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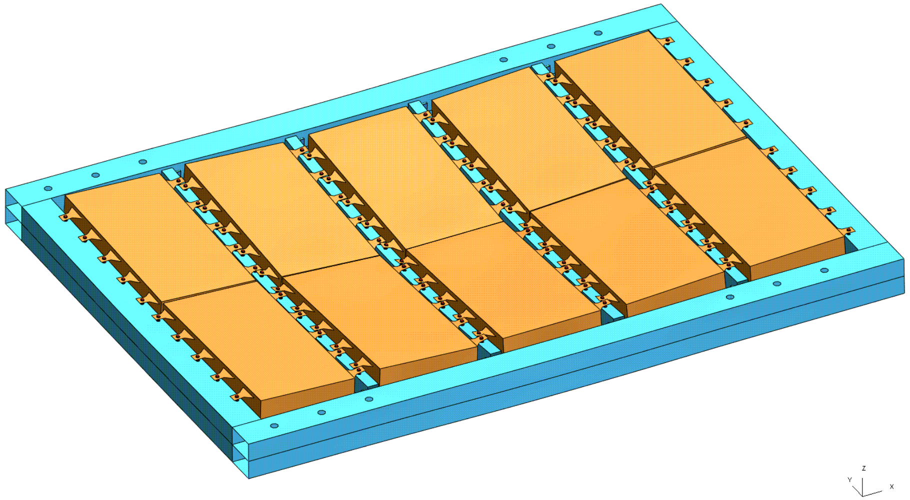
Fatigue assessment of an adhesively bonded EV battery enclosure

Using LS-DYNA implicit tools



David McLennan

*Presented by **Emily Owen***

PR D3 TH RE SH JS

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Automotive consulting

Crash performance

Pedestrian safety

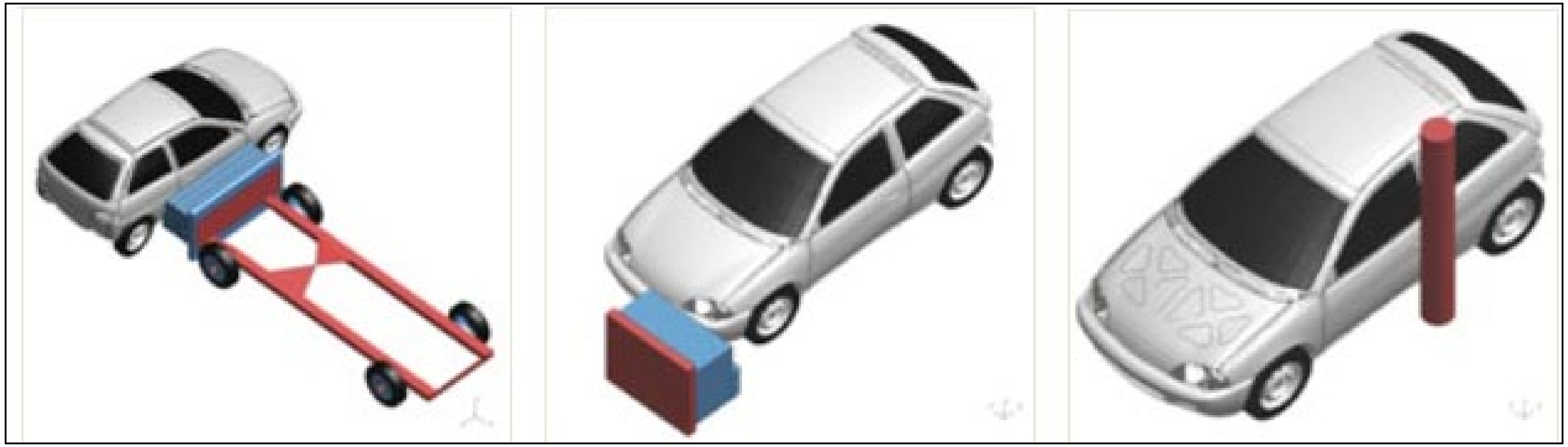
Occupant safety

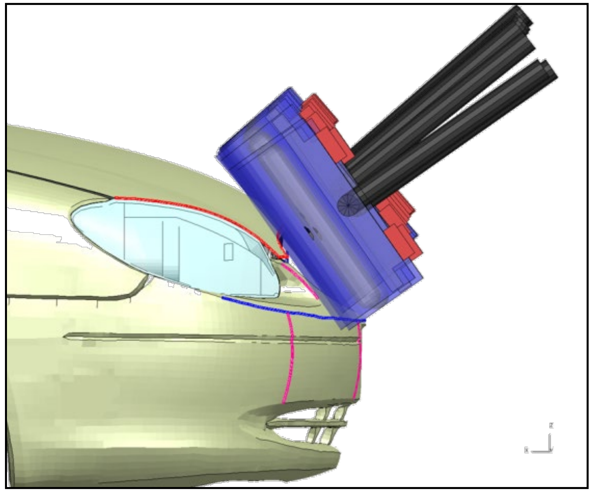
Interior systems

Noise, Vibration, Harshness

Durability performance

Closures performance





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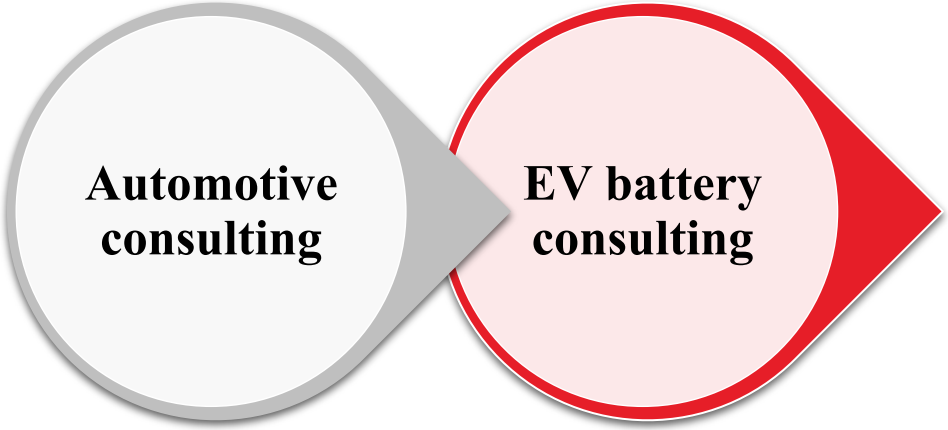
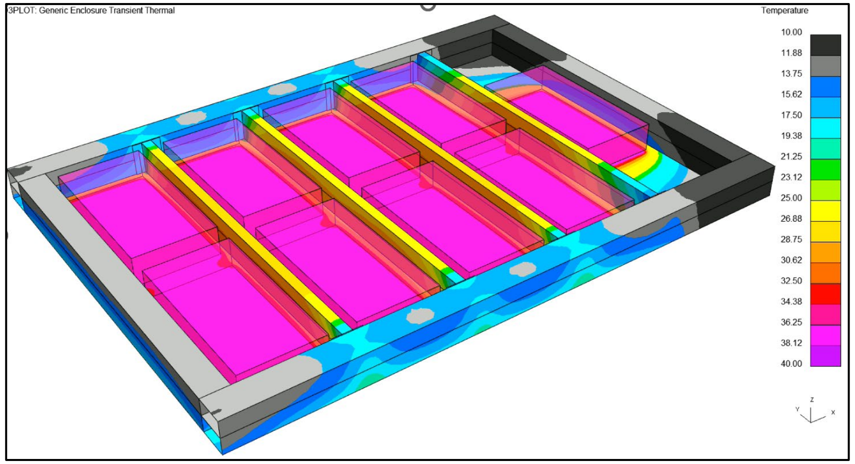
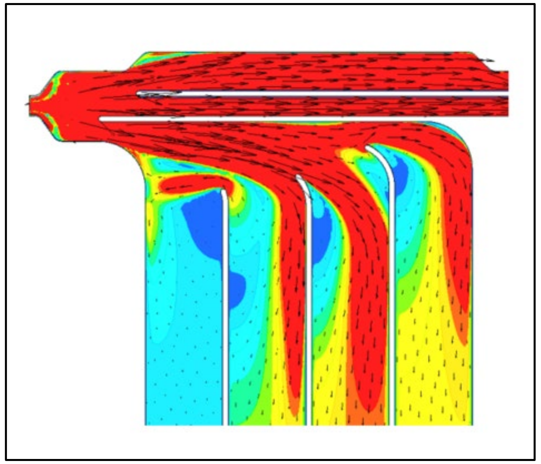


Transient thermal analysis



Coolant flow optimisation



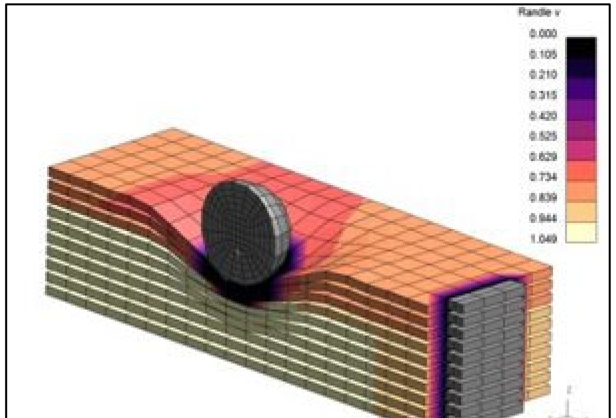
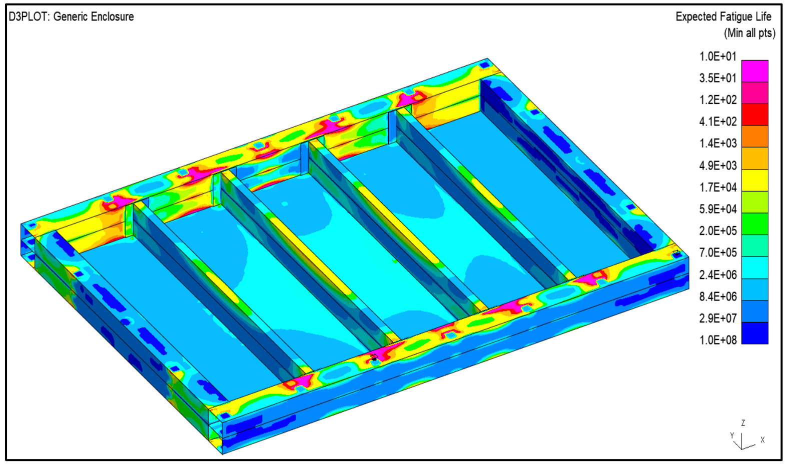


Image courtesy of LST

Cell penetration analysis



Fatigue analysis

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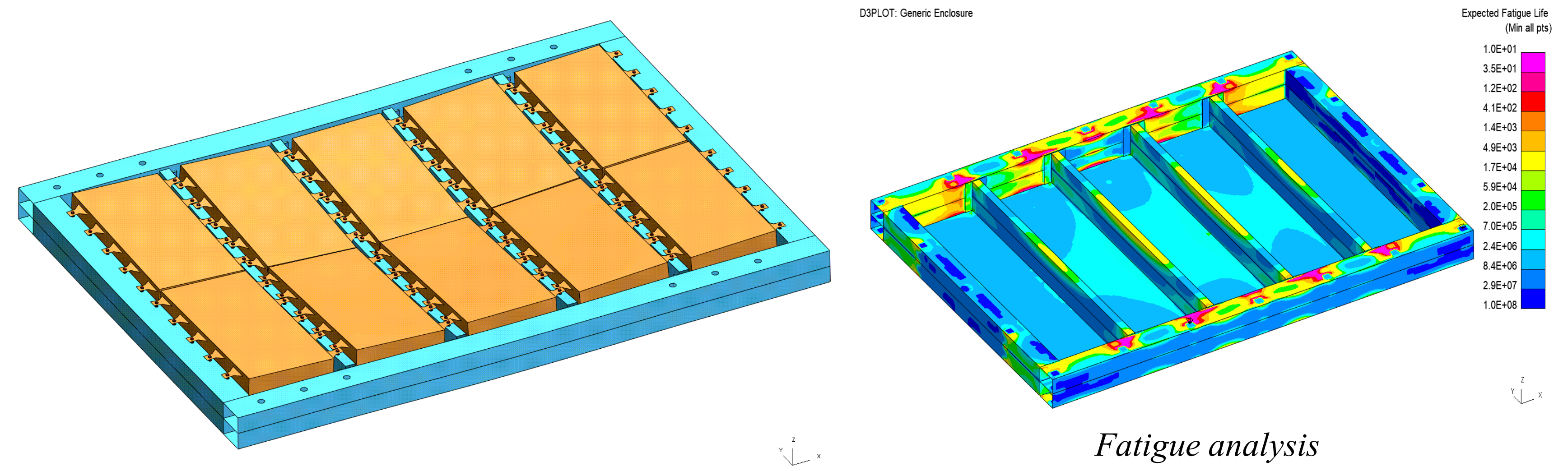
Automotive consulting → EV battery consulting → **EV battery enclosure fatigue**



Fatigue analysis

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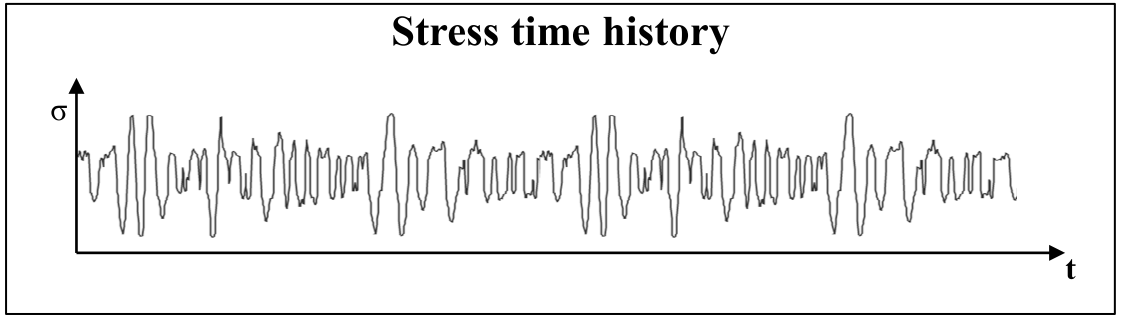
What is fatigue?



- Eurocode 9 definition:

“weakening of a structural component, through crack initiation and propagation, caused by repeated stress fluctuations”

- Fatigue failure occurs from stress cycles *lower* than the component’s yield stress

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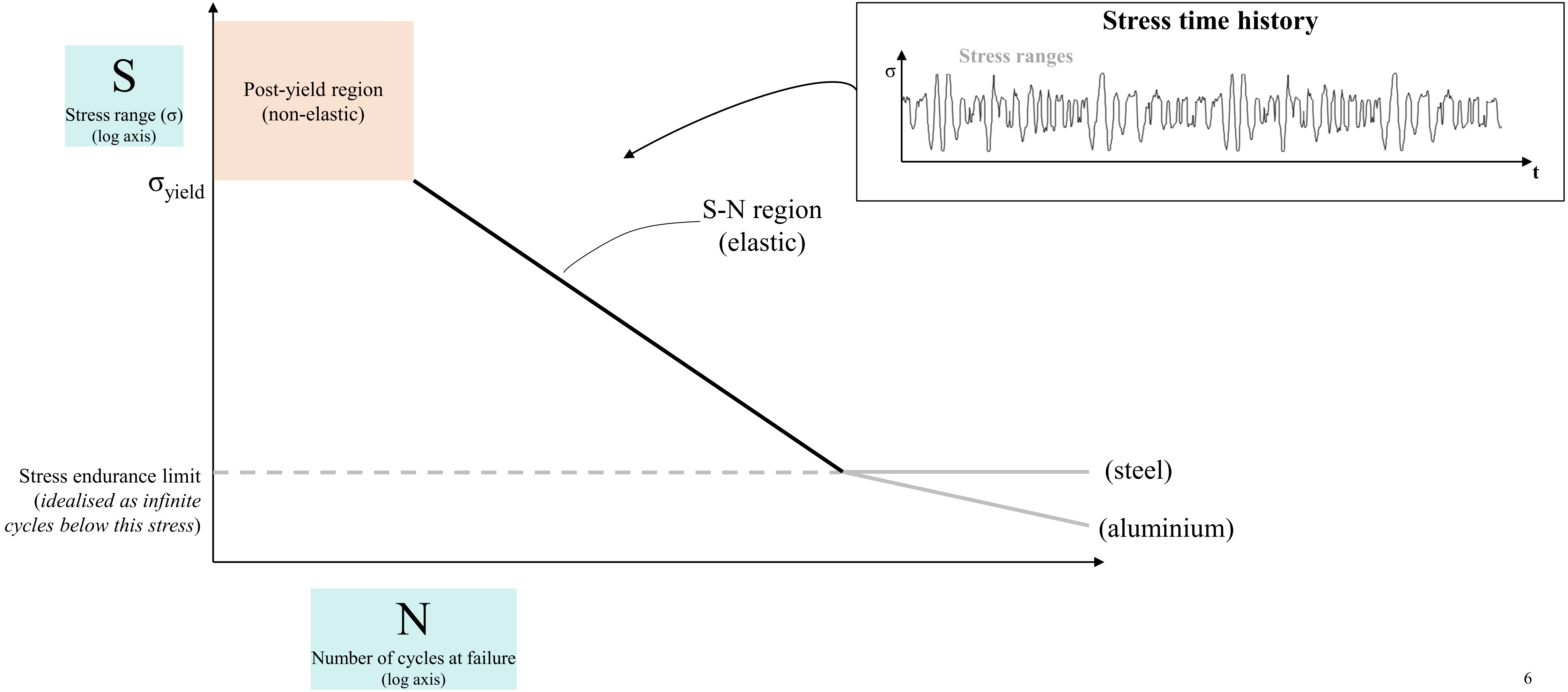
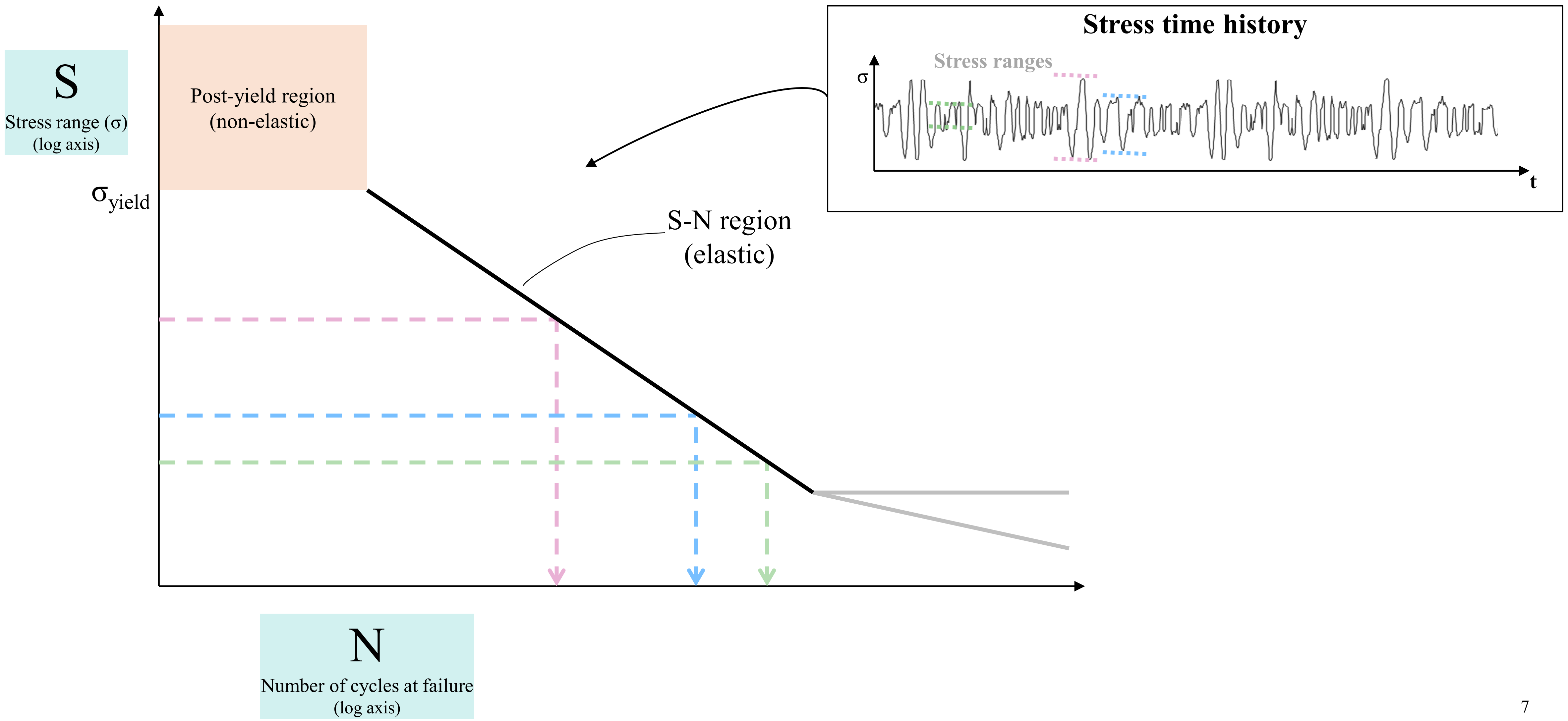
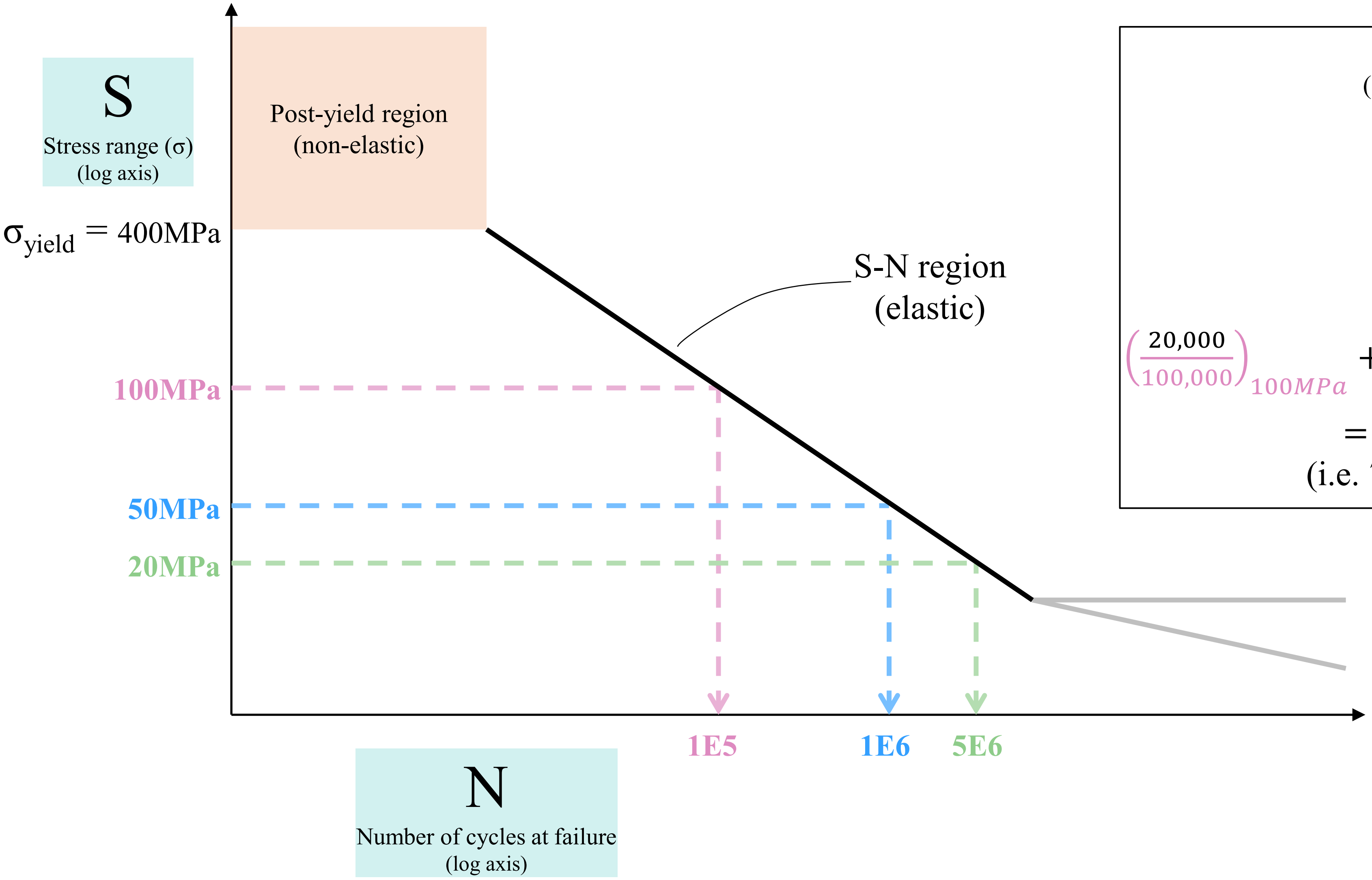
Fatigue assessments – S-N curves



Fatigue assessments – S-N curves



Fatigue assessments – S-N curves



Miner's rule

(Cumulative Damage Ratio)

$$\sum_i \frac{n_i}{N_i}$$

For example:

$$\left(\frac{20{,}000}{100{,}000}\right)_{100MPa} + \left(\frac{100{,}000}{1{,}000{,}000}\right)_{50MPa} + \left(\frac{2{,}000{,}000}{5{,}000{,}000}\right)_{20MPa}$$

$$= 0.2 + 0.1 + 0.4 = 0.7$$

(i.e. 70% of fatigue life used)

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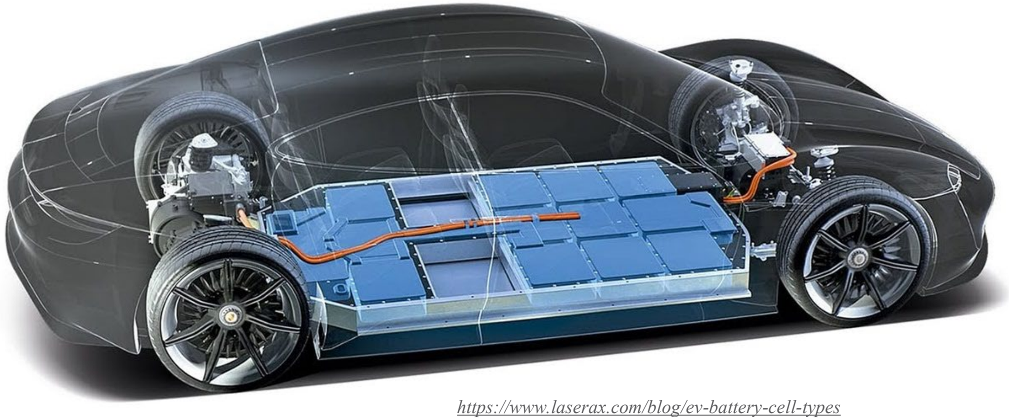
Fatigue risks for EV battery enclosures

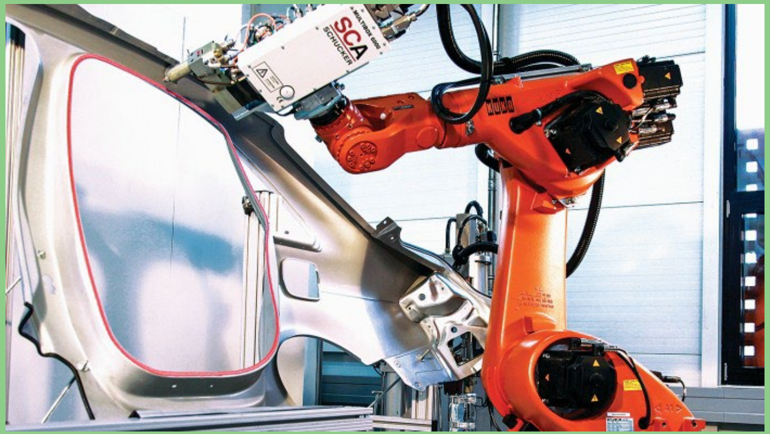
- The battery enclosure must have sufficient strength/stiffness to:
  - Protect the batteries during a vehicle crash event
  - Contribute to overall stiffness of the vehicle
  - Provide containment in the event of thermal runaway
  - Withstand inertial loads from the mass of the batteries
- Total mass of “battery modules + enclosure” can be ~0.5-1.0 tonnes



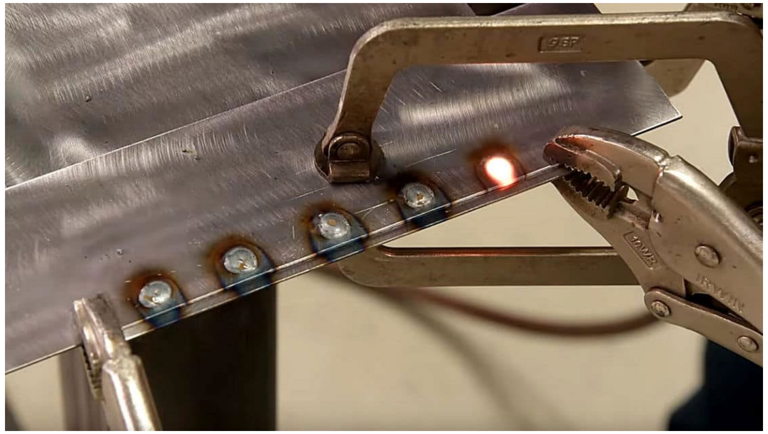
https://www.laserax.com/blog/ev-battery-cell-types

The rise of adhesively bonded designs

	Adhesive bonding	**Spotwelds**
Connection type	Continuous (large area) connections	Discrete (small area) connections
Most common for	Aluminium structures	Steel structures
Material properties	Overall lightweight solution, and does not affect strength of parent aluminium material	Typically not suitable for aluminium, due to heat weakened zone around the weld
Fatigue assessment	Emerging area of study	Established methods



https://cen.acs.org/articles/92/i16/Automakers-Look-Adhesives-Aluminum-Gas.html



https://m.roadkillcustoms.com/how-to-simulate-resistance-spot-welds/

Fatigue assessment: LS-DYNA model

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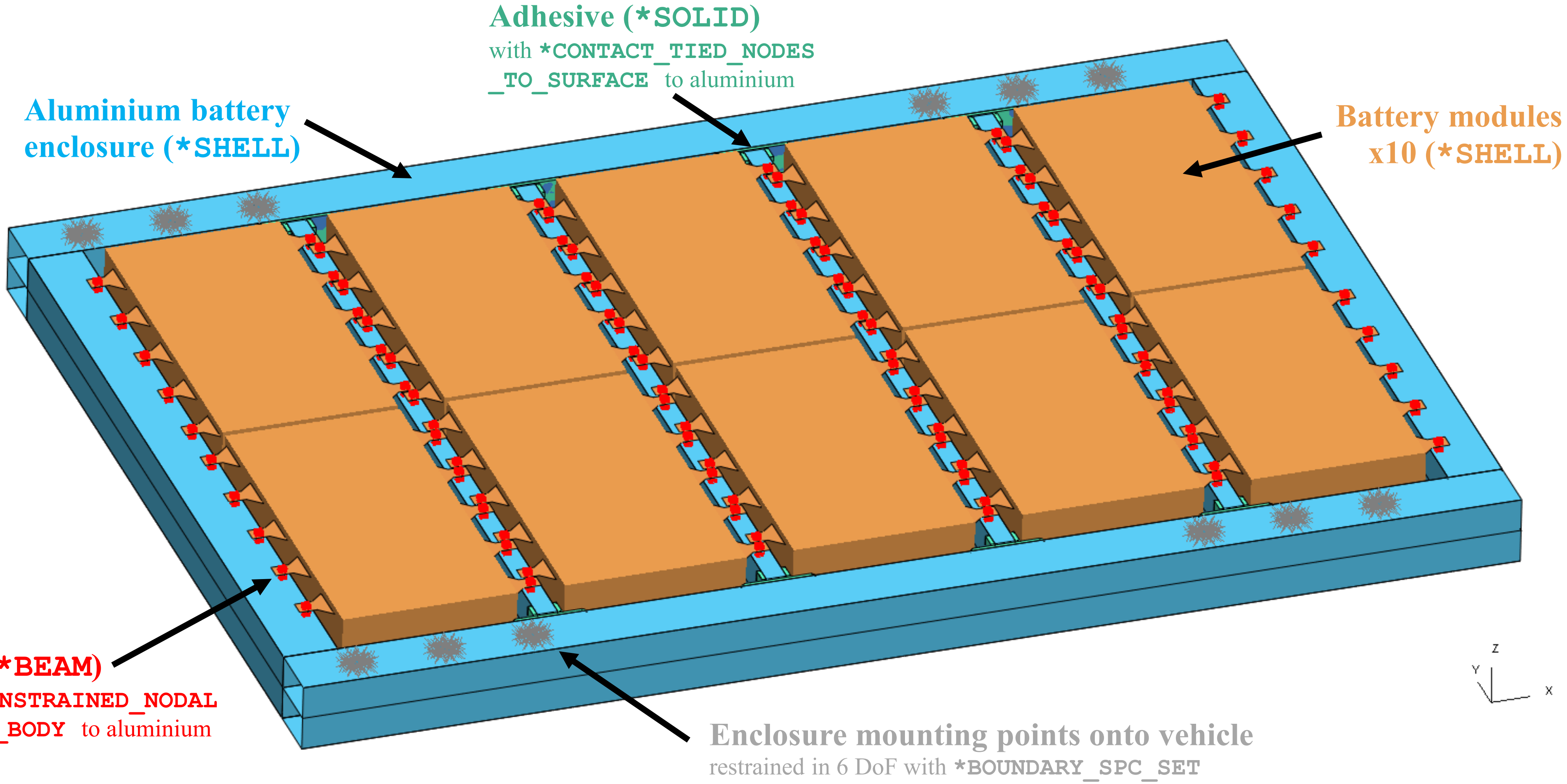
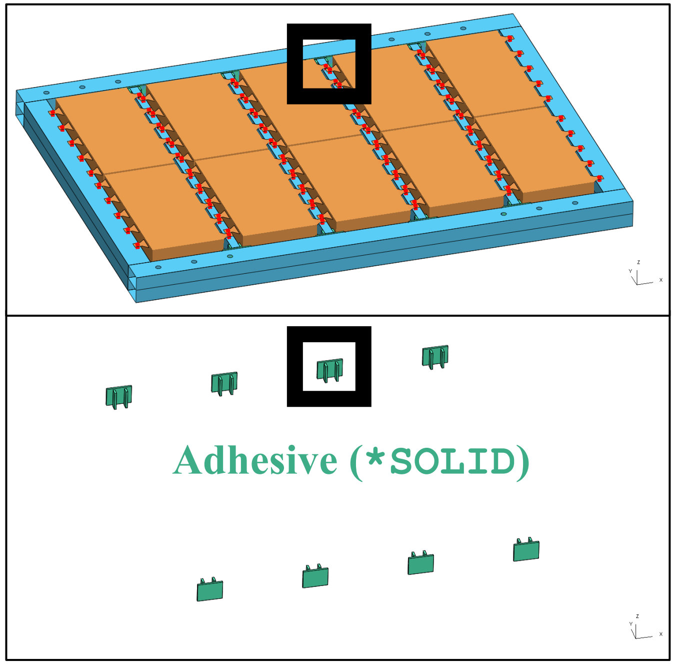
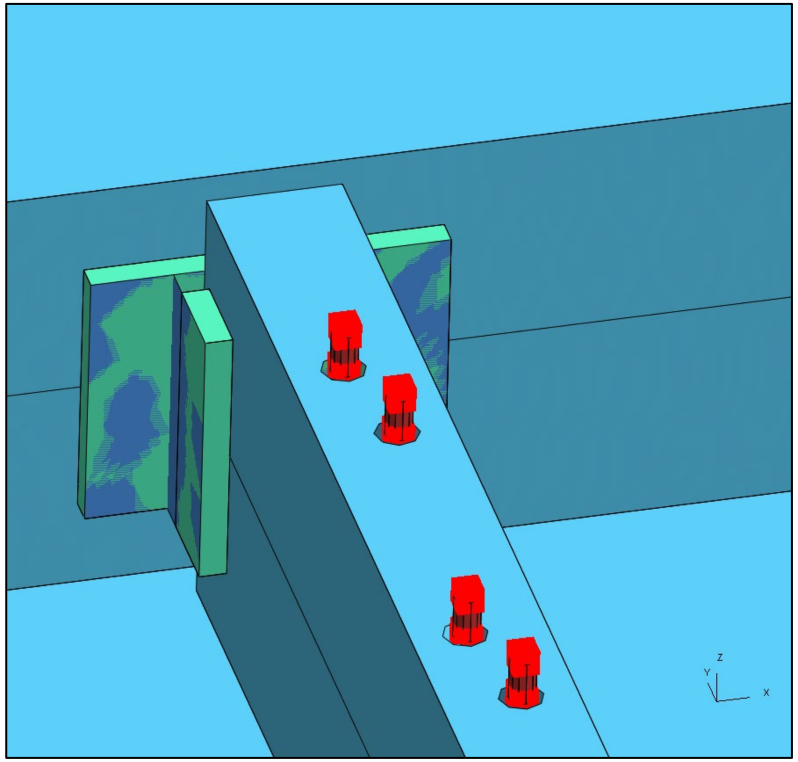
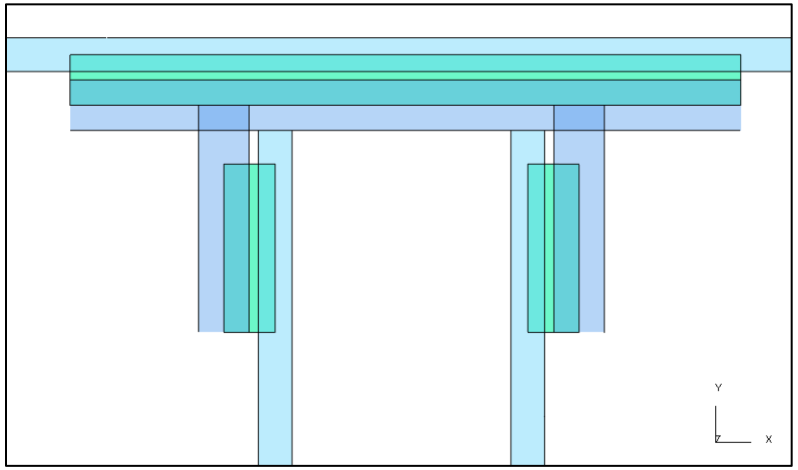


Fatigue assessment: LS-DYNA model







***SHELL** visualised as "*true thickness*"

***SHELL** visualised as "*thin line*"

- Adhesive ***SOLID** elements modelled from mid-surface to mid-surface of adjacent aluminium plates
- Using ***MAT_ARUP_ADHESIVE**, defined with 0.3mm bond thickness

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LS-DYNA implicit solvers

Keyword	Comment
*CONTROL_IMPLICIT_GENERAL	Activates implicit mode and defines timestep
*CONTROL_IMPLICIT_AUTO	Activates automatic timestep control
*CONTROL_IMPLICIT_SOLVER	Defines linear equation solver
*CONTROL_IMPLICIT_SOLUTION	Defines equilibrium search and convergence tolerances
*CONTROL_IMPLICIT_EIGENVALUE	Normal modal analysis Equivalent to NASTRAN SOL103
*FREQUENCY_DOMAIN_FRF	Direct freq-domain response analysis Equivalent to NASTRAN SOL108
*CONTROL_IMPLICIT_DYNAMICS	Direct time-domain response analysis Equivalent to NASTRAN SOL109
*FREQUENCY_DOMAIN_RANDOM_VIBRATION(_FATIGUE)	Modal freq-domain response analysis to random vibration Equivalent to NASTRAN SOL111
*FREQUENCY_DOMAIN_SSD(_FATIGUE)	Modal freq-domain response analysis to steady state dynamics Equivalent to NASTRAN SOL111
*CONTROL_IMPLICIT_MODAL_DYNAMIC	Modal time-domain response analysis Equivalent to NASTRAN SOL112
...and many more	

Predicting fatigue performance of structures

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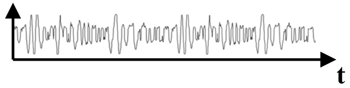
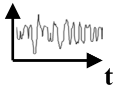
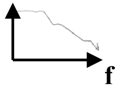
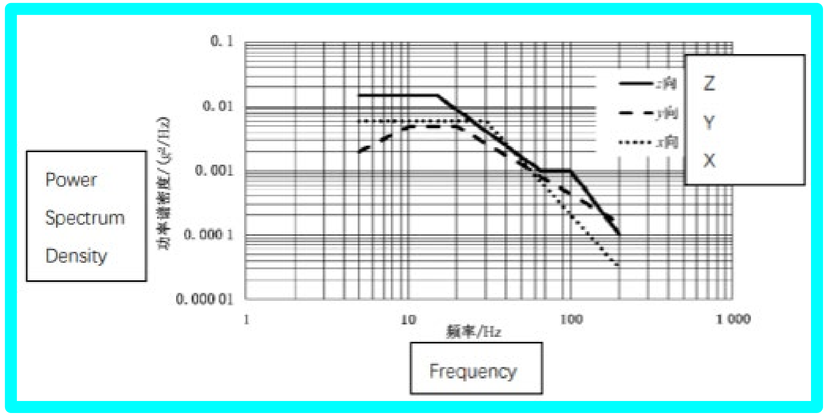
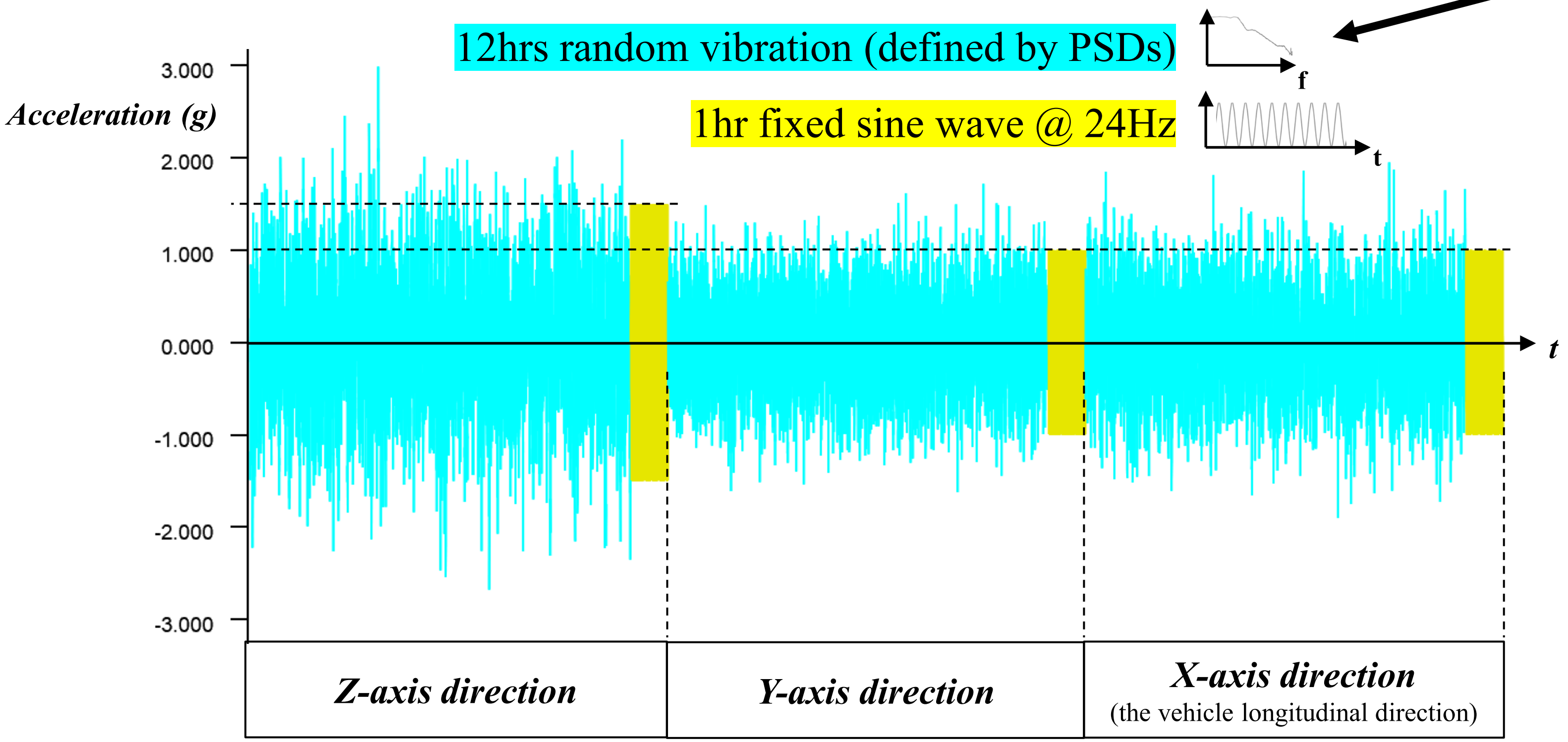
	Random vibration fatigue assessment using…	
	Time domain	Frequency domain
Physical tests	With random cyclic loading, until test specimen fails 	n/a
FE analysis	Random transient input loading  Slower analysis than frequency domain, producing more data (therefore, need to focus on regions of greatest importance) More flexibility with the fatigue assessment methodology (post-processing on time history results) Element stress time histories to count cycles at each stress range	Random input loading from a defined PSD†  Fast analysis method, which outputs element stress PSDs† (therefore, can assess all elements and do many studies) Constrained to standard freq-domain fatigue assessment methods Using PSD† statistics to obtain cycles at each stress range
	Fatigue damage calculated via comparison to failure cycles (S-N curve, Miner's rule)	
	`*CONTROL_IMPLICIT_MODAL_DYNAMIC`	**`*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE`** **`*FREQUENCY_DOMAIN_SSD_FATIGUE`**

† Power Spectral Density

Fatigue assessment: vibration load cases

- **Objective:** to pass the “*GB 38031-2020 China Standard*” electric vehicle vibration load cases*, comprising the following sequence of tests (from Table 3 of the regulations):





* for vehicle types M1 (passenger cars) and N1 (light goods vehicles, up to 3500kg)

Fatigue assessment: vibration load cases

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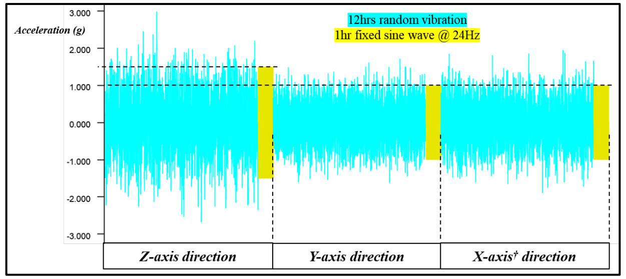
- **Method:** implementing with LS-DYNA implicit solvers, using keywords:

GB 38031-2020 China Standard		**Fatigue assessment for…**	
		Adhesive SOLIDs	Aluminium SHELLs
Loading method…	**Random vibration**	***CONTROL_IMPLICIT_MODAL_DYNAMIC** *X, Y, Z loading* *(analysed in the time domain)*	***FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE** *X, Y, Z loading* *(analysed in the frequency domain)*
	Fixed sine wave	***FREQUENCY_DOMAIN_SSD_FATIGUE** *X, Y, Z loading* *(analysed in the frequency domain)*	



Analysed in the time domain to allow fatigue calculations using the ***Sousa method*** [1], requiring time histories of adhesive element stresses

[1] *F. Castro Sousa, A. Akhavan-Safar, R. Goyal, L.F.M. da Silva (2022) Fatigue life estimation of adhesive joints at different mode mixities, The Journal of Adhesion, 98:1, 1-23*

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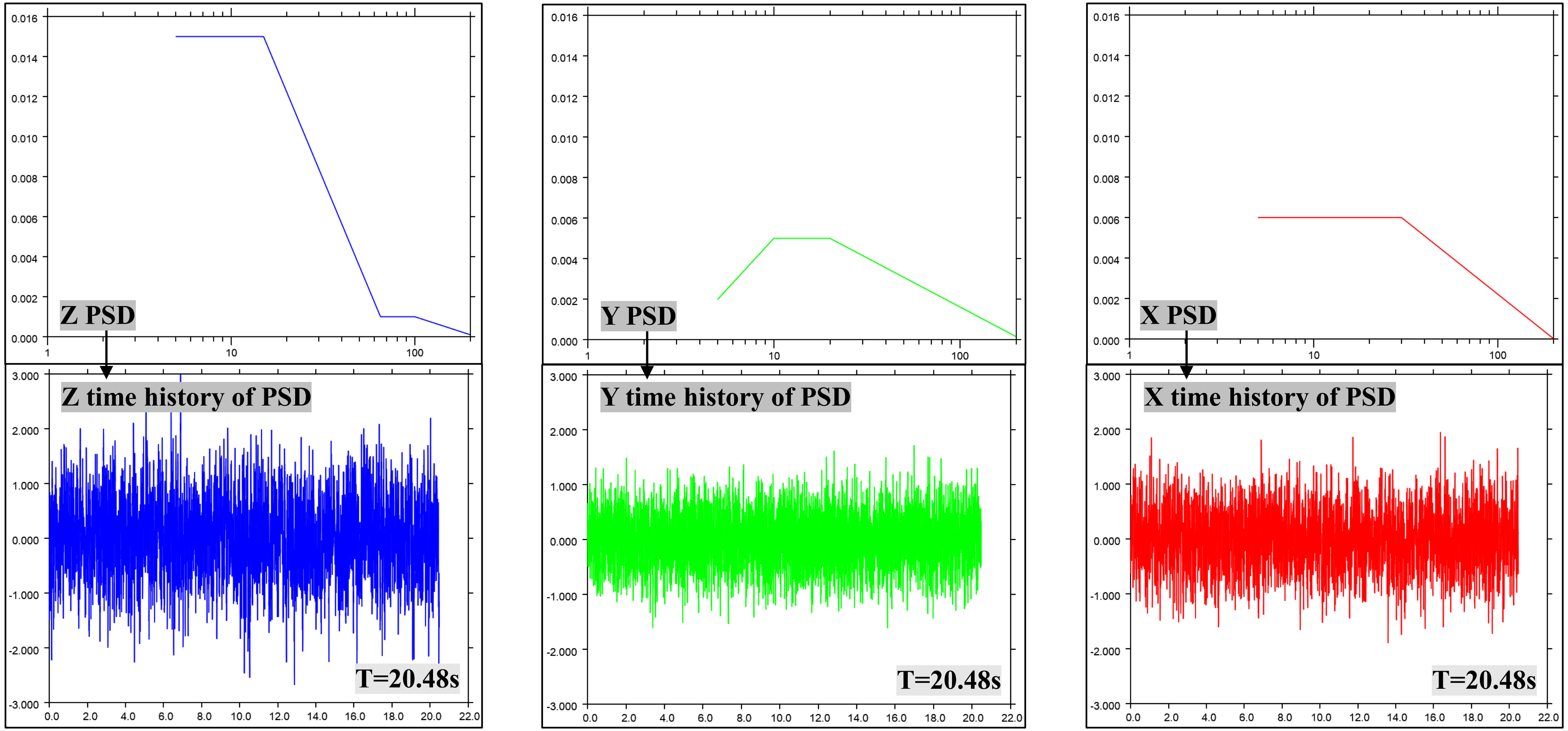
Fatigue assessment: vibration load cases

PSD (g^2 / Hz) vs frequency (Hz)

GB 38031-2020 China Standard

Acceleration (g) vs time (s)



- MATLAB script has generated random time signals from each PSD
- Time signal must be long enough to accurately capture the contents of the PSD
- A good check is then to create a PSD from the generated time signal, to compare to the original

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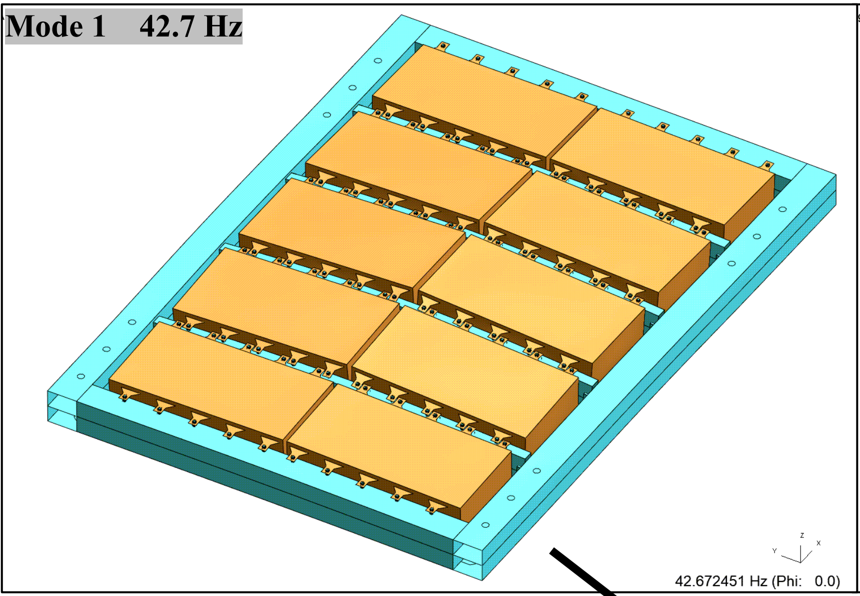
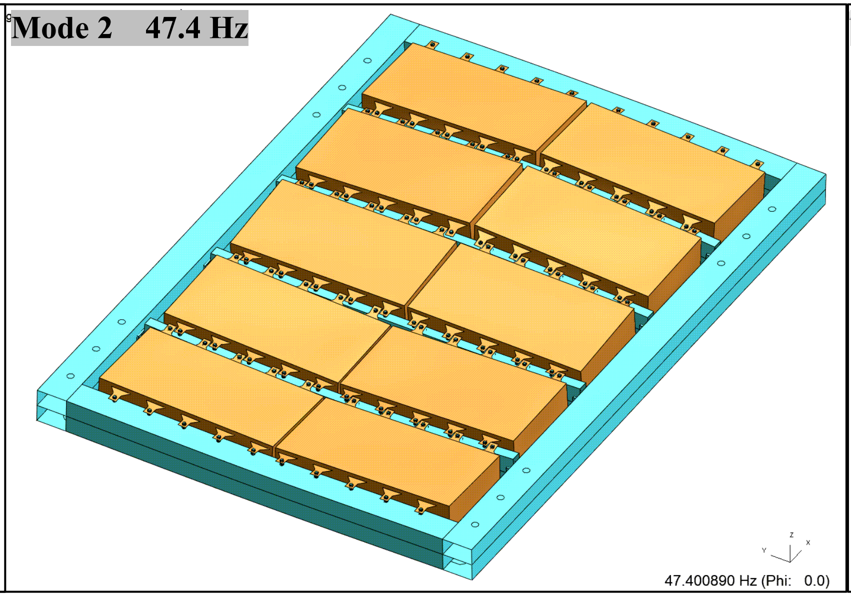
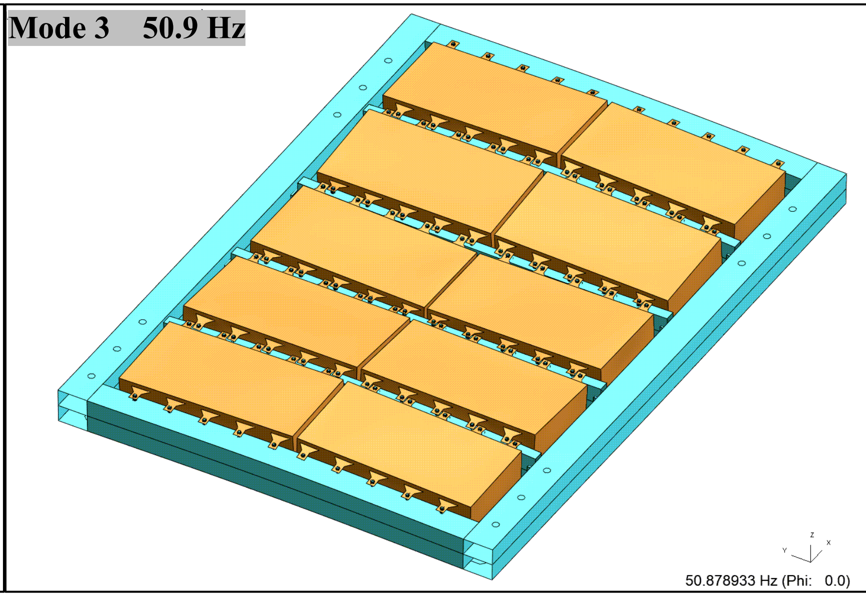
Modal analysis results







From the modal analysis results…

Estimate the number of **cycles within the load case** ($n_{load\ case}$):

$$n_{load\ case} = (12*60*60) \text{ sec} * 42.7 \text{ Hz} = \mathbf{1,844,640 \text{ cycles}}$$

Noting that the load case duration is 12 hours, and assuming vibration purely at the dominant modal frequency of the structure (42.7 Hz) †

† note that there are other methods to estimate the number of cycles within the load case

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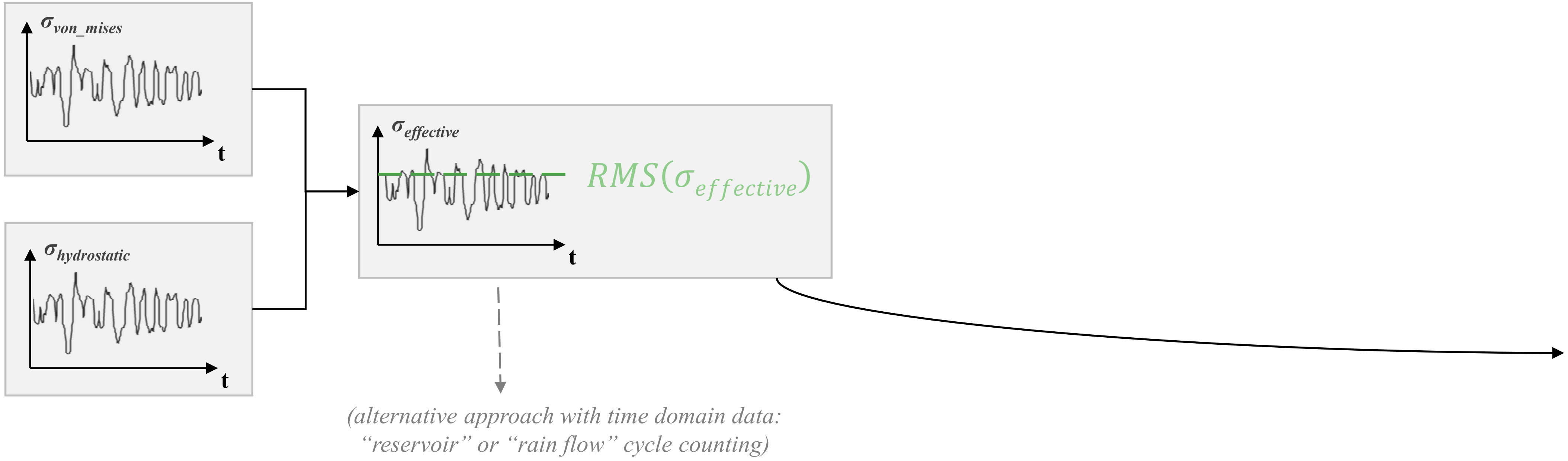
Fatigue assessment: adhesive

The number of **cycles to failure** ($n_{failure}$) for the **adhesive**:

- Requires appropriate values of stress range to be mapped onto the adhesive S-N curve
- ***Sousa method***: using an "effective stress", defined in a paper by *Sousa et al* [1]:

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

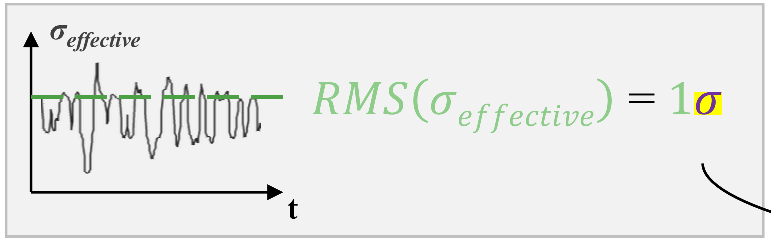
- This "effective stress" was found to correlate best to overall adhesive fatigue damage

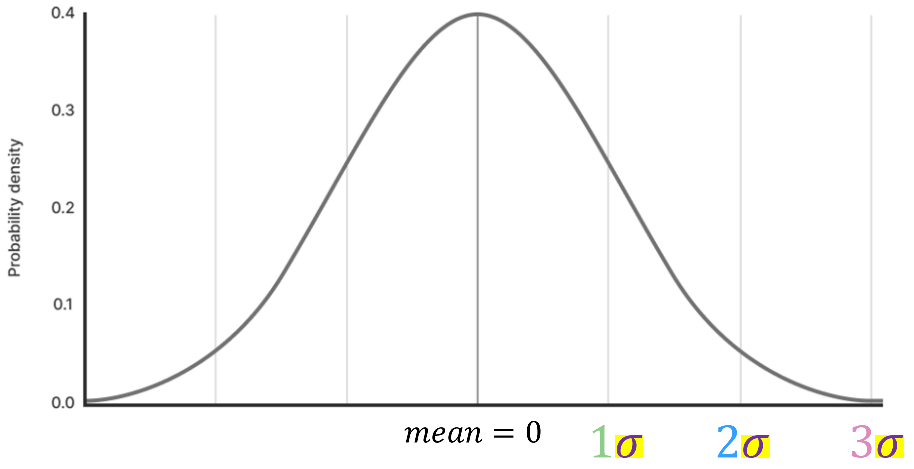


[1] *F. Castro Sousa, A. Akhavan-Safar, R. Goyal, L.F.M. da Silva (2022) Fatigue life estimation of adhesive joints at different mode mixities, The Journal of Adhesion, 98:1, 1-23*

Fatigue assessment: adhesive

- One of many methods for fatigue damage assessment
- Using the ***Steinberg 3-band method***, which assumes a Gaussian distribution of stress
- The stress range is at:
  - the one standard deviation value (1σ = RMS[†]) of mean for 68.3% of the time
  - 2σ for 27.1% of the time
  - 3σ for 4.3% of the time





[†] the Root Mean Square average of the stress time history

σ = the value at ***one standard deviation*** on a Gaussian (normal) distribution

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Fatigue assessment: adhesive

Using the ***Steinberg 3-band method***

$$N_1 = 10^{\frac{(\ln(1\sigma) - b)}{m}} \quad \text{where } 1\sigma = RMS(\sigma_{effective})$$

$$N_2 = 10^{\frac{(\ln(2\sigma) - b)}{m}} \quad 2\sigma = 2 * (1\sigma)$$

$$N_3 = 10^{\frac{(\ln(3\sigma) - b)}{m}} \quad 3\sigma = 3 * (1\sigma)$$

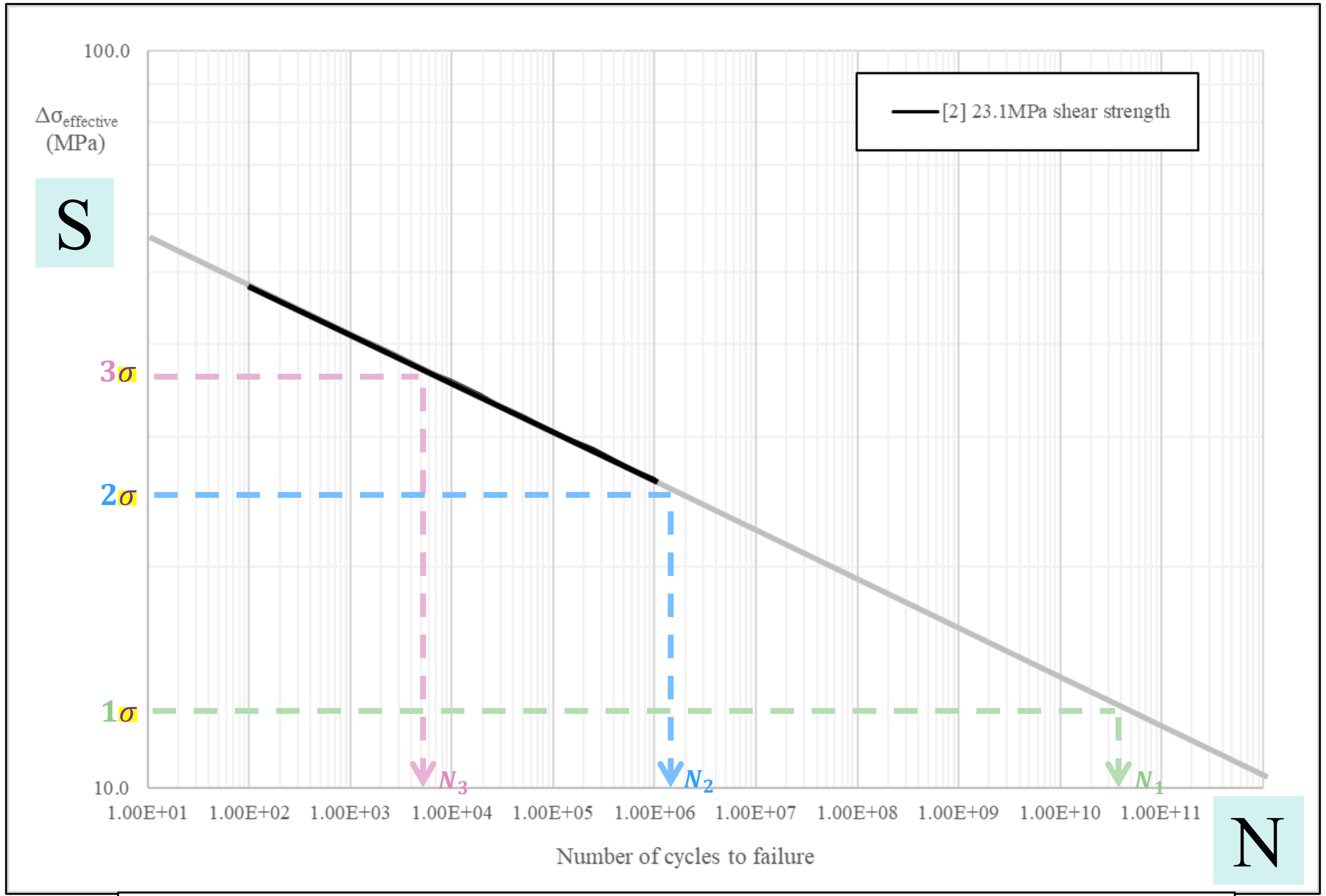
$$n_{failure} = 1.0 \,/\, \left(\frac{0.683}{N_1} + \frac{0.271}{N_2} + \frac{0.043}{N_3}\right)$$

$Fatigue\ damage$

$$= \frac{n_{load\ case}*}{n_{failure}}$$

$$= \frac{\textit{\#cycles during the vibration test}}{\textit{\#cycles at which adhesive will fail}}$$

Note: *Damage > 1 is a prediction of fatigue failure*



Castra Sousa, F, Akhavan-Safar, A, Goyal, R, da Silva, L.F.M. Fatigue life estimation of single lap adhesive joints using a critical distance criterion: An equivalent notch approach . Mechanics of Materials 2021;153

* e.g. 1,844,640 cycles

σ = the value at ***one standard deviation*** on a normal (Gaussian) distribution

Fatigue assessment: aluminium

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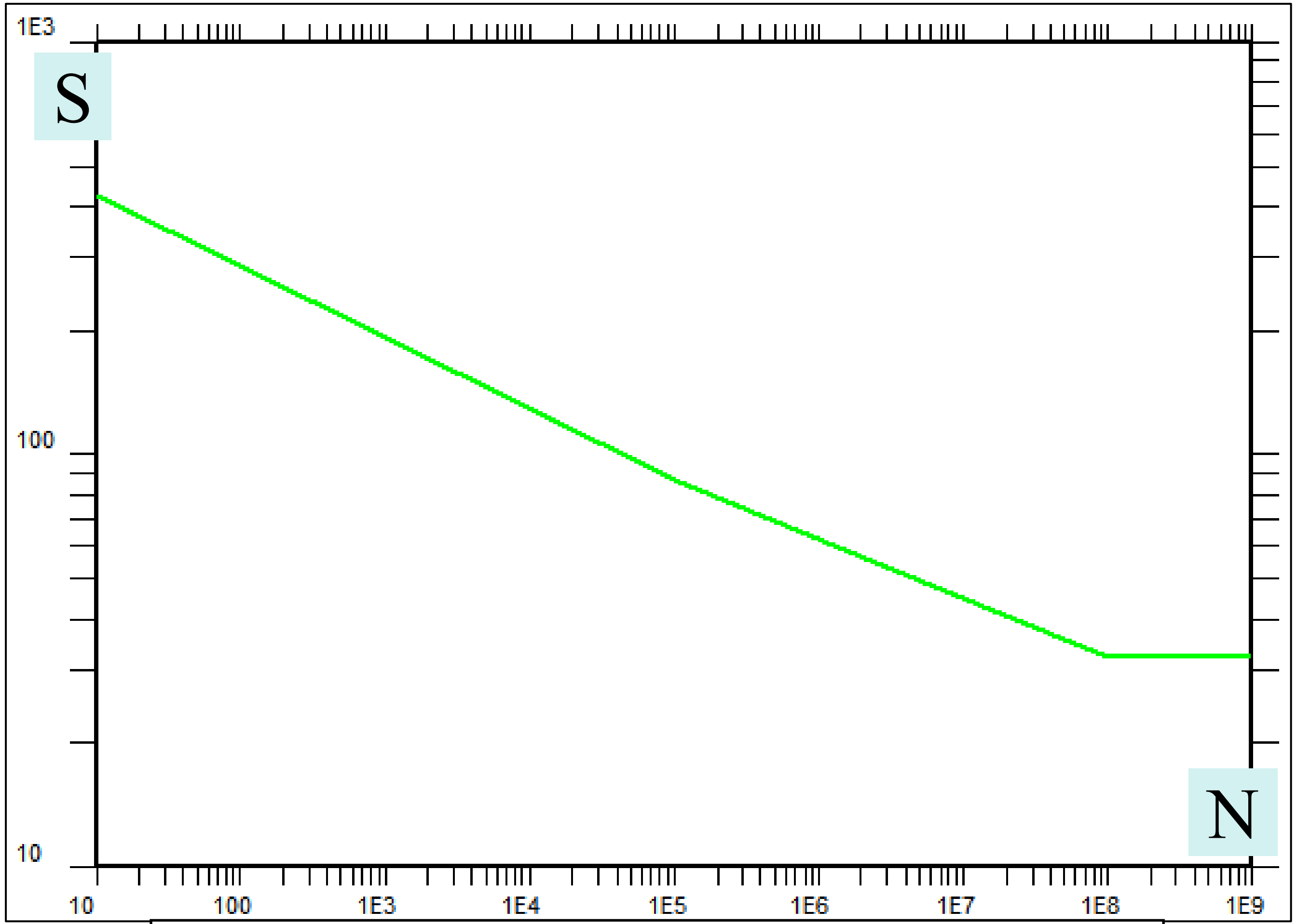
Using the ***Dirlik method***

- Embedded within LS-DYNA
- Converts the PSD into a PDF (probability density function)† to create stress ranges
- Using input exposure time (12*60*60 sec)
- Performs $n_{failure}$ and $n_{load\ case}$ calculations



BS EN 1999-1-3:2007 Eurocode 9: Design of aluminium structures
Part 1-3: Structures susceptible to fatigue
"125-7" from Figure J.1 / Table J.2

$Fatigue\ damage$

$$= \frac{n_{load\ case}}{n_{failure}}$$

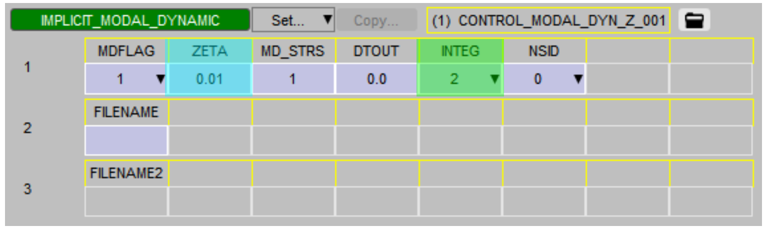
$$= \frac{\#cycles\ during\ the\ vibration\ test}{\#cycles\ at\ which\ aluminium\ will\ fail}$$

Note: $Damage > 1$ *is a prediction of fatigue failure*

† the Dirlik method PDF expression was originally derived from empirical simulations, using Monte Carlo sampling

*CONTROL_IMPLICIT_MODAL_DYNAMIC

- Implicit time-domain analysis using modal superposition
- First computes a modal analysis (**`*CONTROL_IMPLICIT_EIGENVALUE`**)
- Applies the transient loading (using **`*LOAD_BODY`**, for X, Y, and Z separately)
- ZETA = modal damping ratio = 0.01 (1%$_{critical}$)
- INTEG = computed with implicit time integration
- Uses modal superposition to obtain an overall response (a linear combination of the transient results), using all modes from **`*CONTROL_IMP_EIGENVALUE`** (NEIG)



- This modal transient approach is more efficient than a direct transient analysis
- Fatigue damage is calculated separately during post-processing, therefore an S-N curve is not given as input to LS-DYNA (refer back to the explanation of the ***Steinberg 3-band method*** and ***Sousa method*** for assessing the adhesive)

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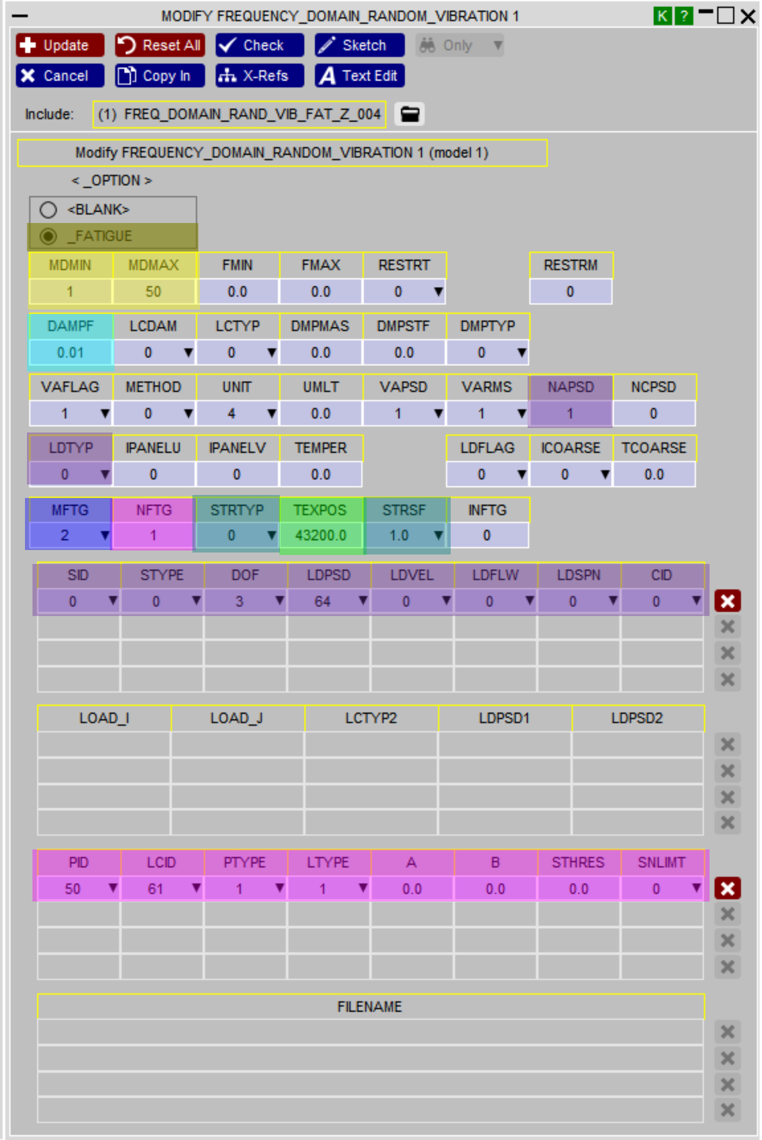
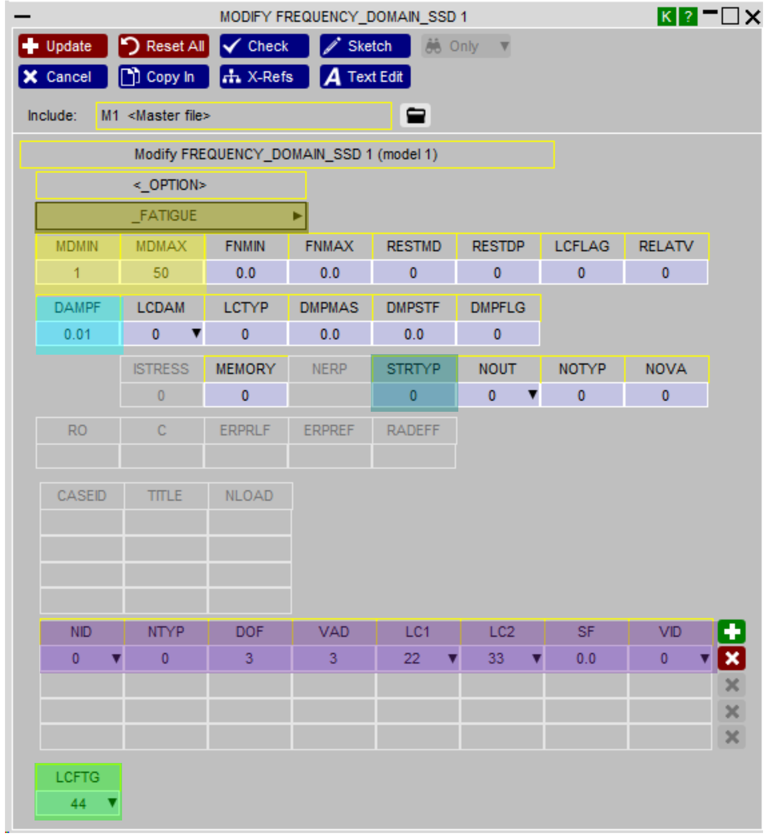
*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE

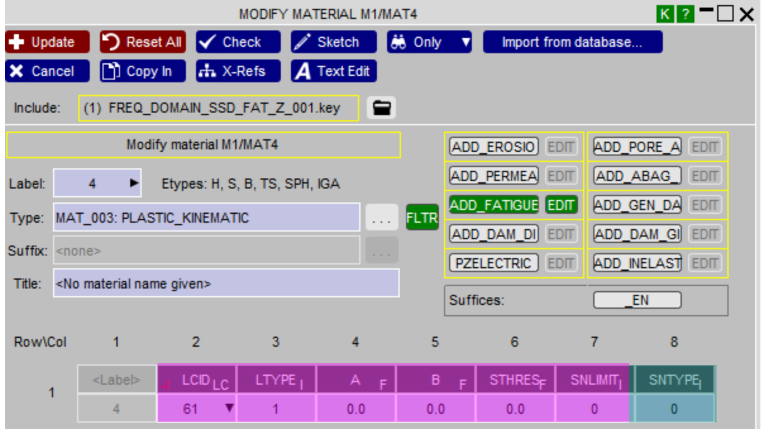
- Implicit frequency-domain analysis using modal superposition
- First computes a modal analysis (**`*CONTROL_IMP_EIG`**)
- Range of modes used for modal superposition
- DAMPF = modal damping ratio = 0.01 (1%$_{\text{critical}}$)
- STRTYP, STRSF = using Von Mises stress, stress range
- TEXPOS = exposure time to the PSD (i.e. length of vibration test) = 12*60*60 = 43200 sec
- Using PSDs (g^2/Hz), with separate analyses for X, Y, Z
- **`_FATIGUE`** option computes cumulative damage
- Fatigue analysis method (2 = ***Dirlik method***)
- S-N curve to be applied to all aluminium parts



*FREQUENCY_DOMAIN_SSD_FATIGUE

- Implicit frequency-domain analysis using modal superposition
- First computes a modal analysis (***CONTROL_IMP_EIG**)
- Range of modes used for modal superposition
- DAMPF = modal damping ratio = 0.01 (1%$_{\text{critical}}$)
- STRTYP = using Von Mises stress
- LCFTG = the duration of each frequency during the vibration test = 1*60*60 = 3600 sec @ 24 Hz
- Acceleration @ 24 Hz, with separate analyses for X, Y, Z
- **_FATIGUE** option computes cumulative damage
- S-N curve to be applied to all aluminium and adhesive parts (defined using ***MAT_ADD_FATIGUE**)
- SNTYP = using stress range





Fatigue assessment: considerations

- Sensitivity of fatigue damage results to inputs:
  - Modal damping – 1%, 2%, 3% – what is real/conservative?
  - Number of modes used in modal superposition – 25, 50, 100 – sufficient for a converged solution
  - Mesh resolution (number of elements), element quality – sufficient for a converged solution
  - Analysis verification with sensitivity studies is recommended
- If fatigue damage is above/below targets:
  - Local structural modifications to increase/reduce stiffness/mass
  - Resizing or redistributing the adhesive bond area
  - In combination with other load cases (also needs to meet other requirements; crash, NVH, etc…)

Now to look at some example results …

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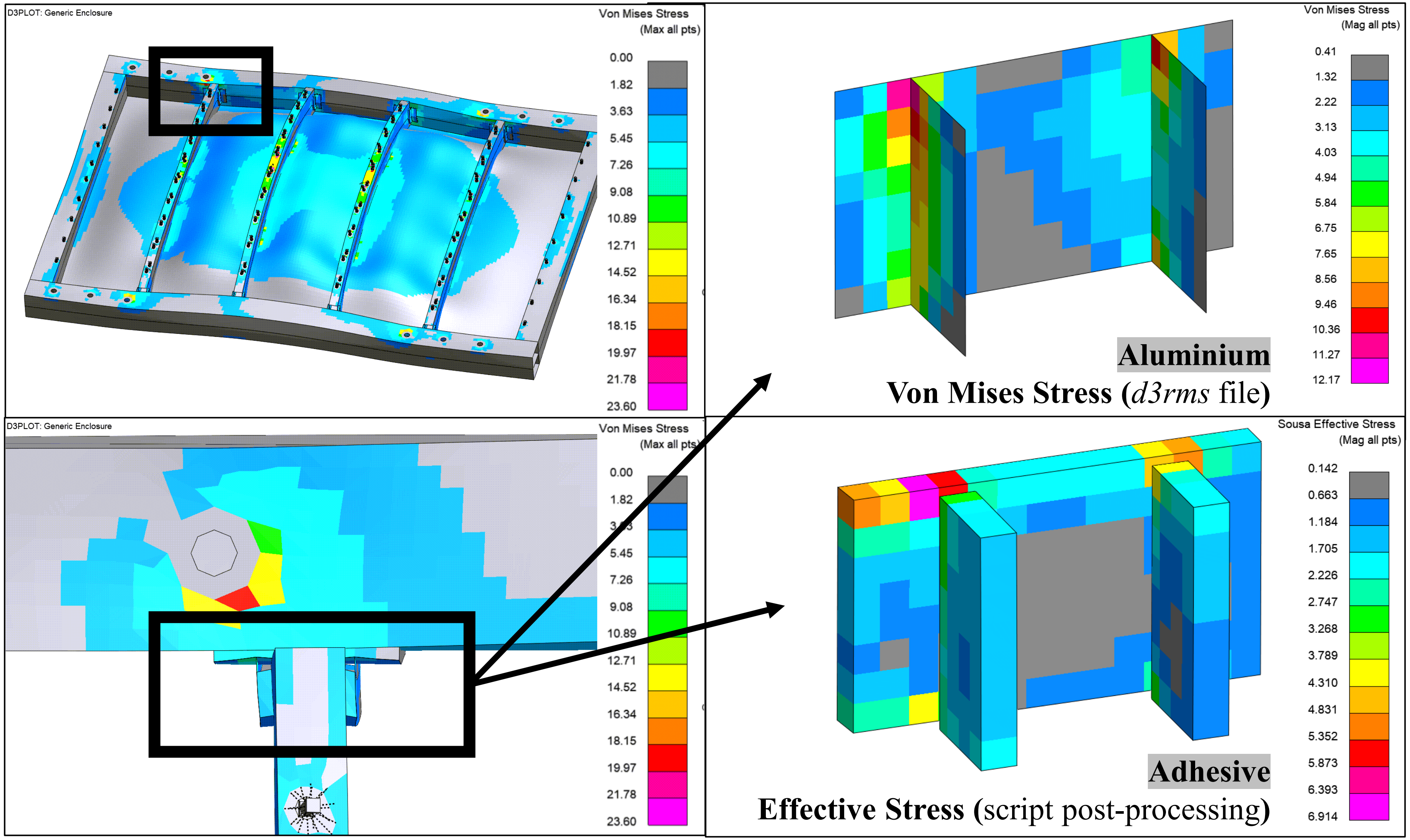
Fatigue assessment: stress results



Element stresses

- From Z PSD random vibration
- Aluminium peak 3σ = 24*3 = 72MPa (compared to yield 360MPa)
- Adhesive peak 3σ = 7*3 = 21MPa (compared to bond shear failure 25MPa)

σ = the value at ***one standard deviation*** on a normal (Gaussian) distribution

Fatigue assessment: stress results

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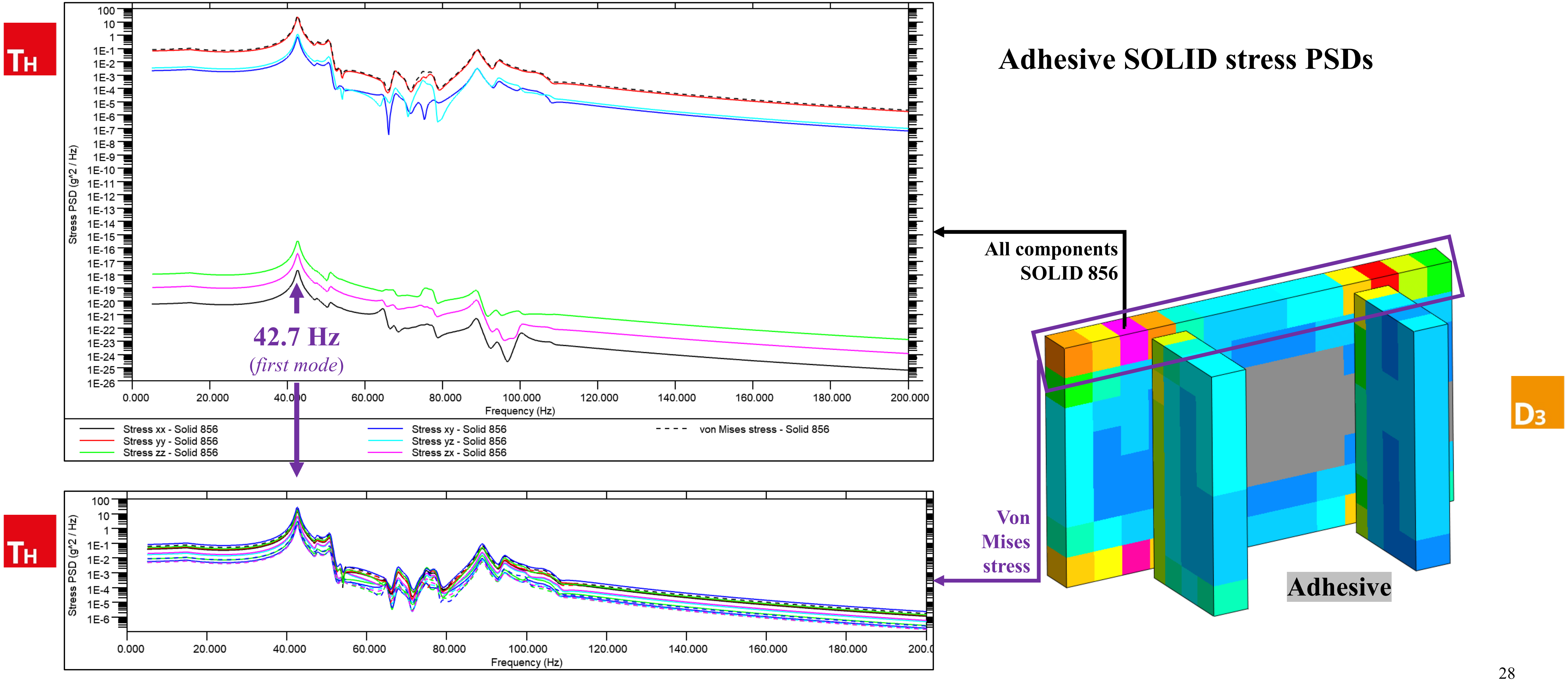

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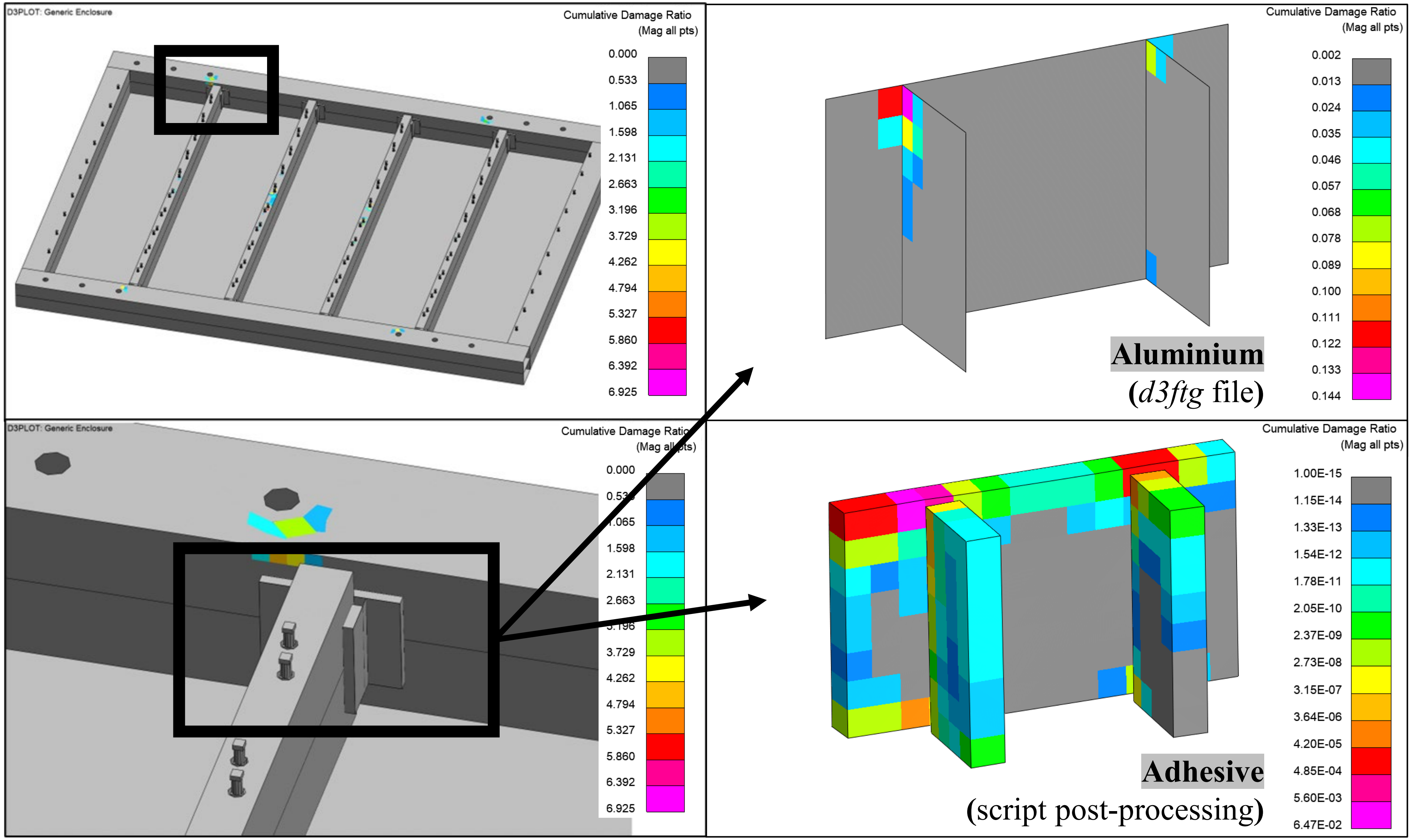
Fatigue assessment: damage results



Fatigue damage

- From Z PSD random vibration
- *In this example:*
- Aluminium predicted to fail locally before the adhesive bond
- However, the joint should be safe during enclosure's operational life

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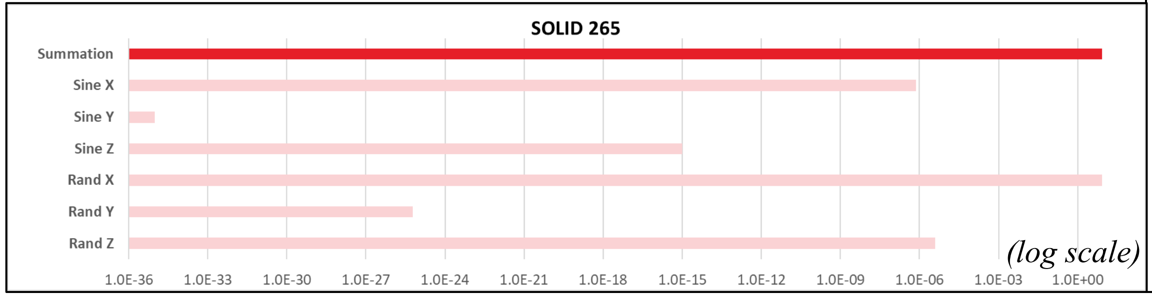
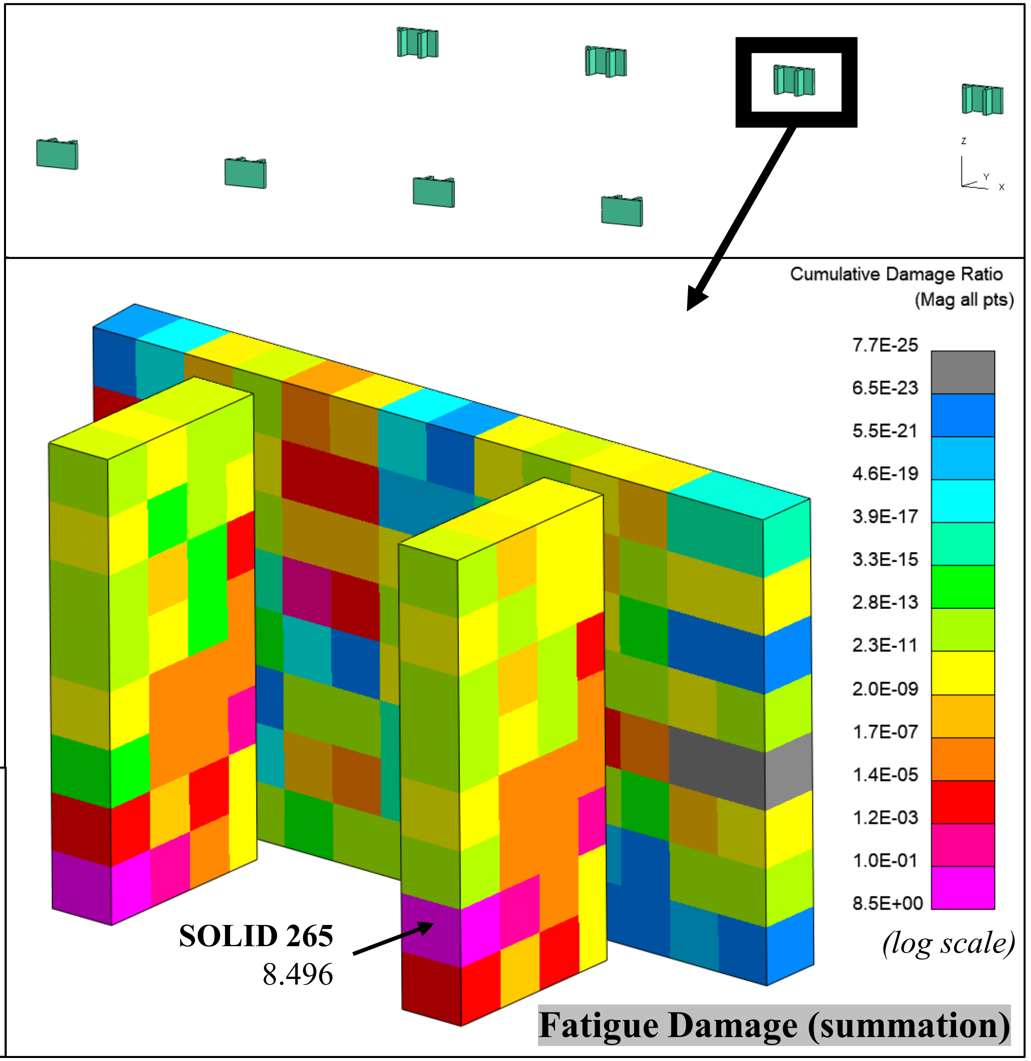
Fatigue assessment: adhesive damage

- Linear summation (6 load cases)
- For example, **adhesive** SOLID 265

Adhesive SOLIDs					
Fixed sine wave			**Random vibration**		
Z	Y	X	Z PSD	Y PSD	X PSD
(analysed in the frequency domain) `*FREQUENCY_DOMAIN_SSD_FATIGUE`			*(analysed in the time domain)* `*CONTROL_IMPLICIT_MODAL_DYNAMIC`		
Fatigue Damage 1E-15	Fatigue Damage 1E-35	Fatigue Damage 7E-7	Fatigue Damage 4E-6	Fatigue Damage 6E-26	Fatigue Damage 8.496
Fatigue Damage (summation - SOLID 265) 8.496					





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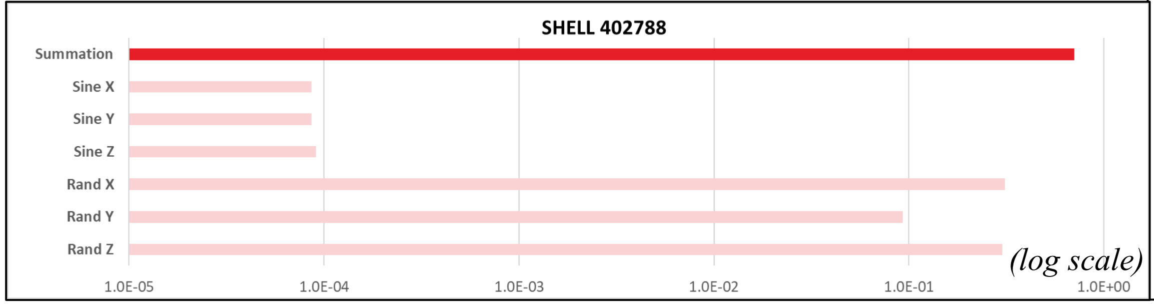
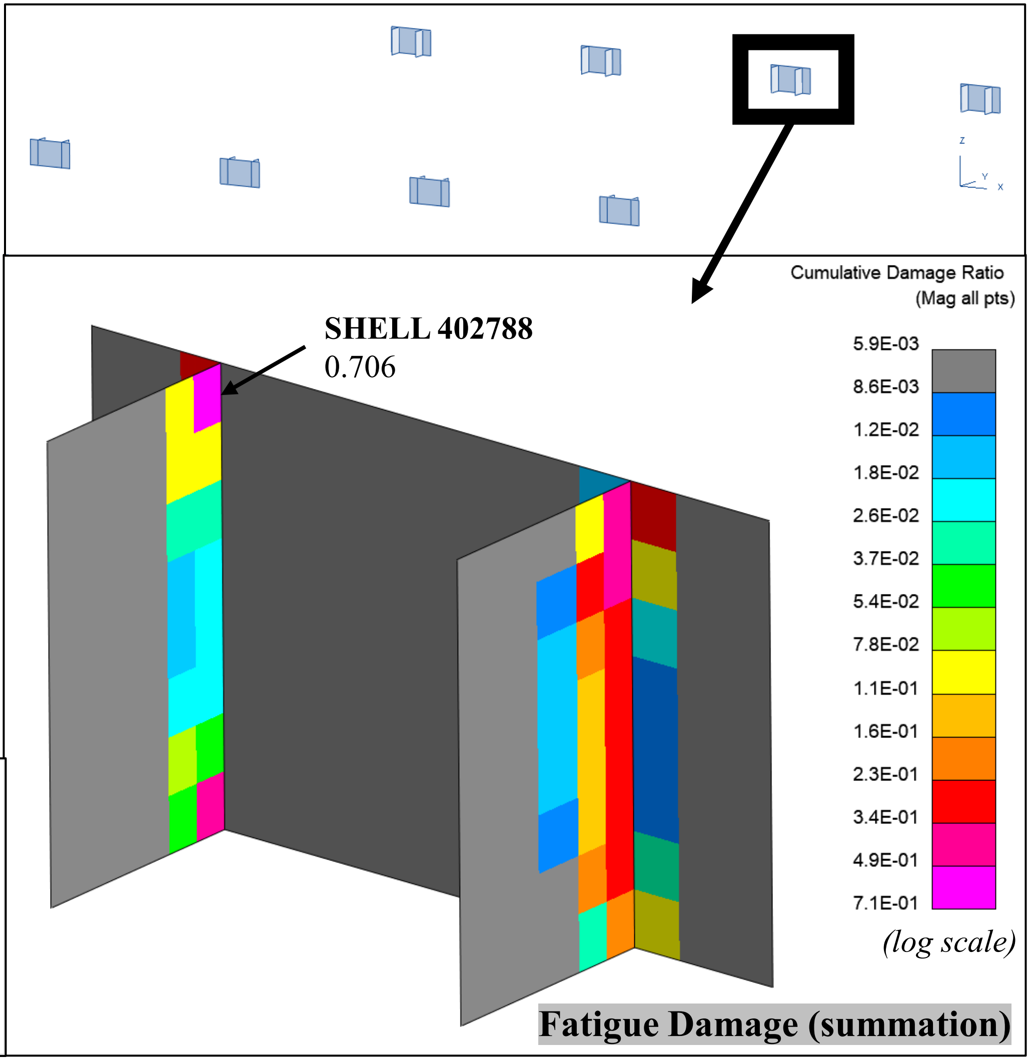
Fatigue assessment: aluminium damage

- Linear summation (6 load cases)
- For example, **aluminium** SHELL 402788

Aluminium SHELLs					
Fixed sine wave			**Random vibration**		
Z	Y	X	Z PSD	Y PSD	X PSD
(analysed in the frequency domain) ***FREQUENCY_DOMAIN _SSD_FATIGUE**			*(analysed in the frequency domain)* ***FREQUENCY_DOMAIN _RANDOM_VIBRATION_FATIGUE**		
Fatigue Damage 0.000091	**Fatigue Damage** 0.000086	**Fatigue Damage** 0.000086	**Fatigue Damage** 0.301019	**Fatigue Damage** 0.092770	**Fatigue Damage** 0.311591
Fatigue Damage (summation - SHELL 402788) 0.706					





Fatigue assessment: overall methodology

	Adhesive SOLIDs						Aluminium SHELLs					
Inputs	**Random vibration**			**Fixed sine wave**						**Random vibration**		
	Z PSD	Y PSD	X PSD	Z	Y	X	Z	Y	X	Z PSD	Y PSD	X PSD
Implicit keyword	*(analysed in the time domain)* `*CONTROL_IMPLICIT_MODAL_DYNAMIC`			*(analysed in the frequency domain)* `*FREQUENCY_DOMAIN_SSD_FATIGUE`						*(analysed in the frequency domain)* `*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE`		
Outputs	** output data for each load case, on an element-by-element basis* Stress Components, Von Mises Stress, Hydrostatic Stress etc											
	Sousa Effective Stress	Sousa Effective Stress	Sousa Effective Stress	Sousa Effective Stress	Sousa Effective Stress	Sousa Effective Stress						
	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage	Fatigue Damage
	Fatigue Damage (summation) *for each adhesive element*						Fatigue Damage (summation) *for each aluminium element*					

Benefits of LS-DYNA implicit fatigue methodology

For adhesive fatigue assessment:

Oasys | LS-DYNA ENVIRONMENT

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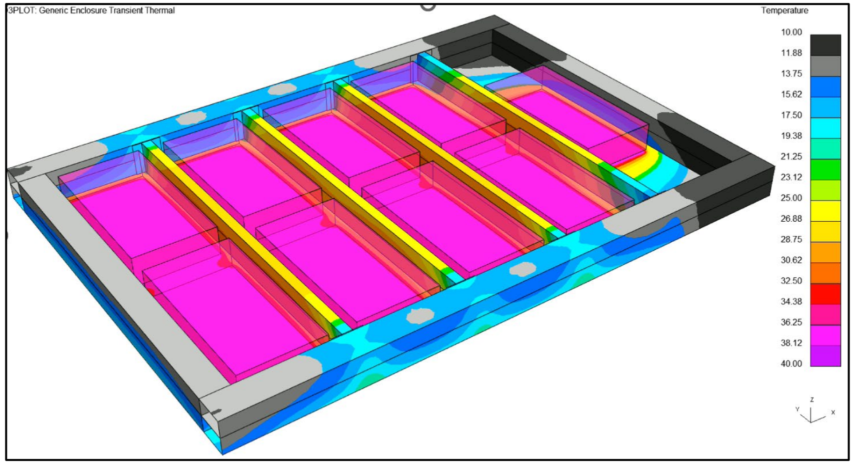
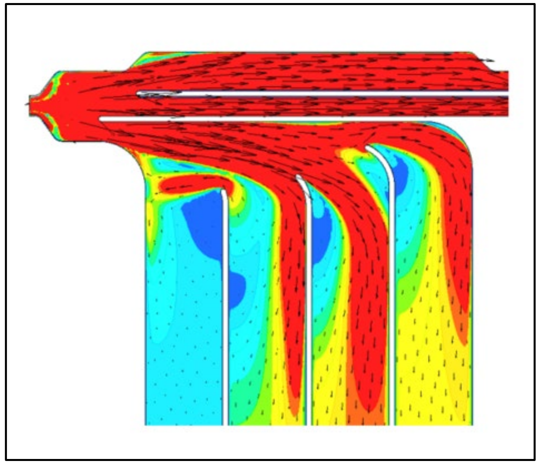
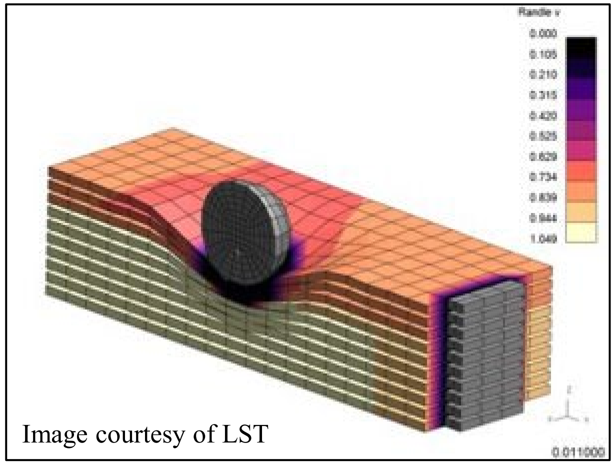
Automotive consulting → **EV battery consulting**

Transient thermal analysis

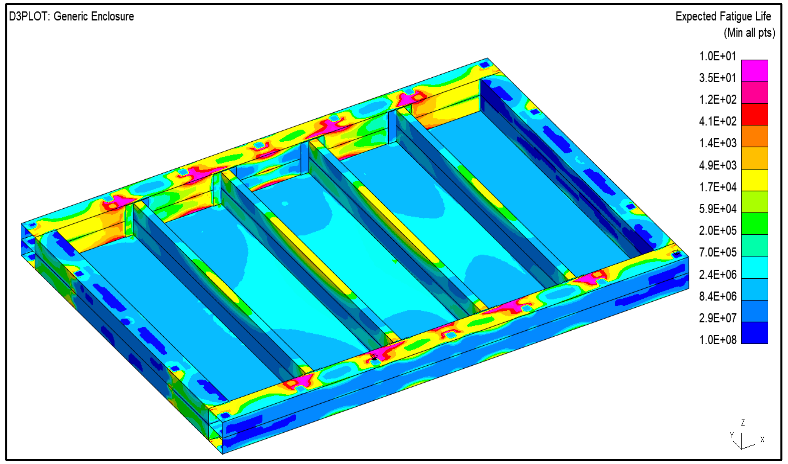


Coolant flow optimisation





Cell penetration analysis



Fatigue analysis

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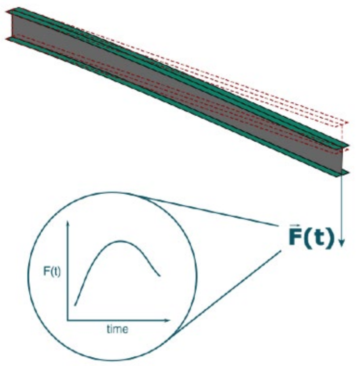
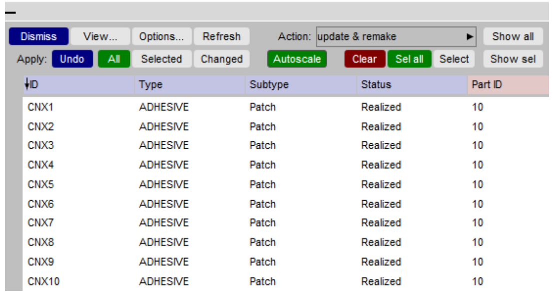
Oasys | LS-DYNA ENVIRONMENT

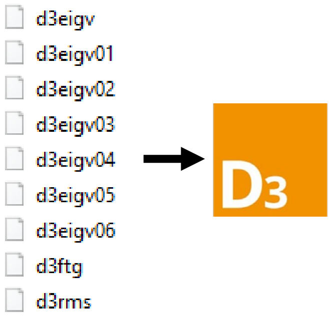
Automotive consulting → **EV battery consulting** → **EV battery enclosure fatigue** → **Oasys software tools used**



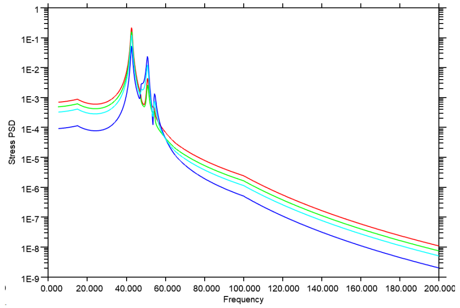
PRIMER implicit setup tool



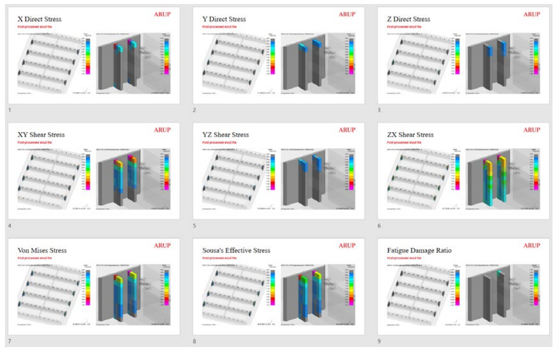
PRIMER connections tool



D3PLOT for d3rms, d3ftg, d3ssd



T/HIS for PSD results



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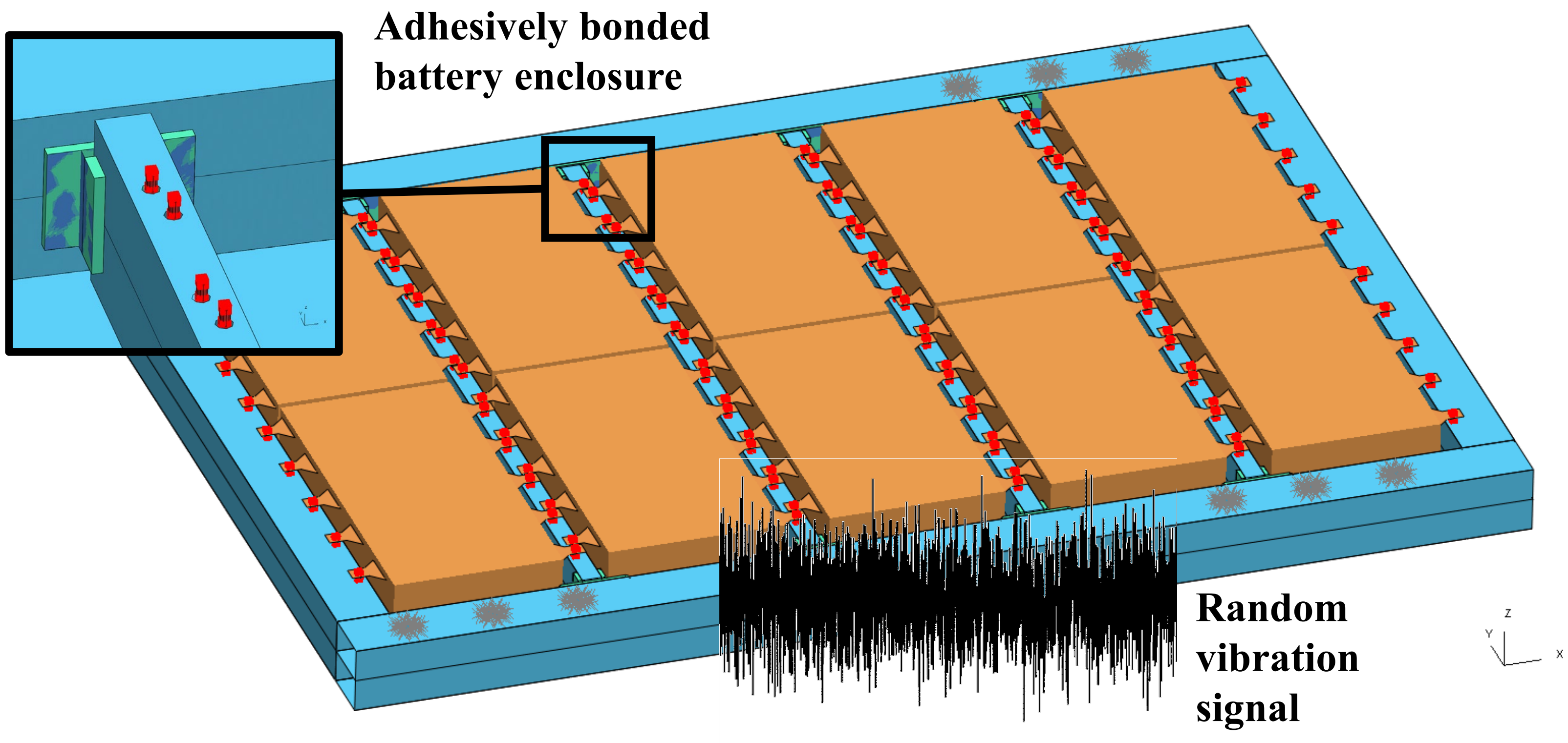

Thank you!