Random Vibration Fatigue Analysis of a Multi-material Battery Pack Structure

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August 1, 2023

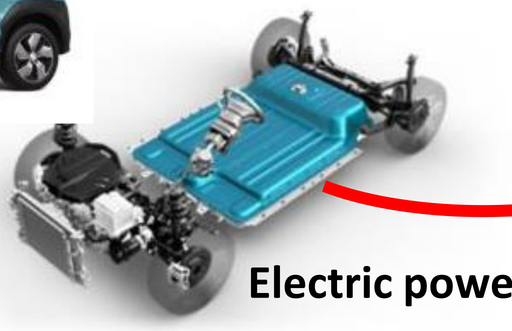
UNIST CMSLab Composite Materials and Structures Laboratory ICCM 23 INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS

Introduction

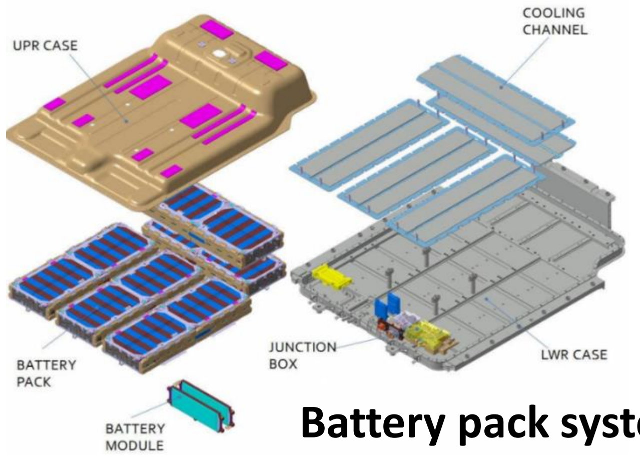
- Electric motors are appealing as power source for eco-friendly automotives
- Weight reduction for fuel efficiency → possibly in battery pack component
  - Increasing usage of fiber-reinforced plastic (FRP) due to high specific stiffness
- Concern: steady random vibration loading during drive
  - Fatigue life of the structure must be considered
  - Possible reduction in design costs by using numerical method
- In this research,

Numerical fatigue analysis of a multi-material battery pack through a typical mode-based approach

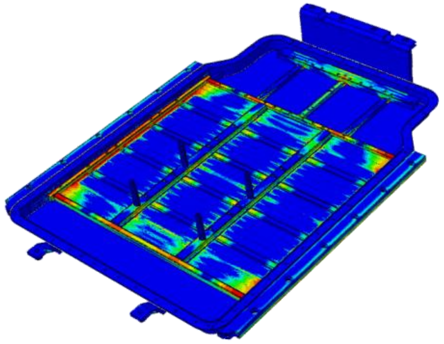
Ex. Hyundai KONA



Electric powertrain



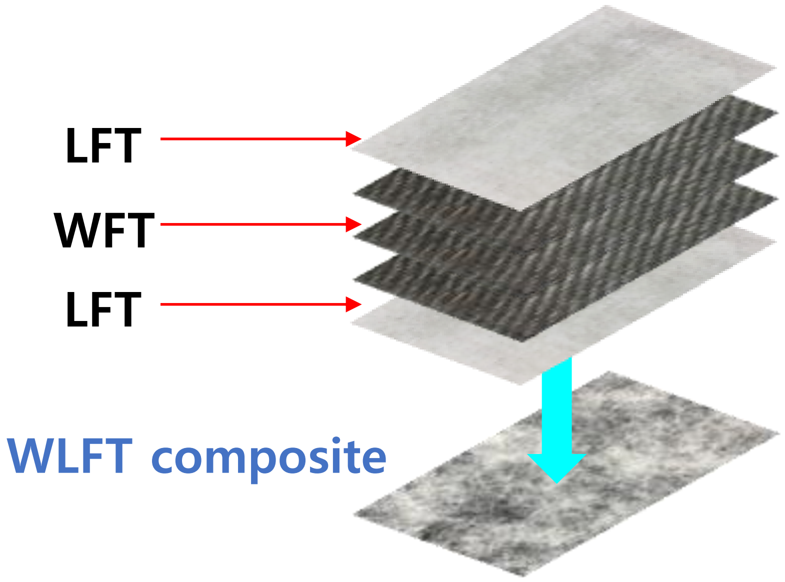
Battery pack system

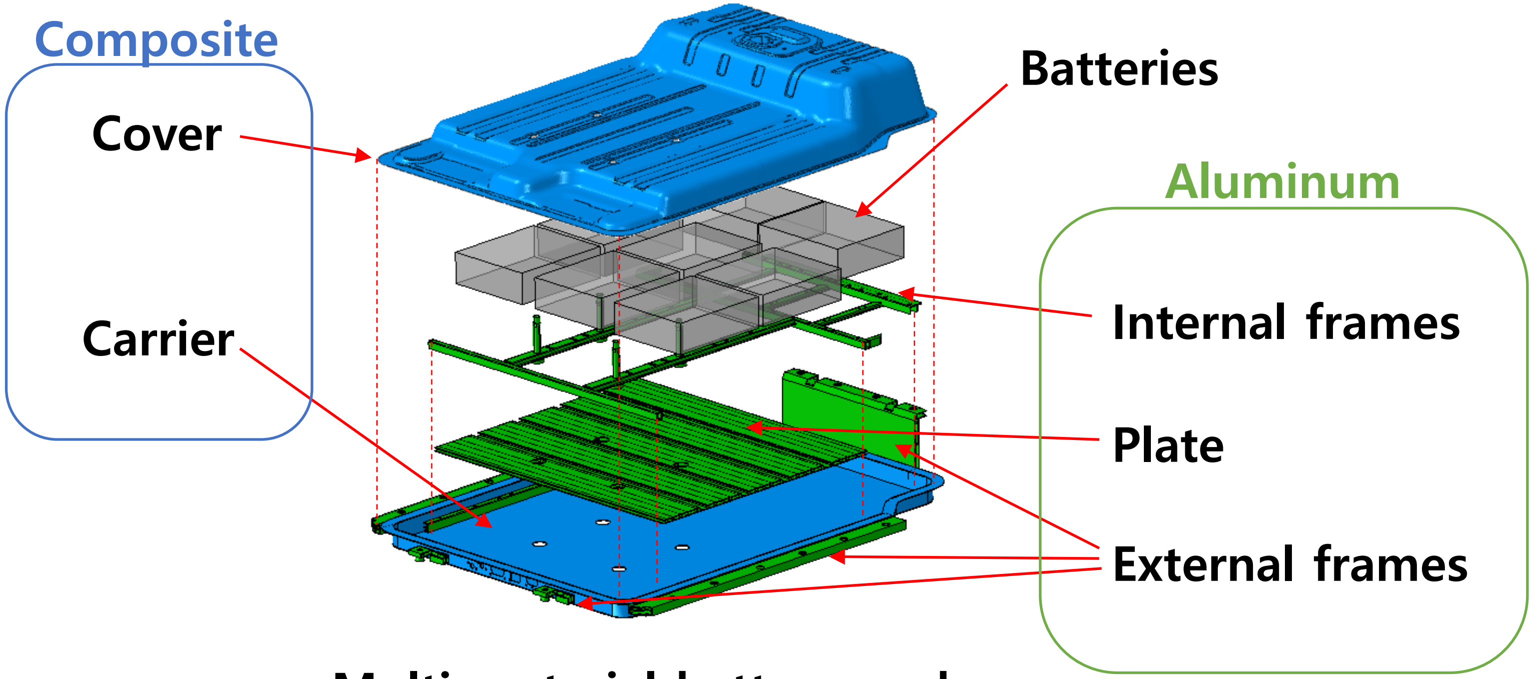


Fatigue life prediction

Composite material

- The multi-material battery pack consists of metal frames and composite casings
- Proposed composite structure
  - Laminate structure: $[LFT_1/WFT_3/LFT_1]_T$ (0.7 mm thickness)
  - LFT : Long Fiber Thermoplastic (discontinuous glass fiber/Polypropylene)
  - WFT : Woven Fiber Thermoplastic (2/2 twill woven glass fiber/Polypropylene)





Multi-material battery pack

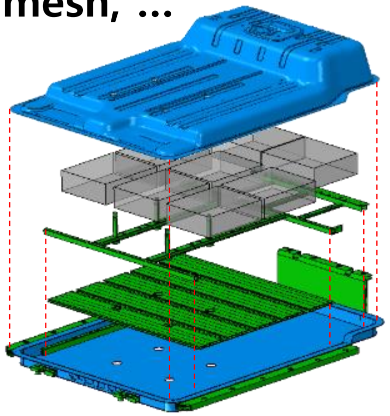
Flowchart of the analysis 1/2

Evaluation stage Obtain vibration properties of the structure

(1) FE modelling (p.6)

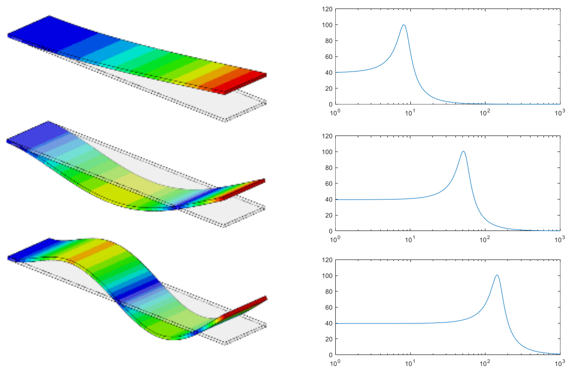
Numerical model of multi-material battery pack

Geometry, mesh, …



(2) Frequency analysis (p.7)

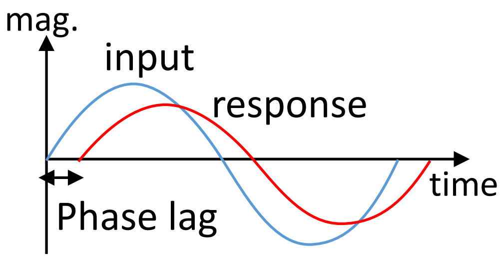
Extract natural modes and natural frequencies

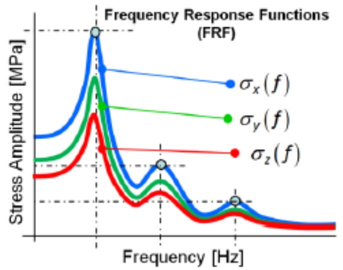


(3) Harmonic response analysis (p.8)

Response functions over freq. (amplitude & phase lag) expressing harmonic response

for each natural mode
for each node
for each stress component

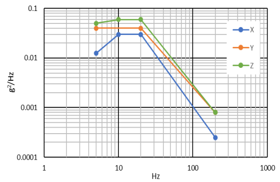




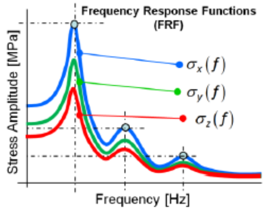
Flowchart of the analysis 2/2

Fatigue analysis stage Apply <u>random vibration loading</u> to the structure

(4) Loading and response (p.9)



Vibration loading defined over freq.



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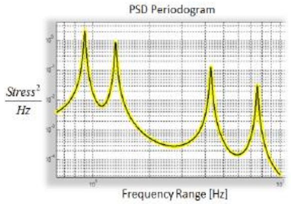
Response functions

=



Amplitude distribution over freq.

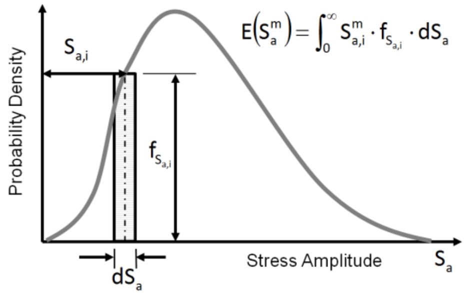
(5) Vibration counting (p.10)

<u>Dirlik's method</u>

Amplitude-frequency relation

⇩

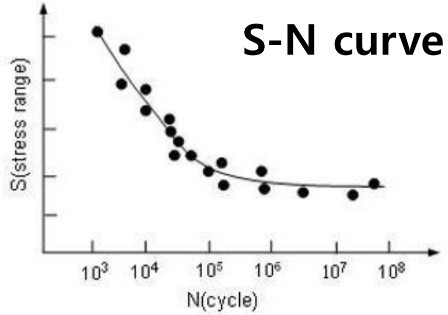
Probability-amplitude relation



(6) Life prediction (p.11)

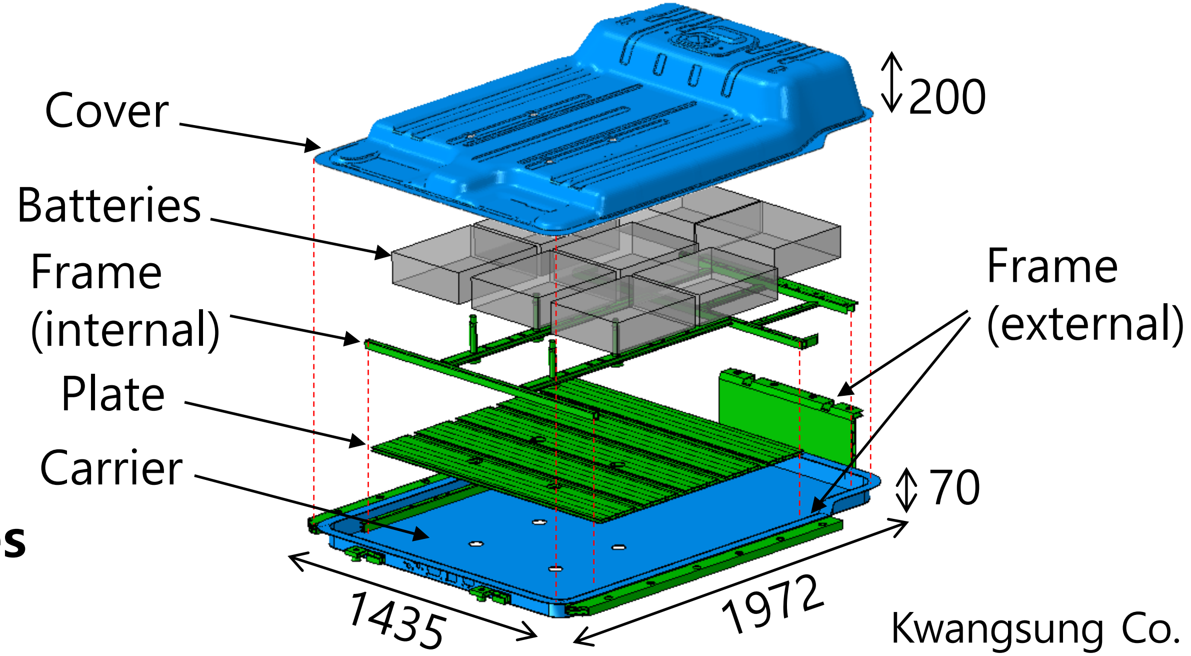
Linear damage accumulation

Fatigue life prediction



Finite Element Modelling

- **Multi-material structure**
  - **Composite : Cover, Carrier**
  - **Aluminum : Frames, Plate**
  - **Rigid body : Batteries**
- **Composite: [LFT$_1$/WFT$_3$/LFT$_1$]$_T$ (0.7 mm)**
- **`*TIE` constraints between connected parts**
  - **No relative motion between two surfaces**



Kwangsung Co. Ltd.

- **Elements of parts:**

Parts		Material	Element type	Number of elements
Cover		Composite	**Shell** (S4R)	61034
Carrier			**Continuum shell** (SC8R)	33841
Frame	Internal	Aluminum	**Continuum solid** (C3D10)	54742
	External			166052
Plate				179403
Batteries		Rigid body	**Rigid solid** (R3D4)	4496×8

Frequency Analysis

- **Extraction of natural modes and natural frequencies**

Mechanical model

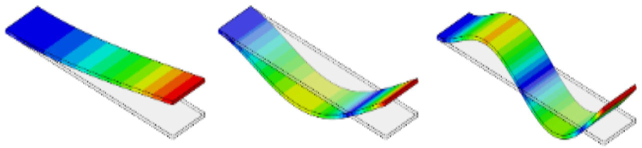
$$M^{NM}\ddot{u}^{M} + K^{NM}u^{M} = F^{N}$$

Solving eigenvalue problem

$$(-\omega_\alpha^2 M^{MN} + K^{MN})\phi_\alpha^N = 0$$

Results

- **Mode shape ϕ_α**
- **Natural frequency ω_α**



M^{MN} : mass matrix
C^{MN} : damping matrix
K^{MN} : stiffness matrix

F^{N} : load at the tip
u^{M} : displacement of the tip
M, N : degrees of freedom

α : mode number
ω_α : natural frequency
ϕ_α : mode shape

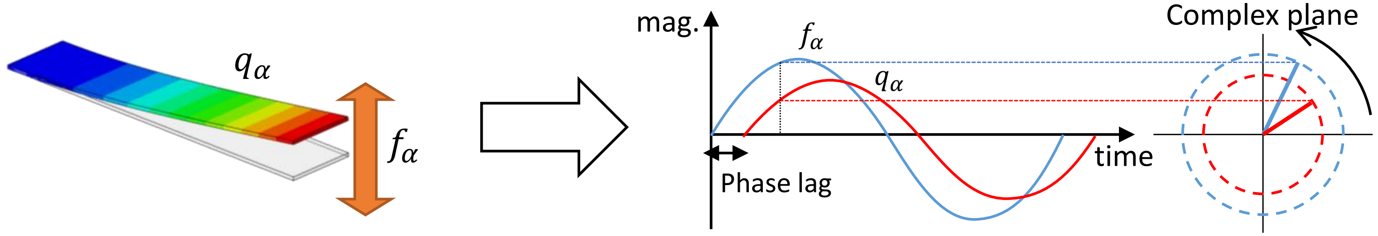
- **These natural modes are**
  - **Harmonic oscillation**
  - **Harmonic loading (input) → Harmonic motion (response)**
  - **Linear combination of modes → Any vibration shape**

→ Harmonic response analysis for relation between input and response

Abaqus 6.14 Documentation: Abaqus Theory Guide, Ch. 2.5.7 Steady-state linear dynamic analysis

Harmonic Response Analysis

- **Frequency response function (FRF), H_α (complex function)**



$$H_\alpha = \frac{A_{\text{resp}}}{A_{\text{input}}} e^{i\theta}$$

$$q_\alpha(f) = H_\alpha(f)\, f_\alpha(f)$$

Response　Input

A_{input} : amplitude of **input loading**
A_{resp} : amplitude of **response motion**
θ : phase lag
α : mode number
$f_\alpha = f_{0\alpha} e^{2\pi i f t}$: input loading
q_α : generalized displacement
f: frequency

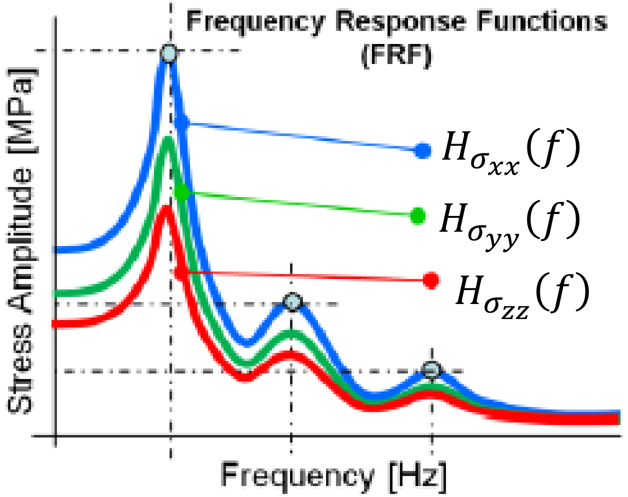
- **Obtaining stress values**

Relation with global FRF

$$\sigma_\square^i(f) = H_\square(f) F(f)$$

Response　Input

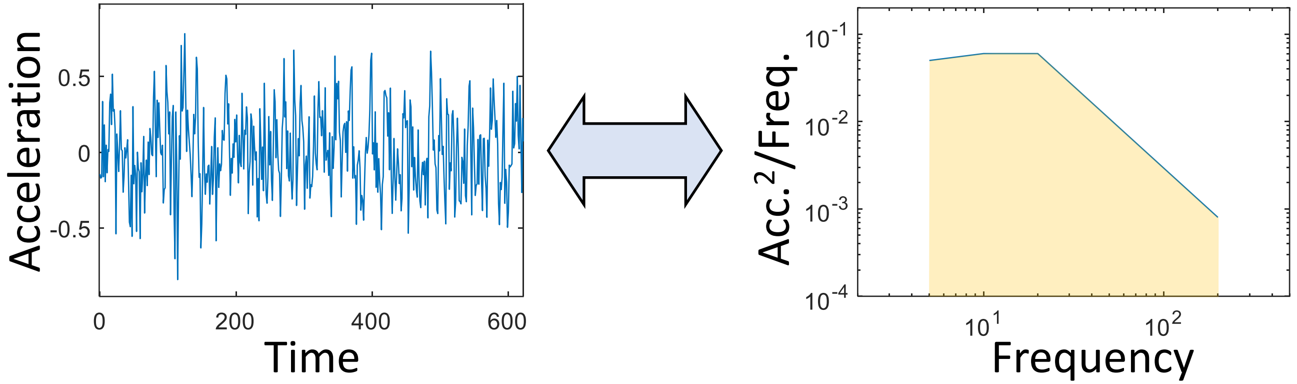
i : node number
$\sigma_\square$: $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{yz}, \tau_{zx}$



Abaqus 6.14 Documentation: Abaqus Theory Guide, Ch. 2.5.7 Steady-state linear dynamic analysis

- **Broad-band loadings in three direction**
  - **Distributed over wide range of frequencies**

Time signal **Frequency distribution (PSD)**



Loading $\mathbf{G} = \begin{bmatrix} F_x(f) & 0 & 0 \\ 0 & F_y(f) & 0 \\ 0 & 0 & F_z(f) \end{bmatrix}$

F_x, F_y, F_z : vibration in x, y, z-directions
f : frequency

- **Single vector containing six stress FRFs (for each direction)**

$$\mathbf{H}^i(f) = \left[H^i_{\sigma_{xx}}(f) \quad H^i_{\sigma_{yy}}(f) \quad H^i_{\sigma_{zz}}(f) \quad H^i_{\tau_{xy}}(f) \quad H^i_{\tau_{yz}}(f) \quad H^i_{\tau_{xz}}(f)\right]^T \quad i = 1,2,3 \ \text{(for } x, y, z\text{)}$$

- **Single response calculation**
  - **Representative response: Von Mises stress**

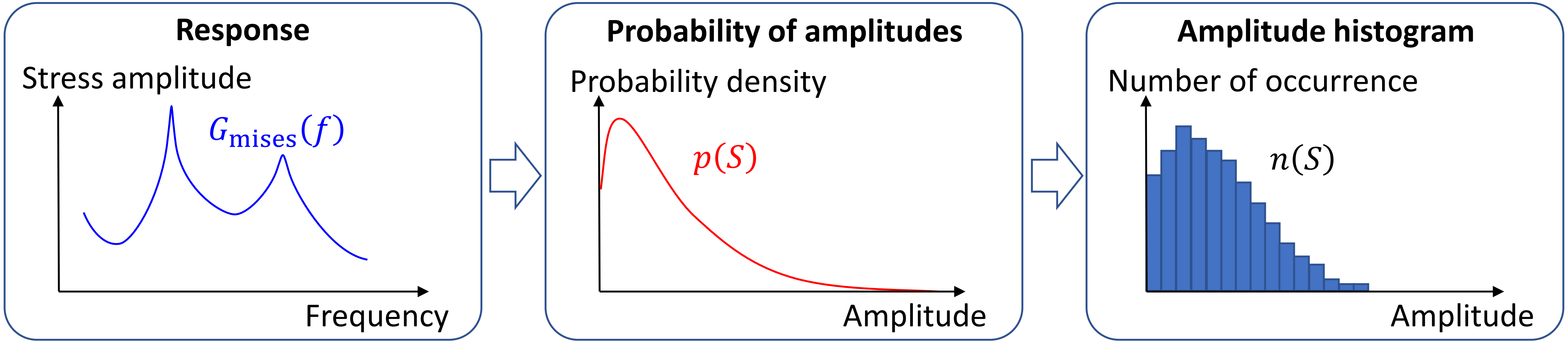
$$G_{\text{mises}}(f) = \sum_{i=1}^{3}\sum_{j=1}^{3} \left(\mathbf{H}^j\right)^* \mathbf{A}\,\mathbf{H}^i G_{ij}$$

$$\mathbf{A} = \begin{bmatrix} 1 & -0.5 & -0.5 & & & \\ -0.5 & 1 & -0.5 & & & \\ -0.5 & -0.5 & 1 & & & \\ & & & 3 & & \\ & & & & 3 & \\ & & & & & 3 \end{bmatrix}$$

$\mathbf{H}^*$: complex conjugate

T. Dirlik and D. Benasciutti, "Dirlik and Tovo-Benasciutti Spectral Methods in Vibration Fatigue: A Review with a Historical Perspective", *Metals* **2021**, 11(9), 2021.
G.M. Teixeira et al., "Random Vibration Fatigue: Frequency Domain Critical Plane Approaches", ASME, IMECE2013-62607, 2013.

- **Dirlik's method**
  - **calculates the probability of the occurrence of a certain amplitude in unit time**



- **Probability density $p(S)$ of the occurrence of an amplitude of S is**

$$p(S) = \left(\frac{c_1}{\tau} e^{-\frac{z}{\tau}} + \frac{c_2 z}{\alpha^2} e^{-\frac{z^2}{2\alpha^2}} + c_3 z e^{-\frac{z^2}{2}} \right) / (2\sqrt{m_0})$$

$$z = \frac{S}{2\sqrt{m_0}} \qquad m_n = \frac{1}{\pi} \int_0^\infty f^n G_{\text{mises}}(f) df$$

$$x_m = \frac{m_1}{m_0}\frac{\sqrt{m_2}}{\sqrt{m_4}} \qquad \gamma = \frac{m_2}{\sqrt{m_0 m_4}} \qquad c_1 = \frac{2(x_m - \gamma^2)}{1+\gamma^2} \qquad c_2 = \frac{1-\gamma-c_1+c_1^2}{1-\alpha}$$

$$\alpha = \frac{\gamma - x_m - c_1^2}{1-\gamma-c_1+c_1^2} \qquad \tau = \frac{1.25(\gamma - c_3 - c_2\alpha)}{c_1} \qquad c_3 = 1 - c_1 - c_2$$

Dassault Systemes Simulia Corp., fe-safe 2017: fe-safe USER GUIDE, 2016.
T. Dirlik, "Application of Computers in Fatigue Analysis", University of Warwick Thesis, 1985.

- **Palmgren-Miner Rule**
  - **Vibration linearly accumulates damage on the structure**
  - **Failure criterion: Fails at damage $D \geq 1$**

➢ **Damage when applied n loading cycles (fixed amplitude):**

$$D = \frac{n}{N}$$

n : number of applied loading cycles
N : fatigue life at this load level (amplitude)

➢ **Damage under variable amplitude load:**

$$D = \sum_{i=1}^{k} \frac{n(S_i)}{N(S_i)}$$

k : number of the different amplitudes
S_i : amplitudes of load
$n(S_i)$: number of cycles of amplitude S_i
$N(S_i)$: fatigue life for amplitude S_i

➢ **Damage under load according to $p(S)$:**

$$D = \int_0^{\infty} \frac{\mu\, p(S)}{N(S)} dS$$

$p(S)$: probability of amplitude S
μ : number of peaks per unit time,
$\mu = \sqrt{m_4} / \sqrt{m_2}$

⟶ **Accumulated damage per unit time**

Dassault Systemes Simulia Corp., fe-safe 2017: fe-safe USER GUIDE, 2016.
T. Dirlik, “Application of Computers in Fatigue Analysis”, University of Warwick Thesis, 1985.

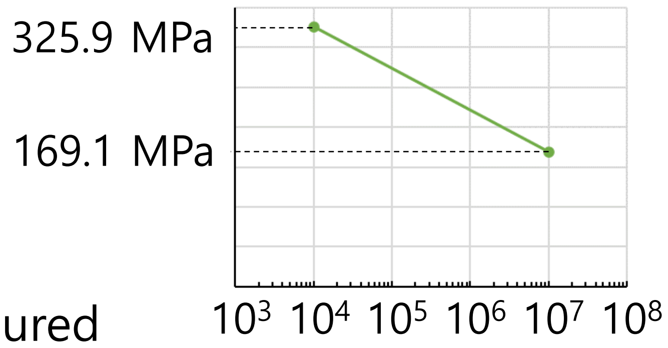
Material Properties and Applied Loadings

- **Mechanical properties and fatigue properties**

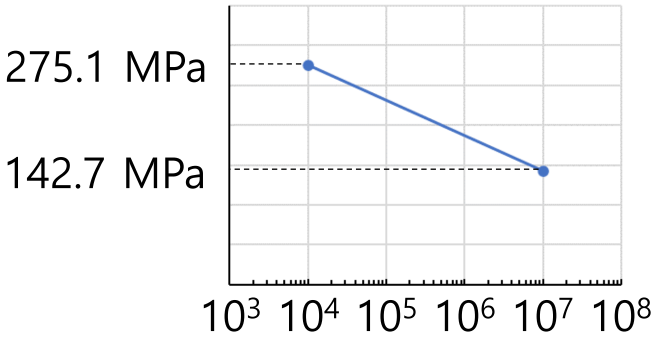
	Al [1]	**LFT***	**WFT***
E_{11}, GPa	68.9	5.49	14.30
E_{22}, GPa			11.47
ν_{12}	0.33	0.3	0.3
G_{12}, GPa	25.9	2.11	6.09

* Measured

Aluminum S-N curve [2]



Composite S-N curve [3]

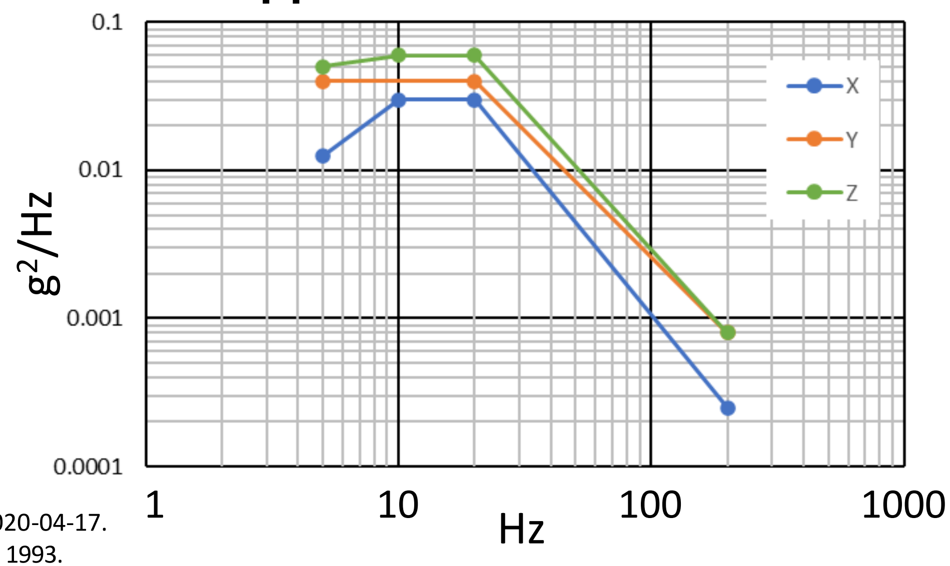


- **Applied random vibration (PSD form)**
  - **Loading time: 21 hours**

Freq. (Hz)	**X-dir. (g^2/Hz)**	**Y-dir. (g^2/Hz)**	**Z-dir. (g^2/Hz)**
5	0.0125	0.04	0.05
10	0.03	0.04	0.06
20	0.03	0.04	0.06
200	0.00025	0.0008	0.0008

Standard: GB/T 31467.3 Unit g = 9.81 m/s^2

Applied random vibration

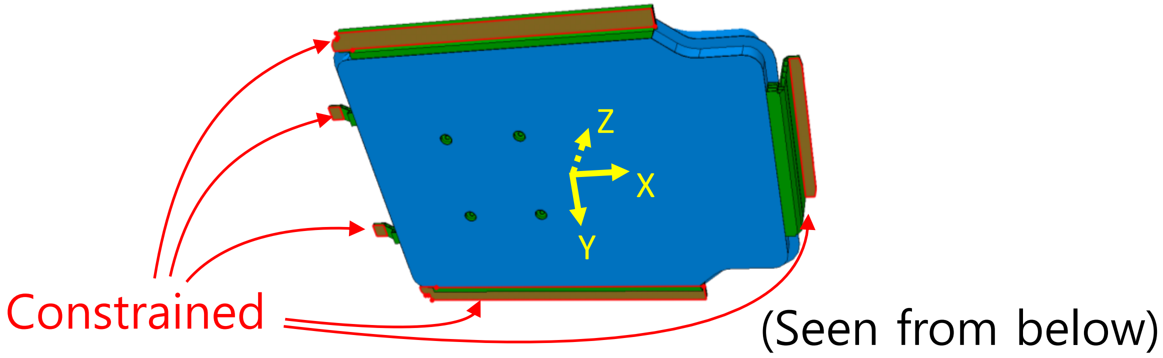


[1] ASM Matweb, "Aluminum 6061-T6; 6061-T651", http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061T6, Retrieved in 2020-04-17.
[2] Yahr, G. T. "Fatigue Design Curves for 6061-T6 Aluminum", United States, doi:10.1115/1.2842286, https://www.osti.gov/servlets/purl/10157028, 1993.
[3] Bureau, M. N. and Denault, J. "Fatigue Resistance of Continuous Glass Fiber/Polypropylene Composites: Consolidation Dependence", *Composite Science and Technology*, 64, 2004

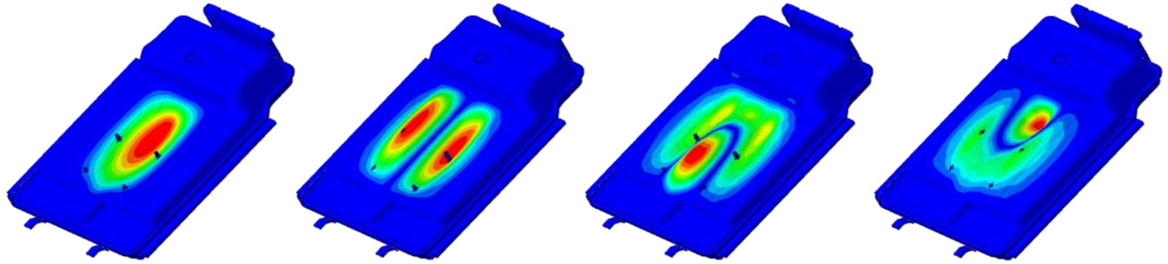
Boundary Conditions and Intermediate Results

Frequency Analysis

- **Boundary conditions**
  - **Fix lower faces of external frame (Ux=Uy=Uz=0)**



- **Results: Total 20 natural modes**

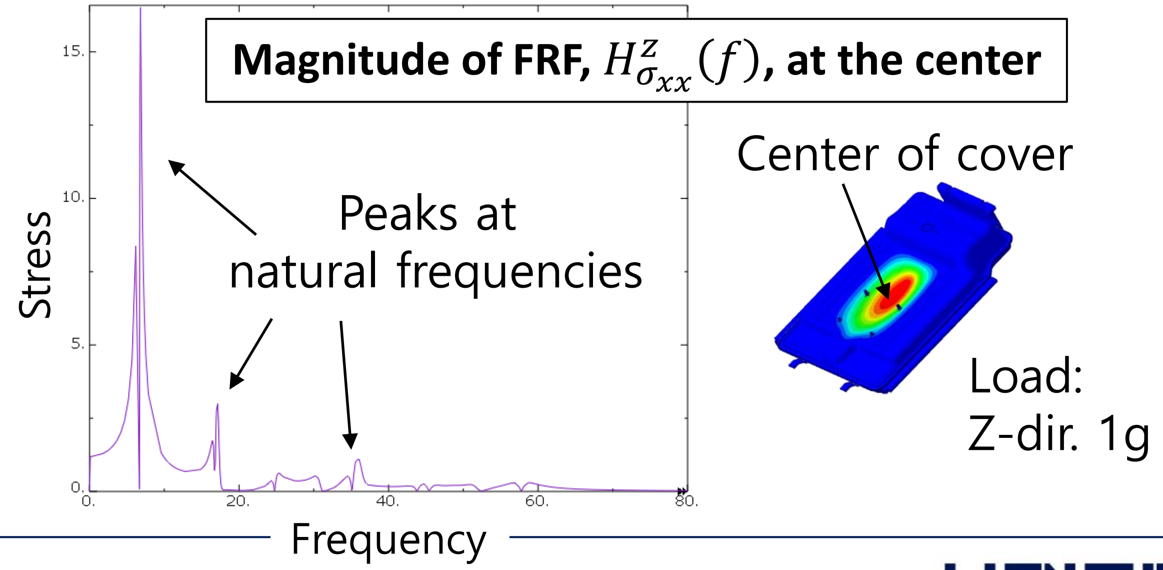


Harmonic Response Analysis

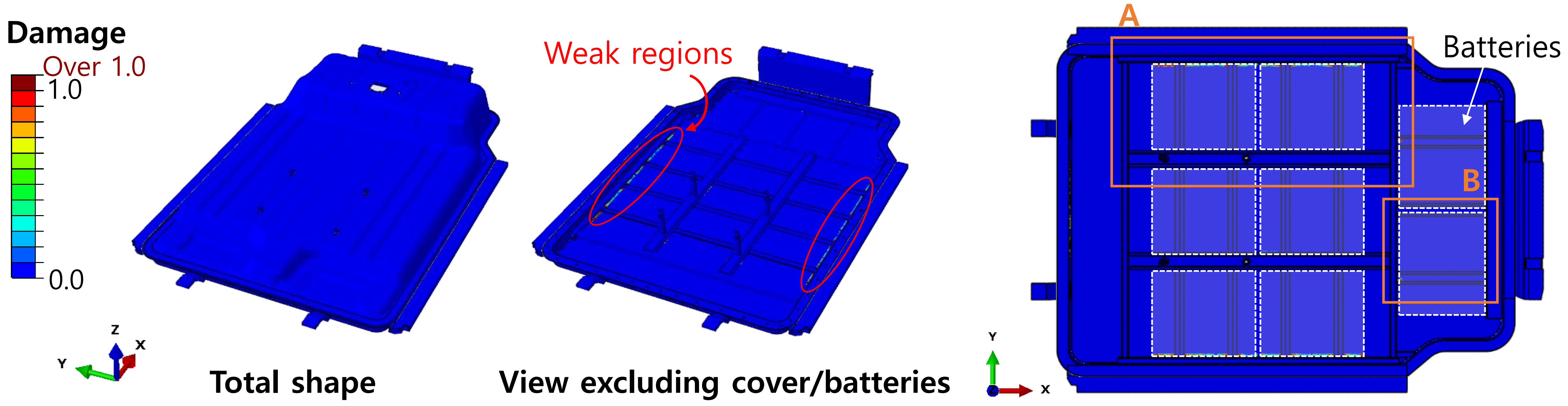
- **Boundary Conditions and applied loadings**

	X-dir.	Y-dir.	Z-dir.
Loading	Amplitude = 1g (9.81m/s^2) Frequency range: 0.1 Hz ~ 200 Hz		
Location	Lower faces of frame		
Constraint	Ux=free Uy=Uz=0	Uy=free Ux=Uz=0	Uz=free Ux=Uy=0

- **Results : FRFs for 6 stress components**



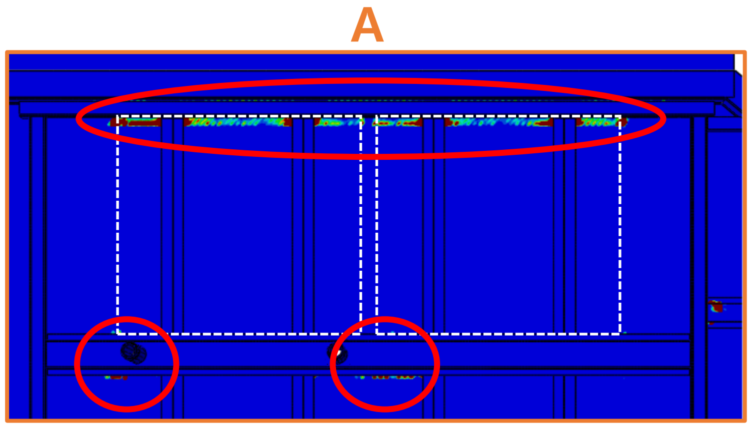
Results – Accumulated Fatigue Damage



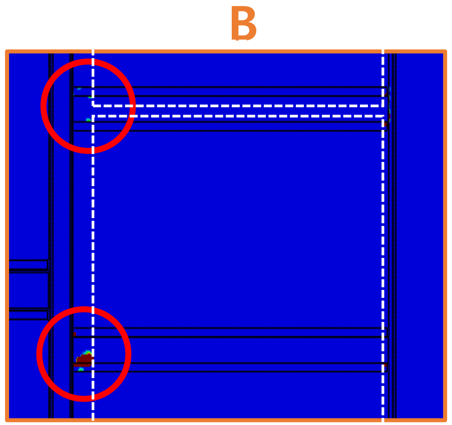
Total shape

View excluding cover/batteries

- **21 hours** of random vibration
  - Standard: GB/T 31476.3
- No damage appeared in composite
- Weak regions appeared in Al frames
  - Due to heavy batteries

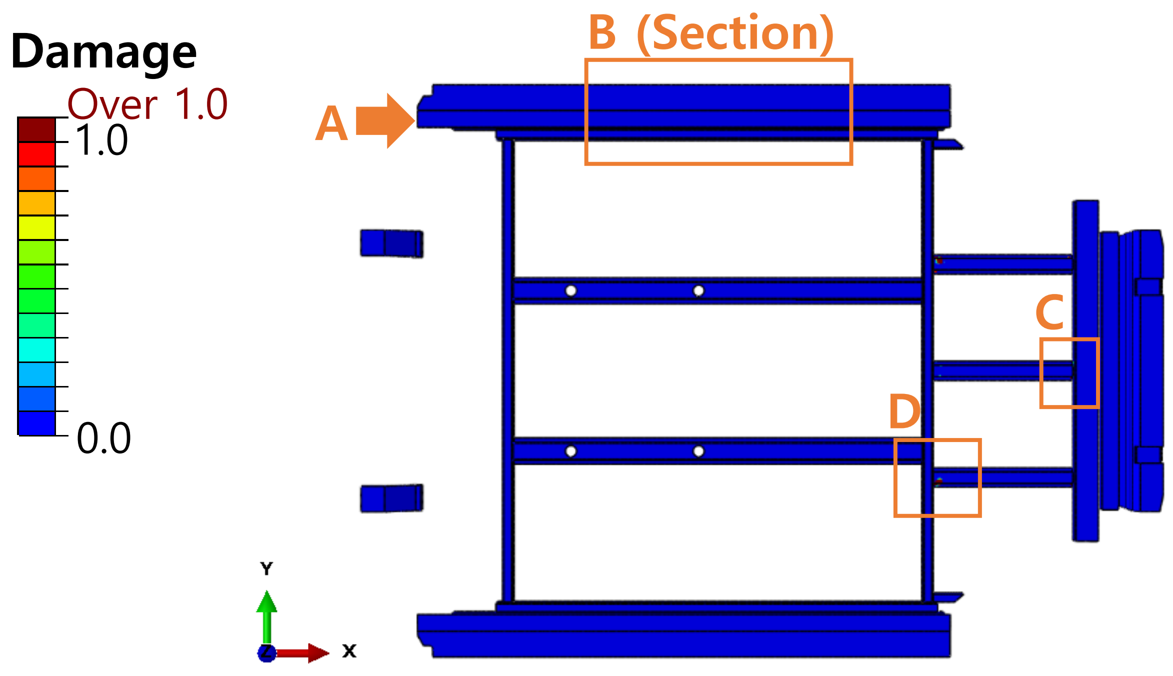


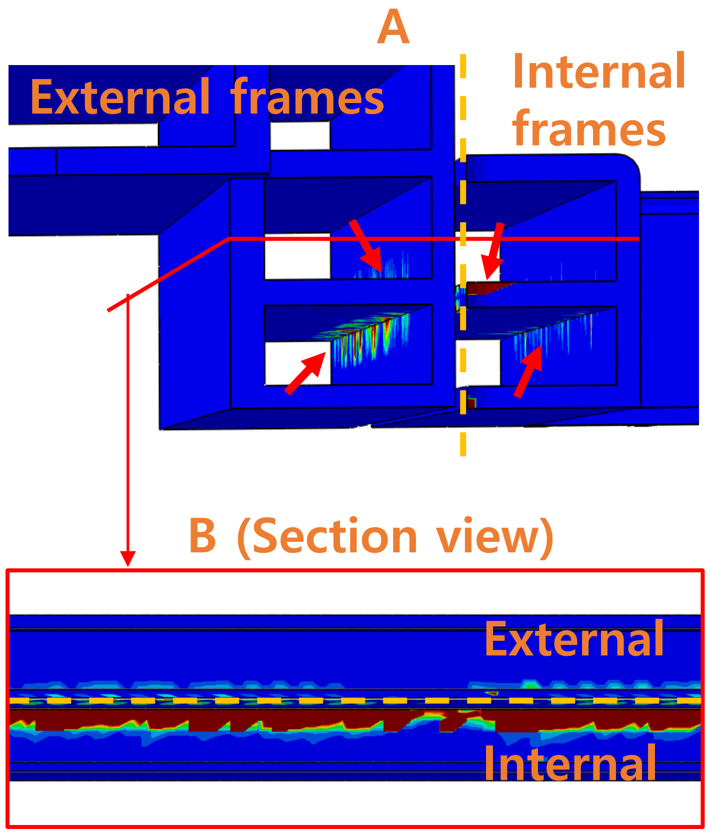
Weak region at the connections

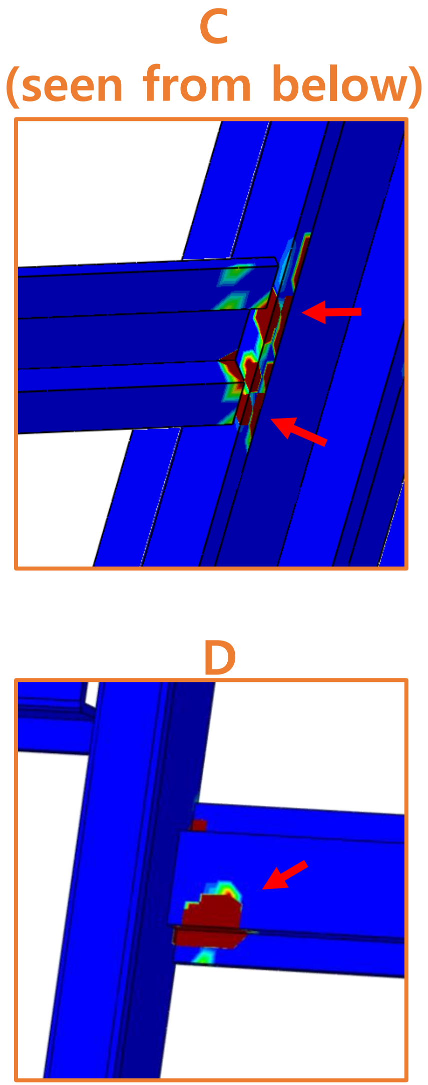


Local weak regions

Results – Fatigue Damage on Al Frame

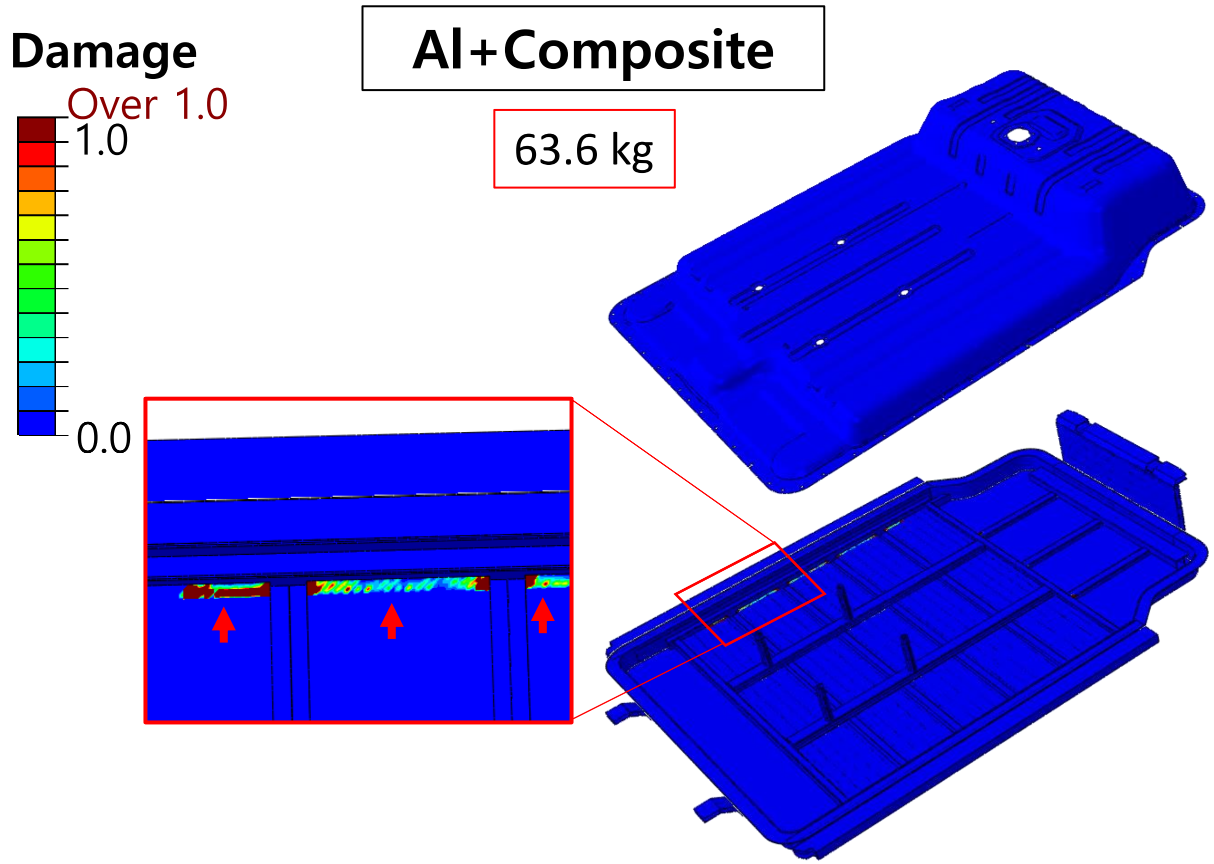


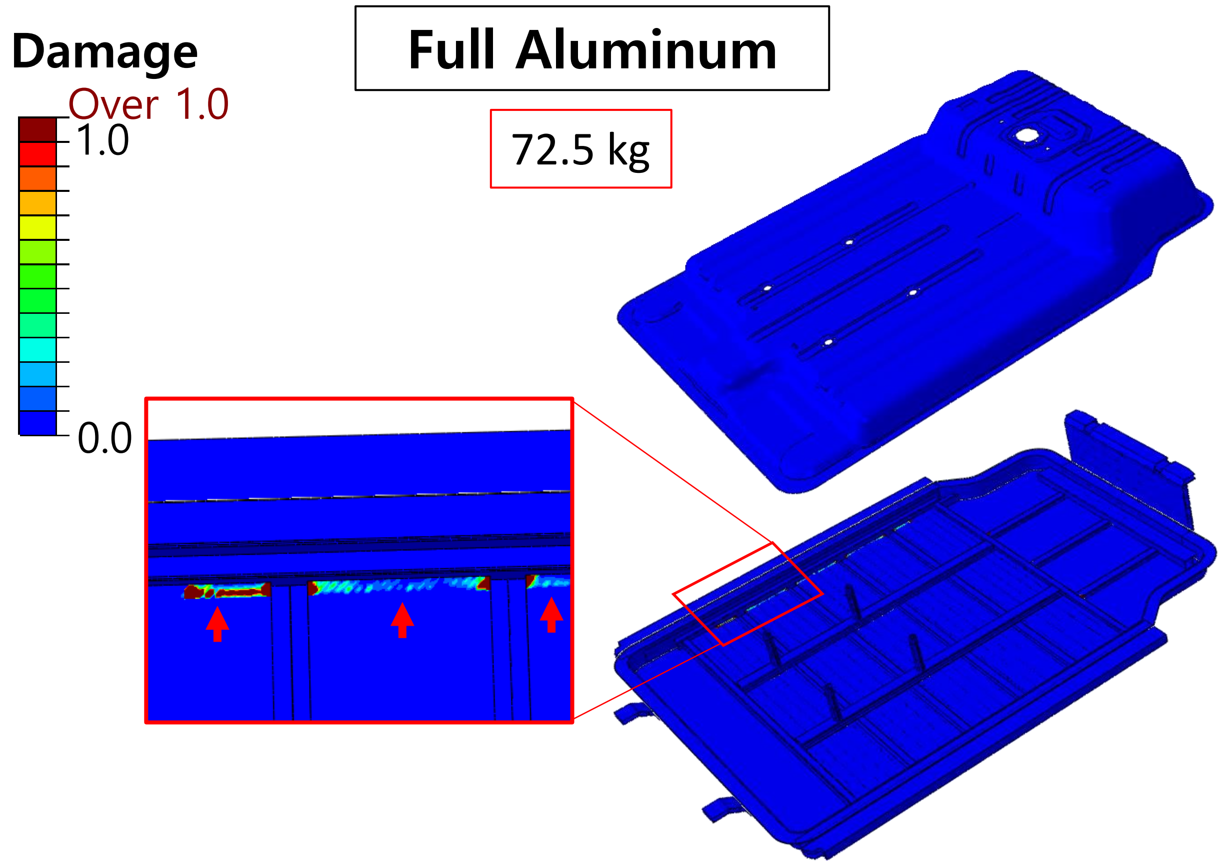




- **A: Weak region inside the frame**
- **B: Section top view inside the frame**
  - **Fatigue accumulated at the root of cantilever**
- **C, D: Weak region at local points**
  - **Frame was connected to heavy batteries**

Results – Al+Composite vs. Full Al





- **With same thickness, 12% weight reduction**
- **Similar locations of weak region (frame-plate connection)**
- **Only local reinforcement at the concentration point was needed**

Discussions

- **Mode-based numerical fatigue analysis on multi-material battery pack structure**
  - **Evaluation stage: Harmonic response of the structure**
    - Frequency analysis: eigenmodes and natural frequencies
    - Harmonic response analysis: frequency response functions
  - **Fatigue analysis stage: Fatigue analysis using random vibration**
    - Variable stress amplitude corresponding to random vibration
    - Fatigue life based on accumulation of fatigue damage

- **Fatigue analysis results**
  - **Regions to be reinforced and to be reduced could be identified**
    - Cover and carrier appeared to be safe from fatigue failure
    - Connection of frames and batteries were weak points

- **Future works**
  - **Fatigue properties dependent to composite direction**
  - **Fatigue failure criteria according to anisotropic stress**

Thank you