical direction and 1.0g in the horizontal directions.

From inspection, the tests will impose many thousands of cycles of inertial loading onto the battery structure and therefore damage may be accumulated through material fatigue. As the amplitudes of acceleration are relatively low, to be representative of normal use, a reasonable approach is to expect that stresses in the structure are also relatively low and can be evaluated with a linear model. Correspondingly, the fatigue phenomena will be consistent with high-cycle fatigue damage which can be evaluated using stress-life (S-N or Wöhler) curves for materials of interest in the pack.

LS-DYNA's frequency domain capabilities can be used for the analysis of vibration tests. Frequency domain analysis offers the following advantages:

- More efficient than time domain due to the long test duration and large number of cycles.
- Vibration loading is defined in the frequency domain in the regulations.
- The response due to vibration loading is likely to be linear.
- It can be easier to understand the structural response in the frequency domain because it can be related to the modes of the structure.

The method used in this paper is to use modal superposition to calculate the response of the structure to vibration loading. Modal superposition uses the mode shapes and natural frequencies obtained from modal analysis to solve the equations of motion for a structure subjected to external excitation. The total structural response is computed as a linear combination of the individual modal responses, where each mode contributes according to its dynamic characteristics and how strongly it is excited.

Modal analysis is invoked in LS-DYNA using the keyword **`*CONTROL_IMPLICIT_EIGENVALUE`**. LS-DYNA will compute a requested number of modes or all the modes within a frequency range. The conventional approach is to request all the models between zero and a frequency that is at least 1.5 times the maximum frequency of forced excitation. This is to ensure that there are sufficient modes available for the superposition calculation in the frequency range of interest. Stress data is required for fatigue analysis, so the field **`MSTRES`** must be activated.

For random vibration, the keyword *__`FREQUENCY_DOMAIN_RANDOM_VIBRATION`__ enables the definition of the excitation as a PSD, the type and direction of loading, the modes to be included in the calculation and damping. For sinusoidal excitation, the keyword *__`FREQUENCY_DOMAIN_SSD`__ (Steady State Dynamics) enables the definition of the same parameters, with the inputs being defined as load curves of acceleration magnitude and phase as functions of frequency.

For both methods, modal superposition is used to calculate the response of the structure. Results are output into binary database files for plotting. The keyword *__`DATABASE_FREQUENCY_BINARY_D3SSD`__ will produce a file d3ssd, which contains a plot state for each frequency requested. Graphing data for individual nodes and elements can be requested via *__`DATABASE_FREQUENCY_ASCII_NODOUT_SSD`__, for nodal outputs as an example.

Random vibration plotted results are output in the binary database d3rms, requested with *__`DATABASE_FREQUENCY_BINARY_D3RMS`__, which outputs a single plot state showing the RMS value of response, for example for displacement or stress. Due to the nature of random loading, the RMS value provides a single measure of the average response of the structure, because deterministic responses at each frequency are less meaningful. Graphing data is requested via *__`DATABASE_FREQUENCY_ASCII_NODOUT_PSD,`__ where curves describing the PSD response of the requested nodes will be output (**`ELOUT`** for elements).

The fatigue life of the structure is calculated using the results from the forced response analysis. For both random and sinusoidal vibration, fatigue life is calculated using input S-N curves for each material of interest. The basic premise for the method is that the number of cycles spent at a stress level in the analysis will be a proportion of the limiting number of cycles on the S-N curve at the same stress level. A fatigue damage ratio, which is the summation of all proportions of life used at different stress levels, is calculated using Miner's Rule, with any value exceeding unity indicating failure.

The addition of the **`_FATIGUE`** option to the **`FREQUENCY_DOMAIN`** keywords shown above will allow fatigue related data to be added, principally being the S-N curves for each material of interest and the exposure time that the structure is subjected to the vibration. S-N curves are usually obtained from material or component testing and are a critical input to the analysis. Special consideration must be given to the nature of the component, the surface finish and stress raisers such as welds which may not be adequately discretised in the model. Certain materials such as polymers and adhesives may not be characterised well for fatigue analysis or require special methods. Fatigue is a complex topic and is not discussed in depth here; it is assumed that a valid S-N curve is available for each material of interest.

For sinusoidal vibration, S-N curve data are added via the **`*MAT_ADD_FATIGUE`** option for each material of interest in the model. Exposure time is defined via **`LCFTG`** on *__`FREQUENCY_DOMAIN_SSD_FATIGUE`__ which is a curve of exposure time versus frequency. The total exposure time is the sum of all ordinate values on the curve. Therefore, for constant amplitude excitation, a single point (after the origin) at the excitation frequency with the entire duration value is required (e.g. 3600s at 24Hz). For a logarithmic sweep (UN R100), care should be taken discretising the sweep to achieve the desired exposure.

For random vibration, the same method can be used, or optionally S-N data are defined on the ***FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE** keyword using sets of parts. In either case the parameter **MFTG** must be defined. Exposure time is defined with **TEXPOS**.

LS-DYNA offers several solutions for calculating fatigue life under random vibration, including Steinberg three-band method, Dirlik method, a narrow band method and several others [14]. All work on the assumption that the excitations are statistically stationary with Gaussian distribution. This allows the calculation of stress probability functions from the stress PSDs for each element in the model. Knowing the probability of each stress range allows the fatigue life to be estimated from the S-N curve and the application of Miner's Rule to calculate total damage ratio. Results are output to the d3ftg database (***DATABASE_FREQUENCY_BINARY_D3FTG**) and fatigue results can be plotted on the model.

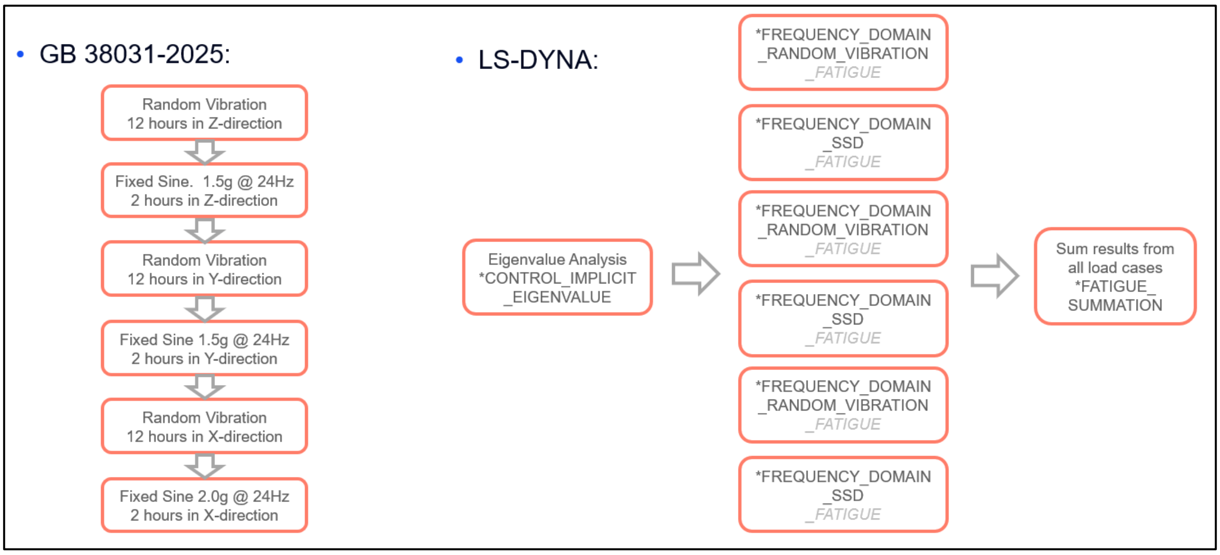

Fig.3: Workflow for analysis of GB 38031-2020 vibration test

Figure 3 illustrates the workflow for analysing the GB 38031-2020 vibration test. Analyses can be run sequentially to follow the prescribed test steps, with the keyword ***FATIGUE_SUMMATION** can be used to sum up the damages from each d3ftg output file. A modal analysis is not required for every analysis; each vibration analysis can refer to a set of d3eigv file via the ***FREQUENCY_DOMAIN_PATH** keyword.

Figure 4 shows an example of the fatigue life result contoured on a simplified example model, with lowest life predicted around the mounting points and mid-spans of structural elements that are bending.

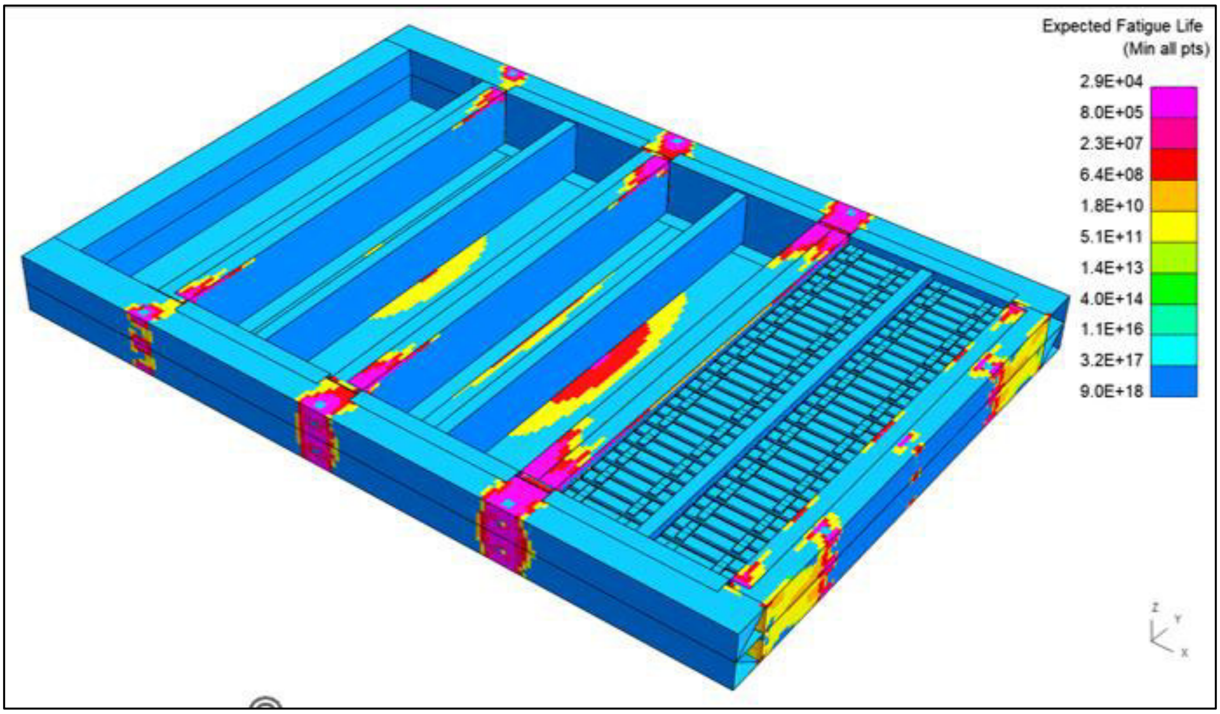

Fig.4: Contoured fatigue life result on simplified example model (some cells blanked)

6 Use of LS-DYNA implicit solver for thermal shock

The thermal shock tests prescribed in the UN Reg 100 and GB 38031-2020 regulations subject the battery pack to large temperature changes, to simulate fluctuations in the ambient temperatures the vehicle may encounter. Both standards specify temperature cycles between -40º C and +60º C, with soak periods of 6-8 hours at each extreme and the transition between extremes occurring within 30 minutes. The cycle is repeated 5 times. Typically, test chambers are used where the temperature of the air surrounding the battery is changed quickly to satisfy the loading profile.

Battery packs are generally densely packed with significant mass; therefore, it is likely that the rapid change in temperature at the exterior will cause a temperature gradient through the pack as the whole mass responds to the imposed change. The test should highlight whether incompatibilities between the many different materials at different temperatures give rise to mechanical failures. The scale of the failures may vary from macro level structural failures to micro cracking in components. The ability of the model to predict these will depend on the degree of discretisation. Material properties, especially in polymeric materials are likely to be temperature dependent, which may affect results.

Two approaches to the problem have been investigated using LS-DYNA:
- Coupled thermo-mechanical analysis
- Uncoupled sequential analysis

The keyword ***CONTROL_SOLUTION** allows selection of a thermal only analysis or a combined mechanical and thermal analysis.

With the first option, the implicit thermal and mechanical solver run concurrently and pass information between solvers. Given the duration of the test (hours), this approach is attractive as a relatively large timestep may be possible. It also has the advantage that the effect of any mechanical response like a gap opening can influence the thermal analysis. However, the implicit mechanical solver must converge at each timestep and if the battery model is complex with many contact surfaces, prestressed components etc, then more time may be required for the solution.

The second approach is to run the thermal simulation first to predict the temperature field and then import the temperature time-histories into a subsequent implicit or explicit mechanical solution. LS-DYNA provides a convenient workflow for this via the keyword ***DATABASE_ASCII_TPRINT** which outputs temperature time history data to the binary binout file. In the subsequent mechanical analysis, the loading is applied using the keyword ***LOAD_THERMAL_BINOUT** which reads the histories from the defined file. The keyword also allows time scaling so that the histories from an implicit thermal analysis can be compressed into the timescale of an explicit analysis if required. If difficulties with convergence in the coupled approach are encountered, this may be the preferred approach.

The main considerations in the thermal analysis are as follows:
- Thermal boundary conditions to simulate test chamber
- Heat transfer mechanisms within the battery pack
- Material thermal properties

As the test chamber controls the temperature of the air surrounding the battery, the main thermal loading is assumed to be from convection. The governing equation is Newton's law of cooling where the energy flux is proportional to a temperature difference and the heat transfer coefficient. The keyword ***BOUNDARY_CONVECTION** allows the input of the heat transfer coefficient (which may be a function of temperature) and the chamber temperature defined as a function of time. The boundary condition can be applied to the segments of the battery model that would be directly exposed to the air in the chamber. Clearly the strongest influence on the amount of energy admitted to the model is the heat transfer coefficient. This is likely to be a characteristic of the test chamber itself and information should be sought from equipment suppliers. Typical values for forced convection lie in the range 10-200 W/m^2K [10].

Typical electric vehicle battery packs are closely packaged due to space requirements; therefore, conduction is likely to be the dominant heat transfer mechanism within the pack. The imposed temperatures are not great enough for radiation to contribute significantly. Generally, large air-filled volumes are unusual due to space constraints and so heat transfer between components due to convection is also likely to be a secondary effect. Conduction and diffusion of heat through solid materials is governed by the thermal conductivity and the specific heat capacity, which are both defined on thermal material models in LS-DYNA.

***MAT_THERMAL_ISOTROPIC** and ***MAT_THERMAL_ORTHOTROPIC** are both suitable for typical materials used in battery construction. LS-DYNA allows temperature dependent properties if the **_TD** version of the models are defined. The thermal material is referenced from the part card for each component. During a thermal analysis, conduction will occur in contiguous meshes if the part references a thermal material. It is usual that many parts in the battery will not be continuously meshed but are in contact. Therefore, heat transfer through LS-DYNA's contact surfaces must also be defined to successfully model all possible heat transfer paths through the structure.

The **_THERMAL** option can be added to selected contact types in LS-DYNA such as ***CONTACT_AUTOMATIC_SURFACE_TO_SURFACE**. Depending on user-defined gap thresholds, heat transfer is modelled as either conduction (in the touch condition), a combination of convection and radiation (when a gap exists between parts) or zero heat transfer (when the gap exceeds a limit). Appropriate values of heat transfer coefficients for each case should be input.

The mechanical response of the structure is governed by the expansion or contraction of the materials depending on temperature change and coefficients of thermal expansion. The latter can be added to the model using the keyword ***MAT_ADD_THERMAL_EXPANSION** with the coefficient optionally being a function of temperature. Different rates of expansion can be applied in the material axes.

To model the effect of temperature on material properties such as modulus and yield strength, several material models are available, for example ***MAT_ELASTIC_PLASTIC_THERMAL**, ***MAT_JOHNSON_COOK**, ***MAT_ELASTIC_VISCOPLASTIC_THERMAL** [11].

Figure 5 shows the results from a coupled thermo-mechanical analysis using an example model, showing the temperature gradient through the structure during heating.

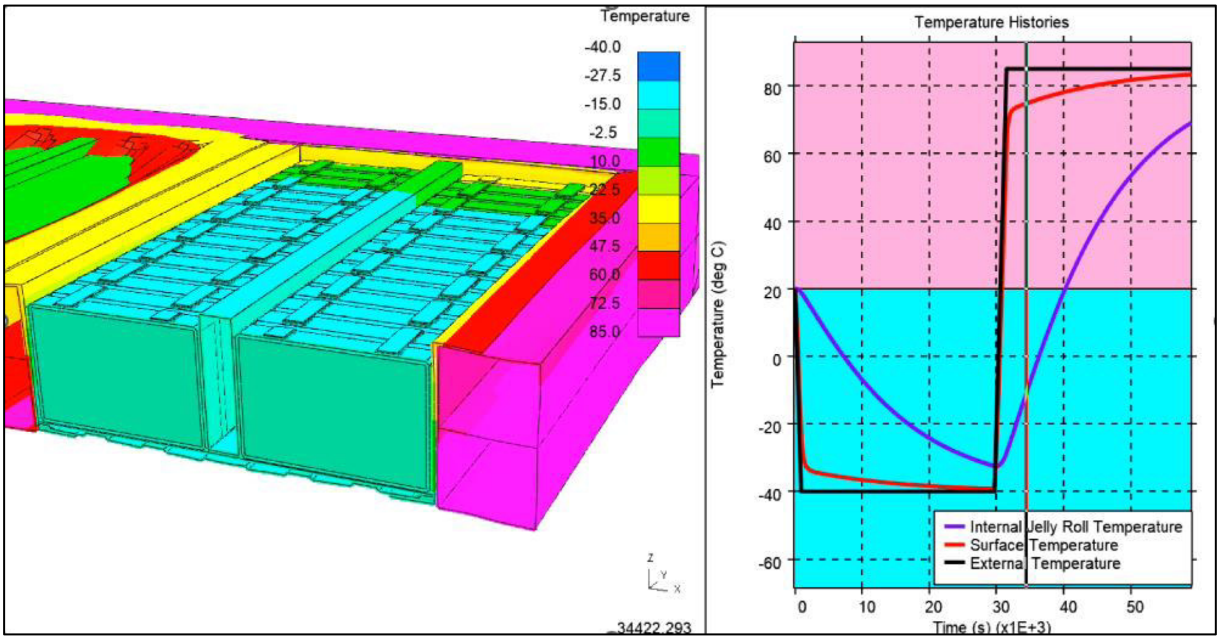

Fig.5: Temperature distribution in an example model, shown with contour plot and time histories at exterior surface and interior node, with chamber temperature profile shown for reference

7 Analysis of related load cases with LS-DYNA

The preceding sections have described how LS-DYNA can be used to analyse some of the mechanical and thermal tests specified in battery safety regulations. It is acknowledged that not all tests are considered, including:

- Fire loading
- Over charge / discharge
- Thermal propagation / runaway test

It may be possible to extend the thermal shock method described above to fire loading, accepting that temperatures will be much higher and therefore radiation effects may be significant. The increased temperatures may lead to material burning or melting of battery components and increase the risk of cell thermal events.

LS-DYNA has extensive features related to the modelling of battery cells with Randles circuit models that couple the electromagnetic, thermal and mechanical domains [12]. These capabilities allow the modelling of the cell charge and discharge cycles and associated ohmic heating of the cell. A generalised approach to model internal short circuits is provided, triggered by user-defined functions that consider electrical, thermal and mechanical inputs. The short circuit model will cause a rapid drop in charge accompanied by ohmic heating, which can be supplemented with additional heating via the keyword ***EM_RANDLES_EXOTHERMIC_REACTION**.

The thermal runaway phenomenon is physically complex, involving rapid decomposition of the cell internals at elevated temperatures with gas generation. Battery cells and enclosures are vented to prevent excessive pressure build up and the hot gases from the cell will travel through the pack interior interacting with the structure mechanically and thermally. Issues may include distortion and failure of sealed volumes leading to improper venting of the pack. If adequate heat from one cell reaches neighbouring cells, they may also burn and vent, leading to runaway of the pack. The topic of gas generation and venting is an area of research with the use of a Continuum-based Particle Gas approach [13]. Coupled with the Randles circuits capability, a convincing solution to modelling runaway in LS-DYNA is available.

The application of LS-DYNA to battery system design is not limited to damaging events. A further example of a multi-physics solution is for battery cooling. A standard approach to cooling is for heat from the cells to be conducted into a metallic plate, inside which fluid runs in tracks, moved with a pump.

The fluid is heated via conjugate heat transfer and transports the heat away to the cooling module. LS-DYNA's Incompressible Computational Fluid Dynamics (ICFD) solver can be used to model this process [15]. Coupled with the electromagnetic capabilities mentioned above, a complete solution for the thermal management of cells during charge and discharge is possible, enabling optimisation of cell packaging and cooling system design.

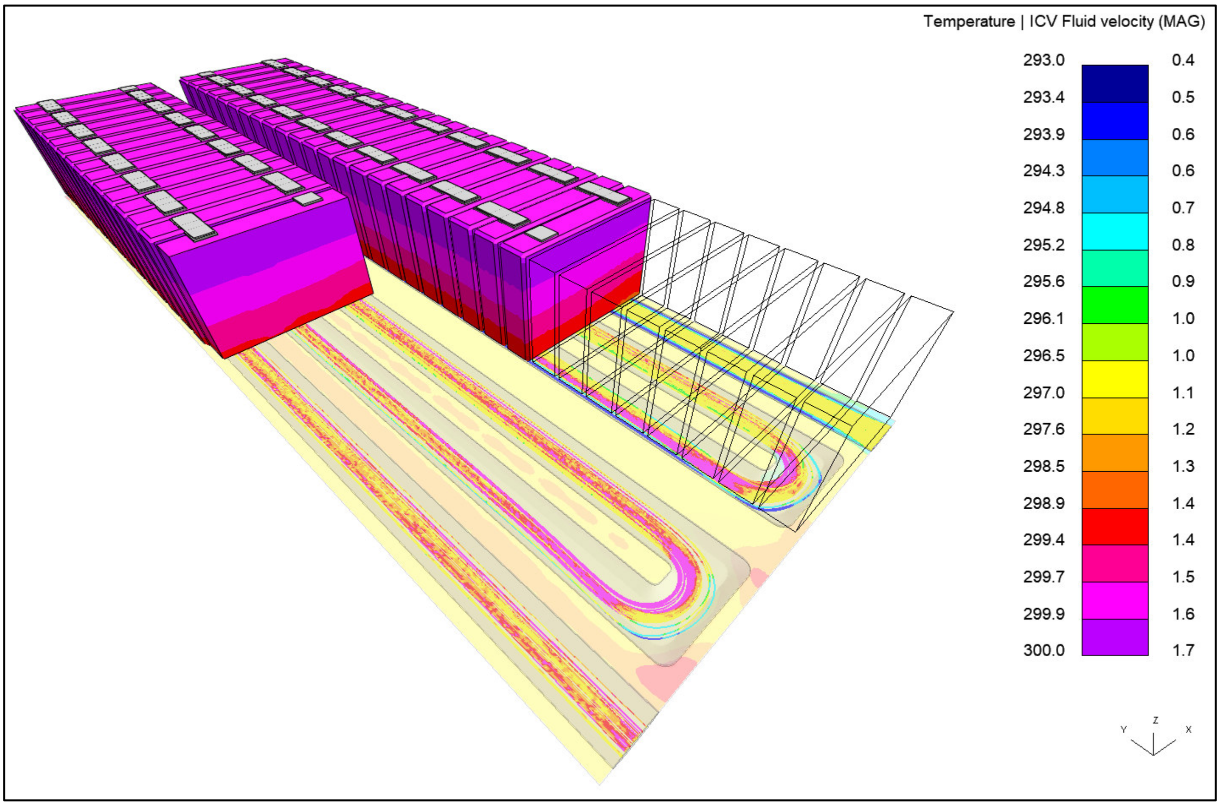

Fig.6: Conjugate heat transfer from cells to cooling fluid using ICFD solver

8 Summary

Using LS-DYNA it is possible to simulate many of the safety tests required to demonstrate battery system safety before introduction into the market. Thus, virtual prototyping of these systems is possible, enabling a more efficient and cost-effective design process that aligns with the established simulation route for automotive products. LS-DYNA's multi-physics capabilities enable the simulation of many complex phenomena and research is ongoing to expand these capabilities further.

9 Literature

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