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Physics Informed Surrogate Model for Lifetime Prediction in Power Electronics Assembly based on Mission Profiles

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Motivation

- Power modules face reliability risks from temperature-driven thermo-mechanical fatigue under realistic mission profiles
- Rainflow counting with empirical lifetime models:
  Fast and simple
  Cannot capture local transients and sequence effects
- Full FE simulation:
  Accurate but computationally prohibitive (hours to days)
  Too slow for design studies or multiple driving scenarios
- Need: Surrogate model combining FEM accuracy with fast computation

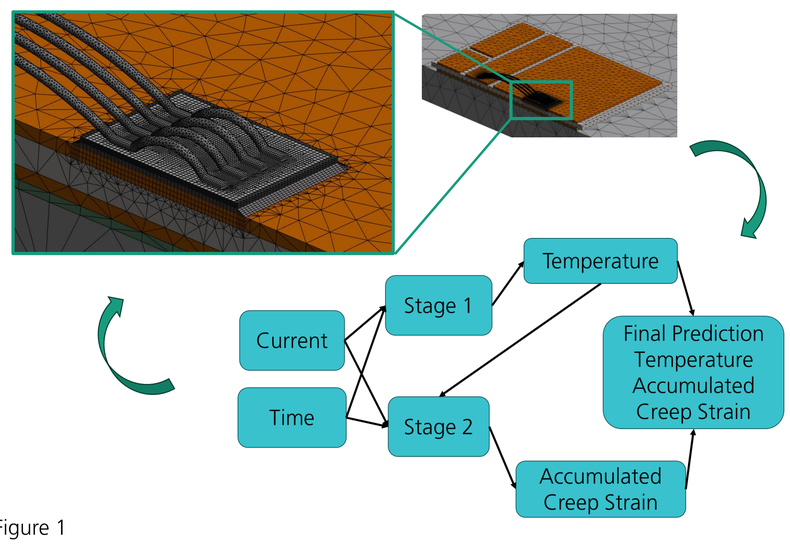


Figure 1

Methodology

- Preserves physical causality:
  Current → Temperature → Strain
- Physics-Informed Two-Stage Architecture
  - Stage 1 (GRU): I(t) → T̃(t)
  - Stage 2 (TCN): T̃(t), I(t) → $\hat{\varepsilon}_{cr}(t)$
- Non-negativity constraint ensures monotonic strain accumulation
- Hyperparameter optimization using Optuna

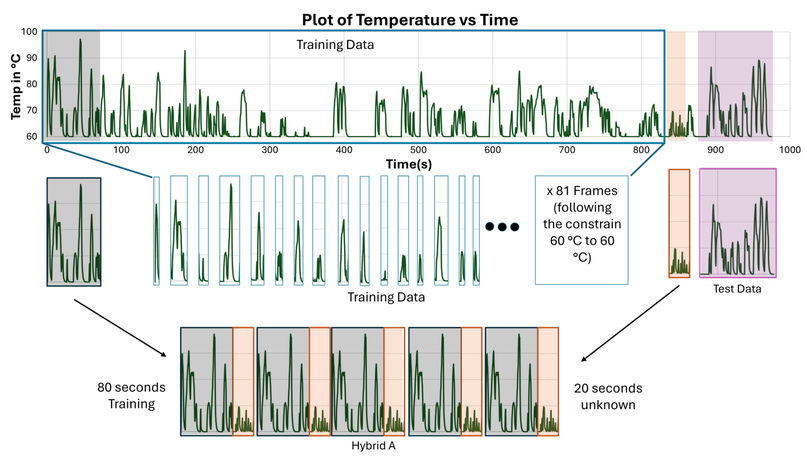


Figure 2

Mission Profile Segmentation

- ARTEMIS Automotive Mission Profiles
- Training Data:
  - 81 frames extracted from known portion
  - Each frame: 60°C → thermal cycle → 60°C
  - Wide variation of cycle shapes and amplitudes
- Evaluation Data:
  - Hybrid A: 100s (80s known + 20s unknown)
  - Test Data: 100s fully unseen profile
- All profiles: 5 repetitions for stable creep strain increment

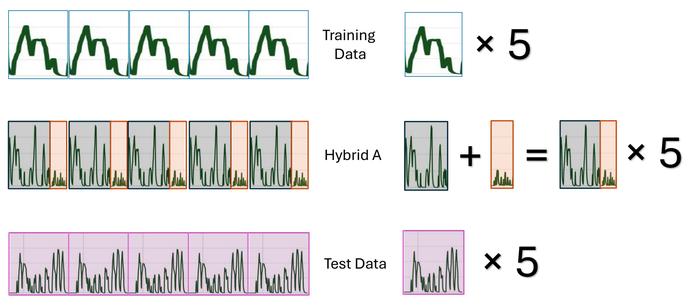


Figure 3

Temperature Estimation

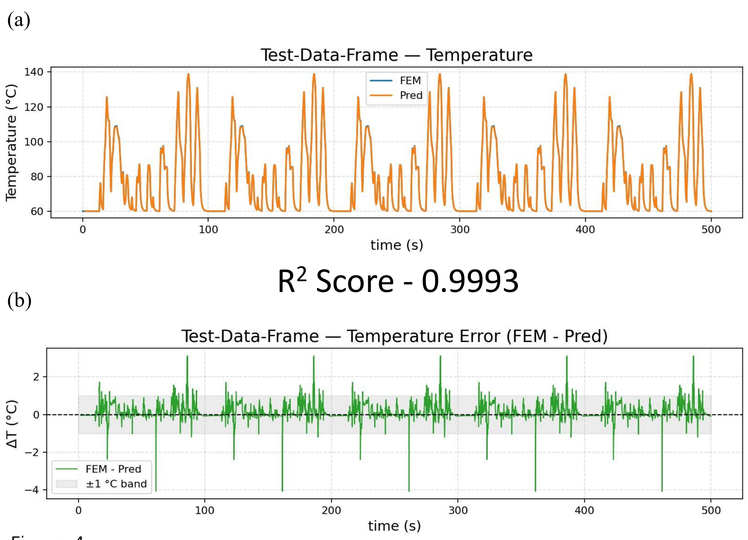


Figure 4

Solder Creep Strain Estimation

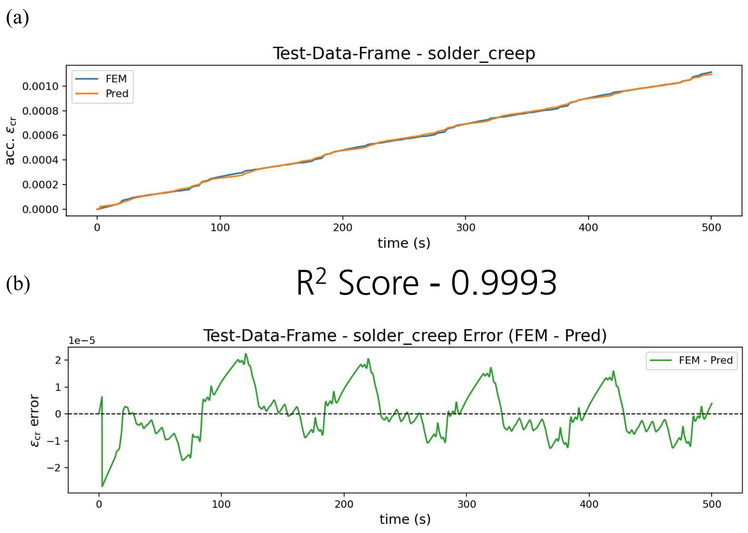


Figure 5

Lifetime Estimation

Lifetime calculation through Coffin–Manson relation:

$$N_f = C_1(\Delta\varepsilon_{in})^{C_2}$$

where the inelastic strain range per cycle is:

$$\Delta\varepsilon_{in} = \varepsilon_{in|_{500s}} - \varepsilon_{in|_{400s}}$$

- Lifetime error < ±1% (threshold: ±10%)

Table 1

	N_f FEM	N_f ML	Ratio	Error
Test Data	646k	653k	0.990	-0.99%

- Sensitivity Analysis: ±1%/±2% strain error → only ±2.3%/±3.6% lifetime deviation

Table 2

Scenario	$\Delta\epsilon_{in}$ Error	N_f (Cycles)	Deviations from FEM
FEM (Baseline)	—	653,236	—
ML Prediction	0%	646,777	-0.99%
ML + 1%	+1%	638,056	-2.32%
ML – 1%	–1%	655,670	+0.37%
ML + 2%	+2%	629,502	-3.63%
ML – 2%	–2%	664,741	+1.76%

Computational Efficiency

- FEM: ANSYS Mechanical 2025 R1, 48 CPU cores
- Surrogate: NVIDIA A100 GPU (80 GB)

Table 3

	FEM	Surrogate	Speed-Up
Temperature	3 – 4 h	< 10 s	~10^3X
Creep Strain	10 – 12 h	< 30 s	~10^4X

Conclusion

- Two-stage surrogate preserves causality (I → T → ε_{cr})
- Temperature & Creep Strain: R^2 = 0.999
- Lifetime estimation error using surrogate < ±1%
- Speedup: 10^3–10^4×

Outlook

- Extend surrogate to solder plastic strain
- Include bond wire lift-off prediction
- Experimental validation of lifetime predictions
- Develop mission-profile-inspired power cycling tests

Table 1 Test Data: Surrogate vs FEM life-time benchmark

Table 2 Deviations from FEM in different scenario.

Table 3 Computational cost comparison between FEM and surrogate inference.

Figure 1 FE model and surrogate modeling strategy

Figure 2 Segmentation of ARTEMIS mission profile into training frames, Hybrid A and Test profiles.

Figure 3 Input Signal for the FE model

Figure 4 (a) FEM vs Prediction plot of Deep Model (GRU) of Test dataset; (b) difference plot between FEM vs prediction of the test data with temperature surrogate model.

Figure 5 (a) FEM vs Prediction plot of Deep Model (TCN) of Test dataset; (b) difference plot between FEM vs prediction of test dataset with creep strain surrogate model.