END-OF-LIFE PREDICTION FOR SOLDER JOINTS IN ELECTRONIC SYSTEMS EXPERIENCING LOW-CYCLE FATIGUE UNDER IMPACT LOADING

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OUTLINE

- Background and Introduction
- Methodology
- Experimental approach
- Results
- Conclusions and future work

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HIGH-RATE MECHANICAL SHOCK

- Mechanical Shock
  - Sudden change in force, position, velocity, or acceleration[1]
  - Induces transient states in the system [1]
  - Can excite system frequencies [1]
  - Can lead to unpredictable responses within the structural integrity of components

Blast against civil structures

Automotive impact and crashes

High Speed aircraft and airframes

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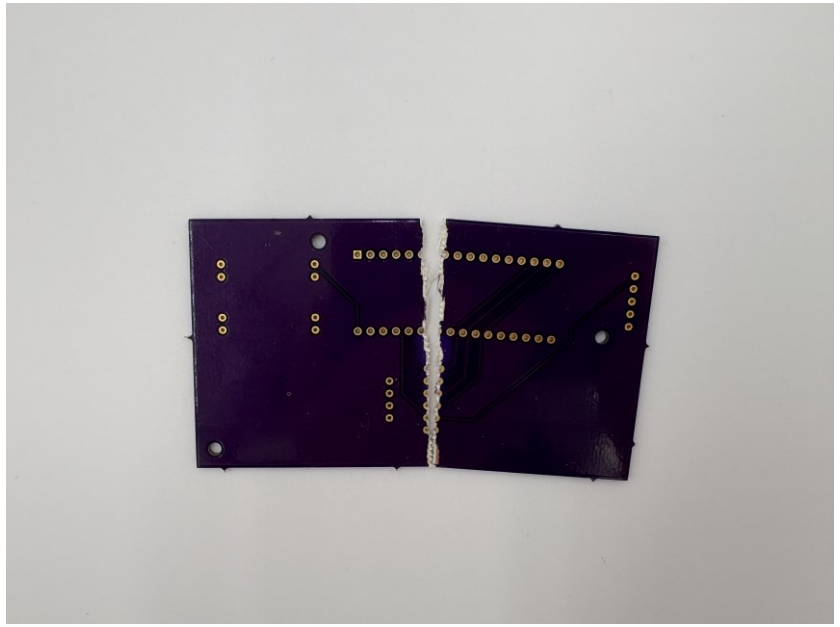
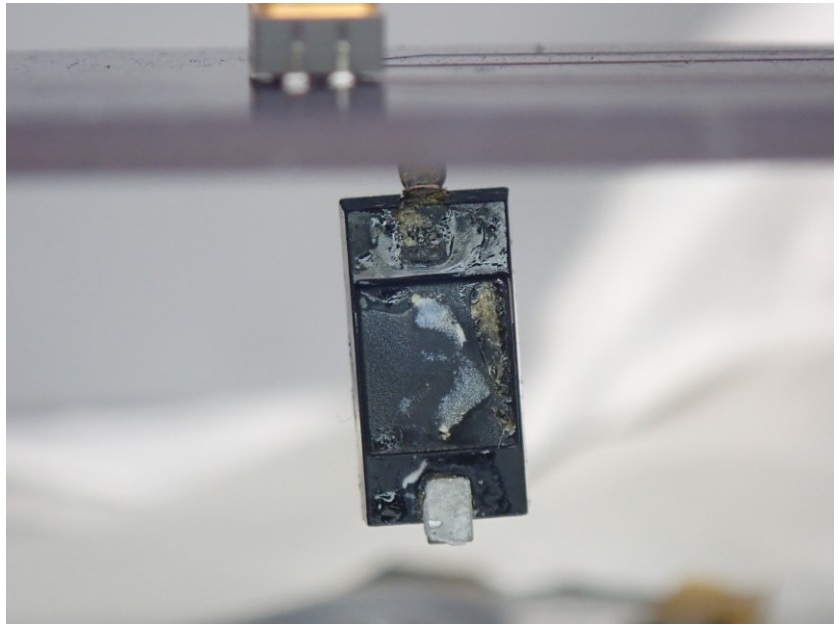
INTRODUCTION

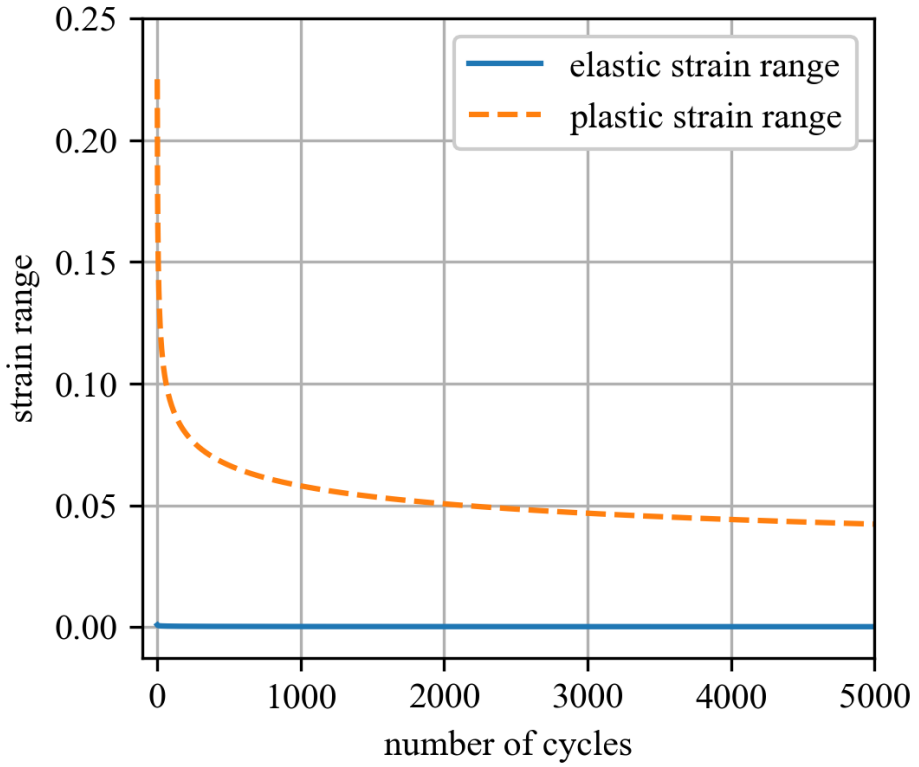
- Importance:
  - Systems subject to fatigue can experience sudden failure
- Problem:
  - Repeat inspection is not always practical
- Proposal:
  - Construct an algorithm to estimate remaining useful life of system
- Objective:
  - Track remaining useful life of system across intermittent impacts





BACKGROUND - FATIGUE

- Fatigue
  - Load applied over time
  - Can cause sudden structural failure



Example strain-life curve

BACKGROUND – MODELING FATIGUE

Initiation life estimation

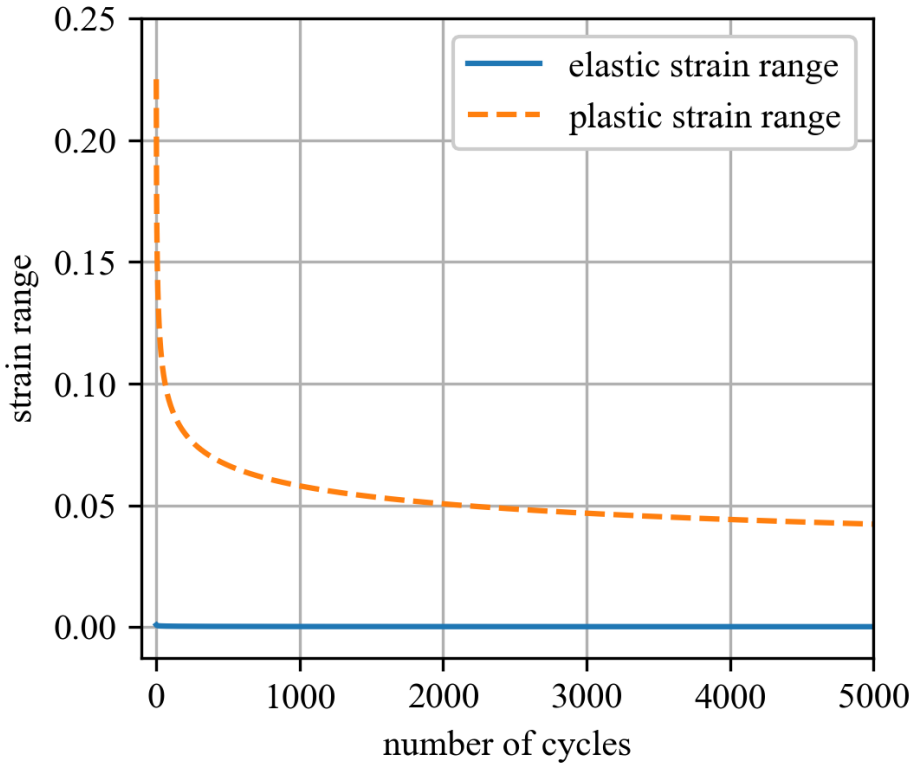
- Simulates fatigue damage at points of stress concentration
- Models when a crack occurs
- Modeled through stress-life or strain-life

Propagation life estimation

- Tracks length of crack in material
- Models when crack grows beyond critical length
- Modeled through fracture mechanics

BACKGROUND – FATIGUE

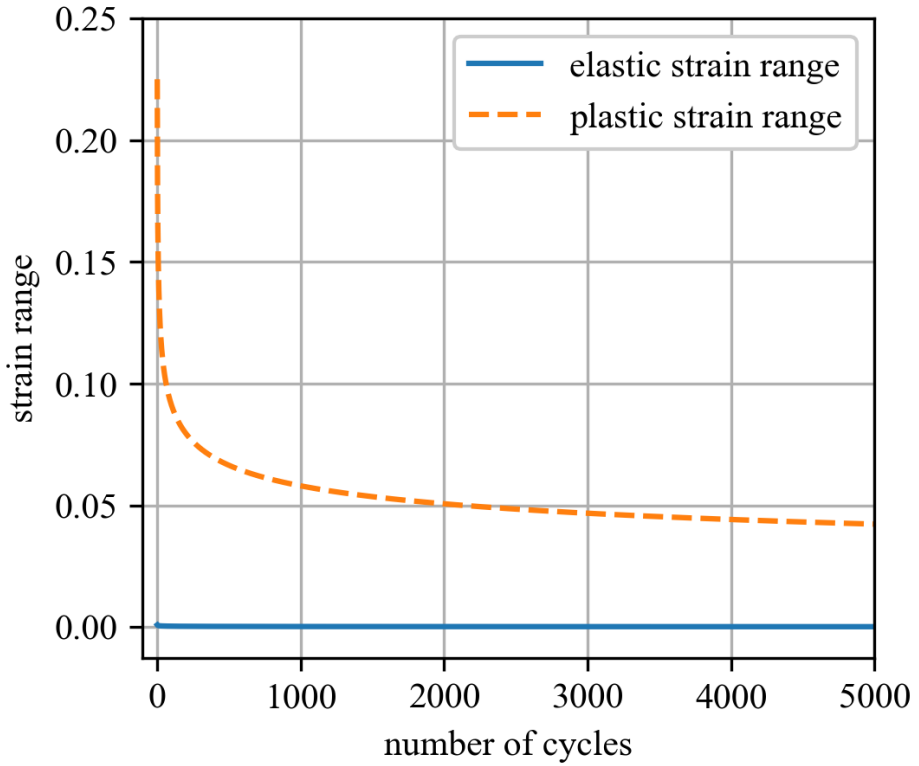
- Strain-life method
  - Estimates damage from strain amplitude
  - Better for low-cycle fatigue
- Elastic strain
  - $\frac{\Delta\varepsilon_e}{2} = \frac{K}{E} \cdot (2N)^{-B_0}$
- Plastic strain
  - $\frac{\Delta\varepsilon_p}{2} = \epsilon_f \cdot (2N)^{-\beta_0}$
- Coffin-Manson Relation
  - $\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2}$



Example strain-life curve

BACKGROUND – FATIGUE SUMMARY

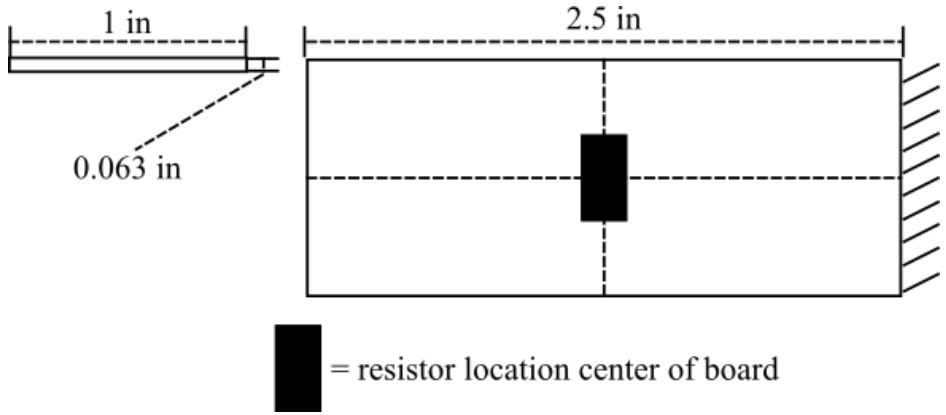
- Fatigue is damage over time
- Strain splits into plastic and elastic component
- Both represented by exponential decay functions

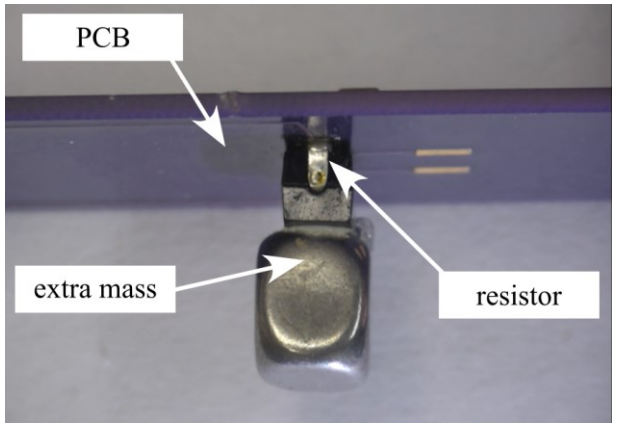


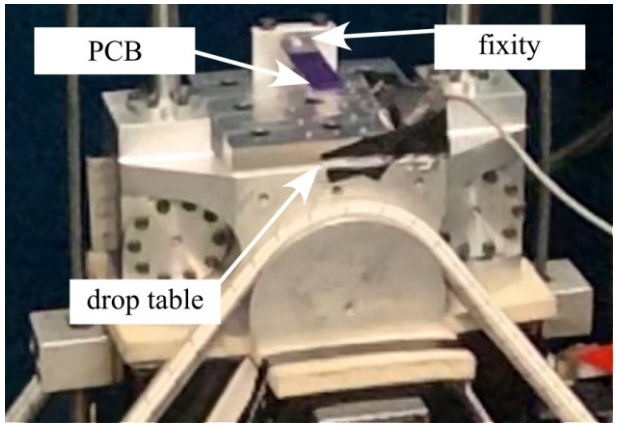
Example strain-life curve

METHODOLOGY

- Sensor breakdown:
  - Piezoresistive accelerometer
  - 2 strain gauges
  - Resistor/mass
    - Voltage divider circuit
- High-speed camera







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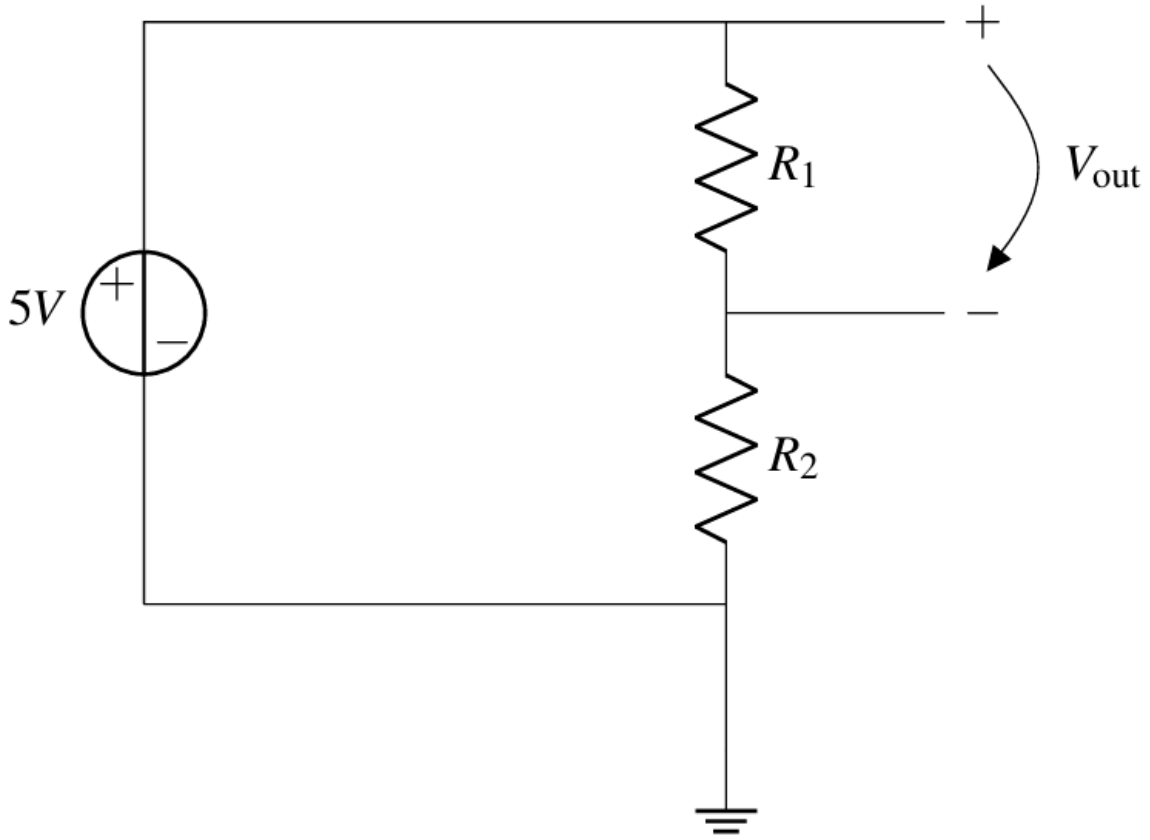
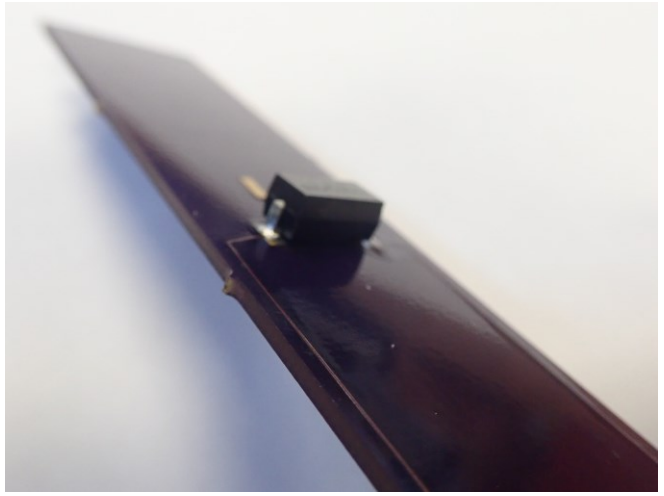
METHODOLOGY

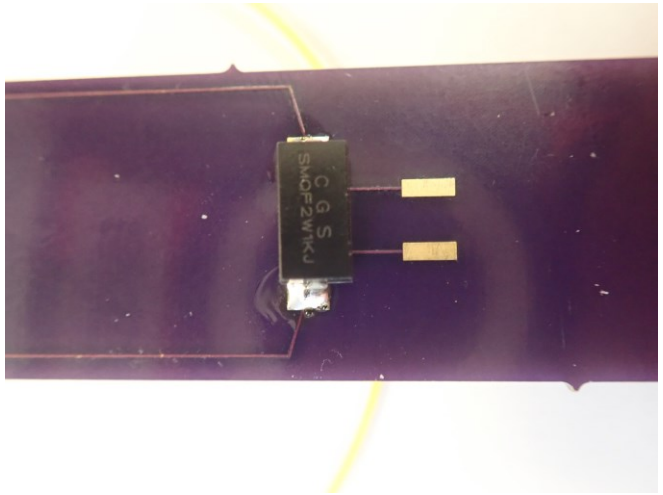
- Resistor circuit used to get a time reference on the exact moment of failure
  - Voltage divider keeps a 2.5 V signal until failure, which then drops to 0 V

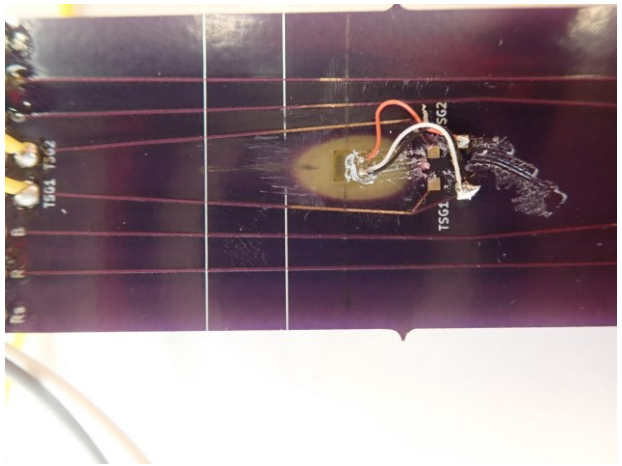


METHODOLOGY

Material	Density (lb/ft^3)	Young's Modulus (psi)	Poisson ratio
FR4	118.64	2,697,707	0.2







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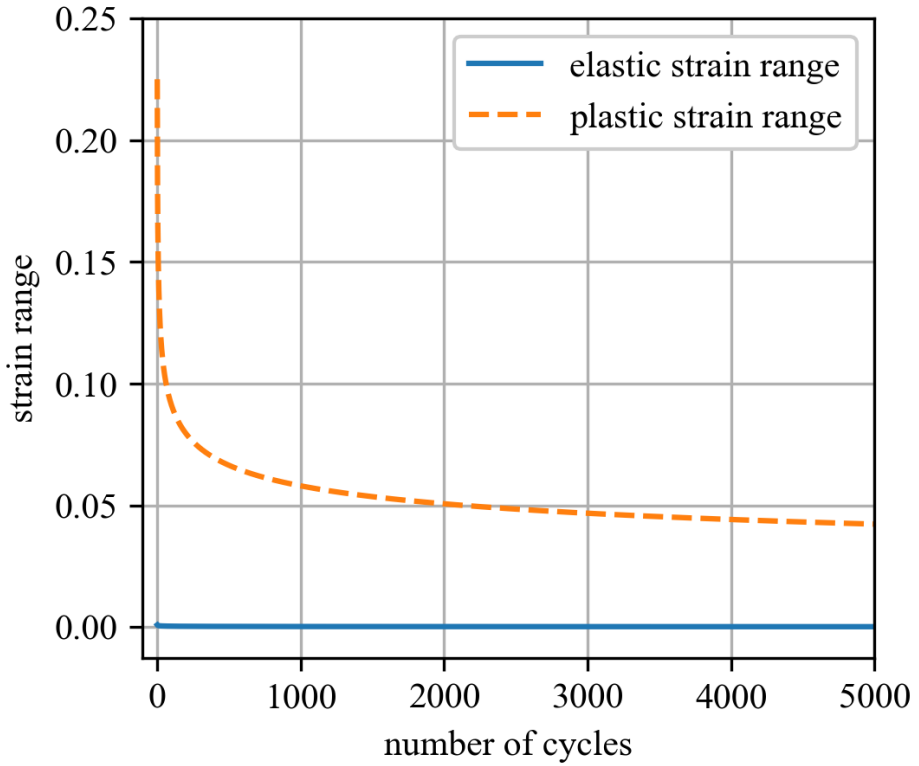
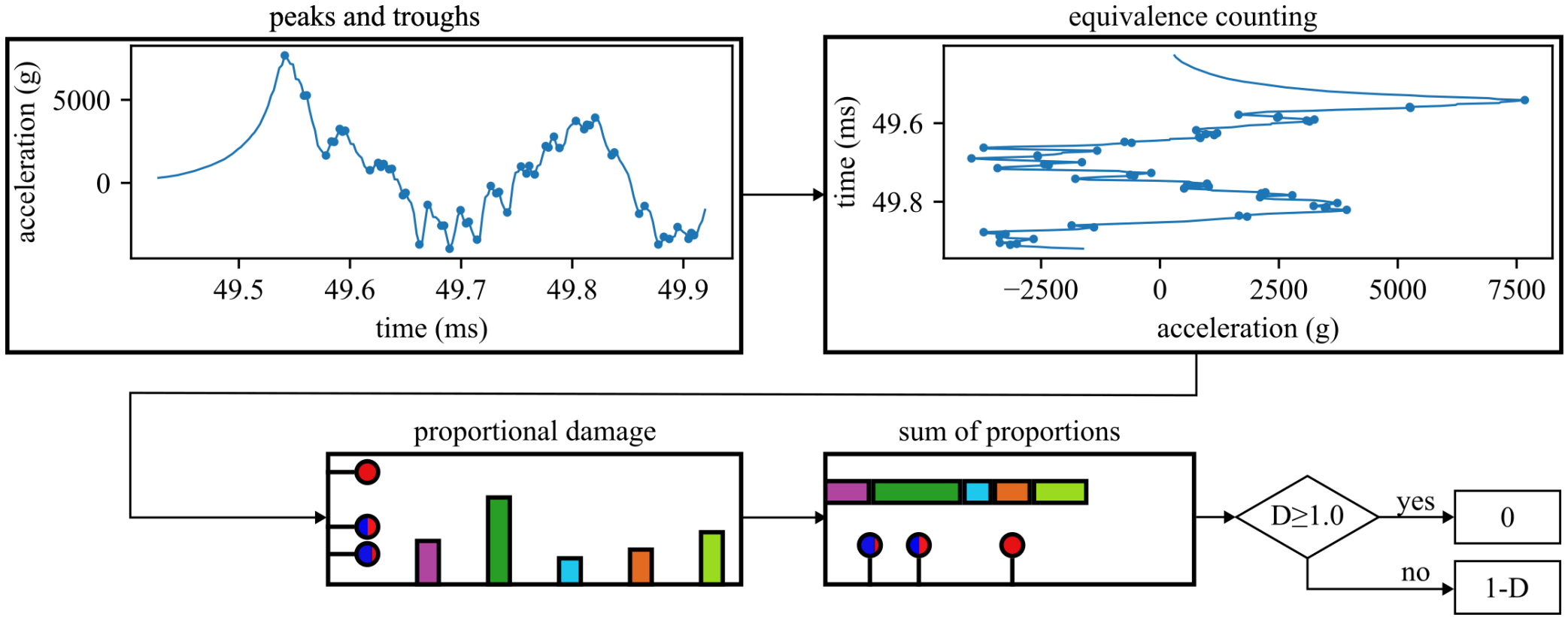
METHODOLOGY

- Assumes constant strain amplitude
- Miner's rule[2]
  - Damage from strain cycles are independent
  - Order of strain cycles does not matter



Example strain-life curve

METHODOLOGY



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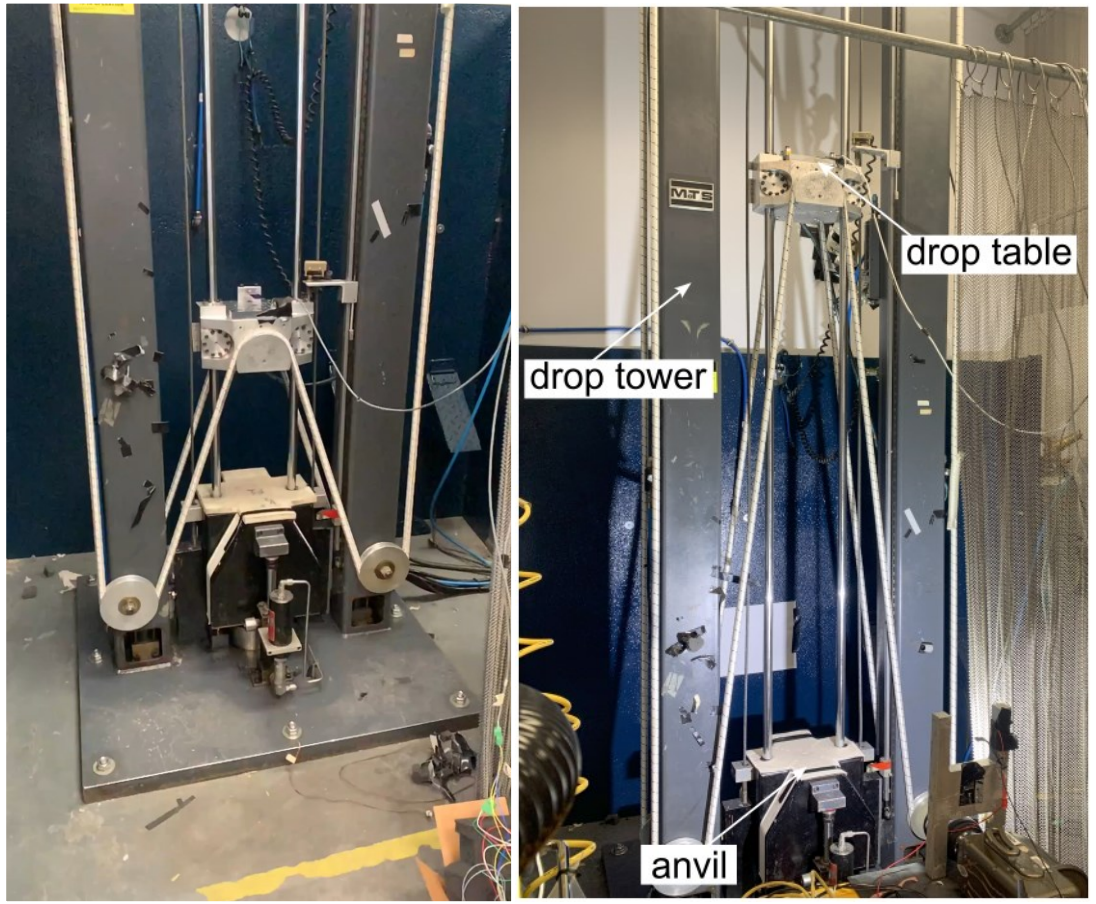
EXPERIMENTAL APPROACH

- Drop tower (simulates high-rate impacts)
- Cantilever printed circuit board with sensors
- Resistor/mass component meant to exaggerate the change in dynamics
- Several impacts at varying heights
- Intended to fail the resistor/mass and measure the differences in the response



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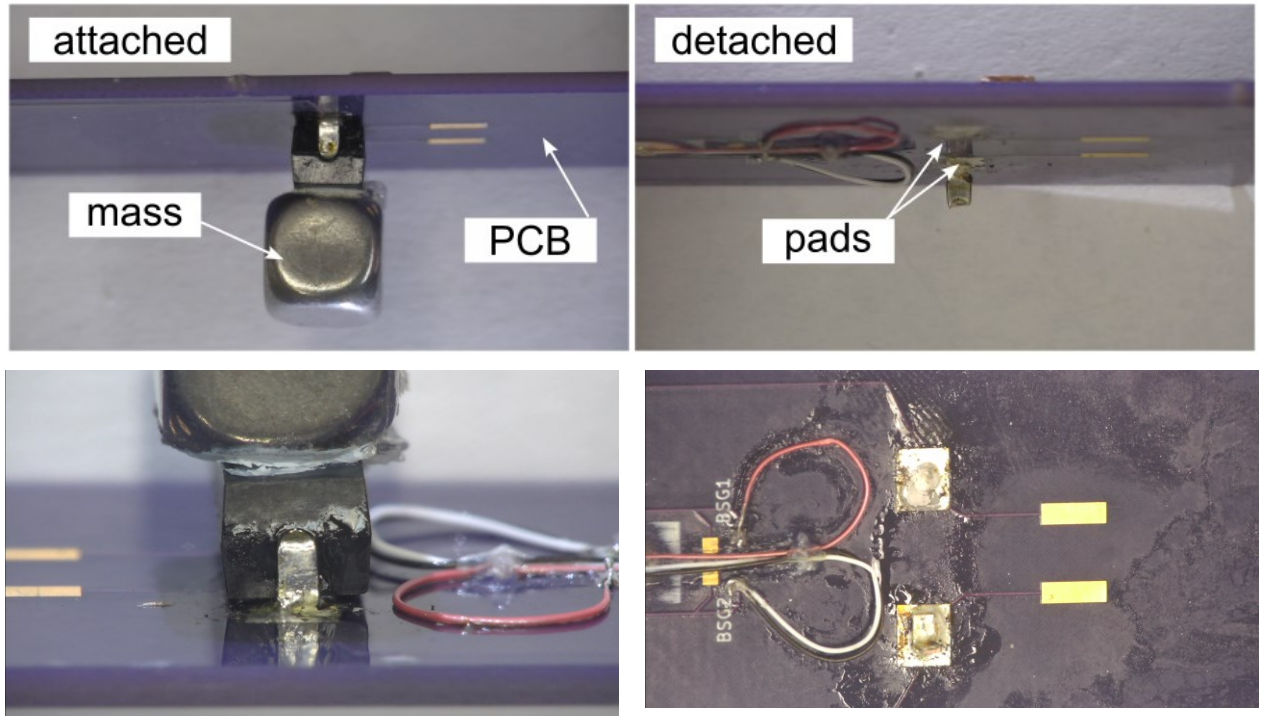
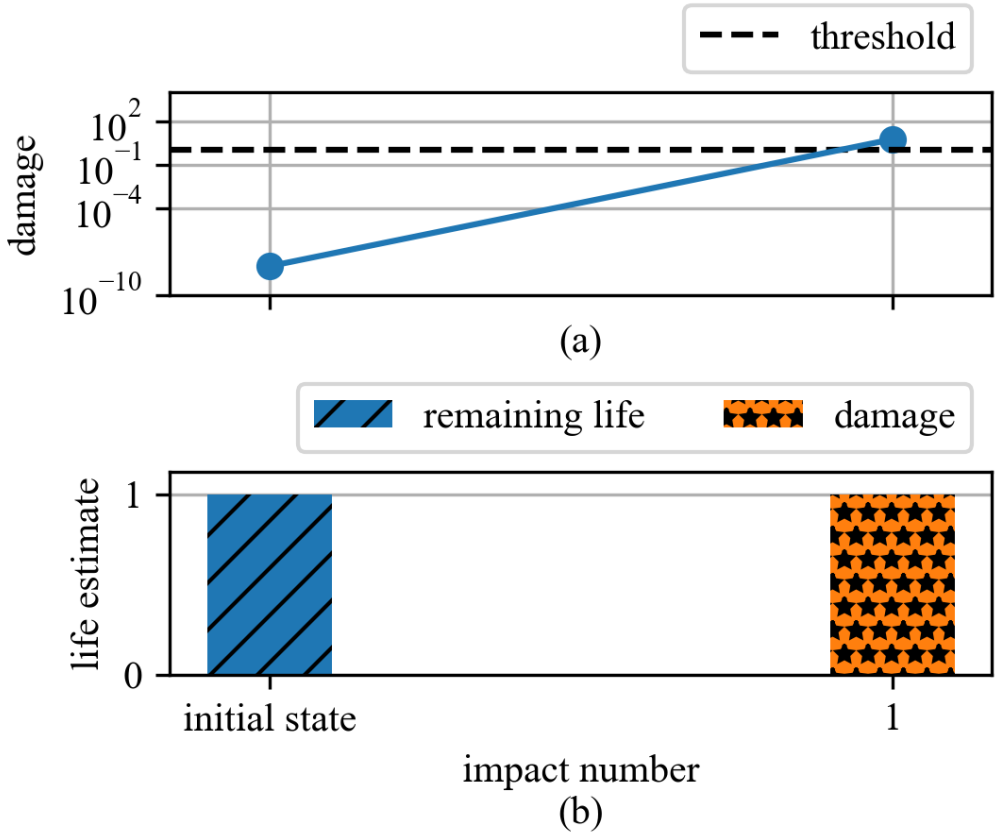
EXPERIMENTAL APPROACH

- Close-up of PCB and resistor
- Measured resistance for duration of impact
- If resistance was close to 0
  - device failed
  - Replace resistor
- Otherwise
  - Inflict another impact
- Impact set: impacts until device failure



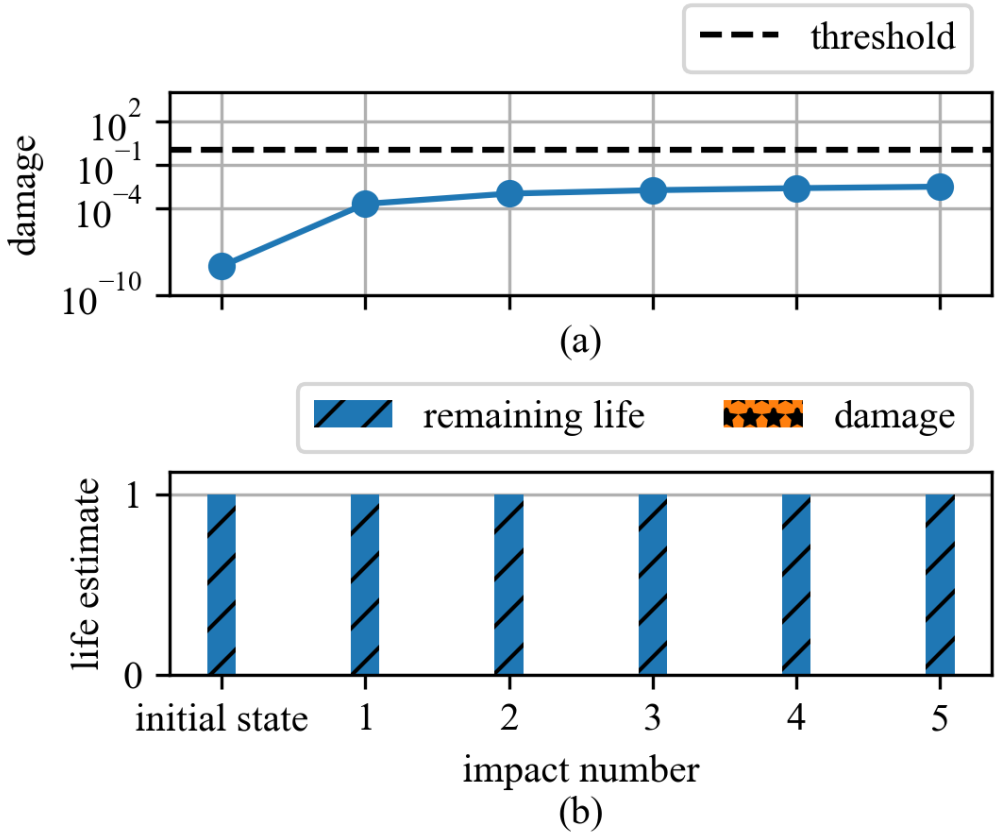
RESULTS – SET 1

- First impact set
  - Failed after one impact
  - Damage estimate changed 0->100%



RESULTS – SET 2

- Second impact set
  - Failed after five impacts
  - Damage estimate remained near 0%
  - Why?
  - Failure occurred at solder-pad interface
  - Our prediction is for solder failure



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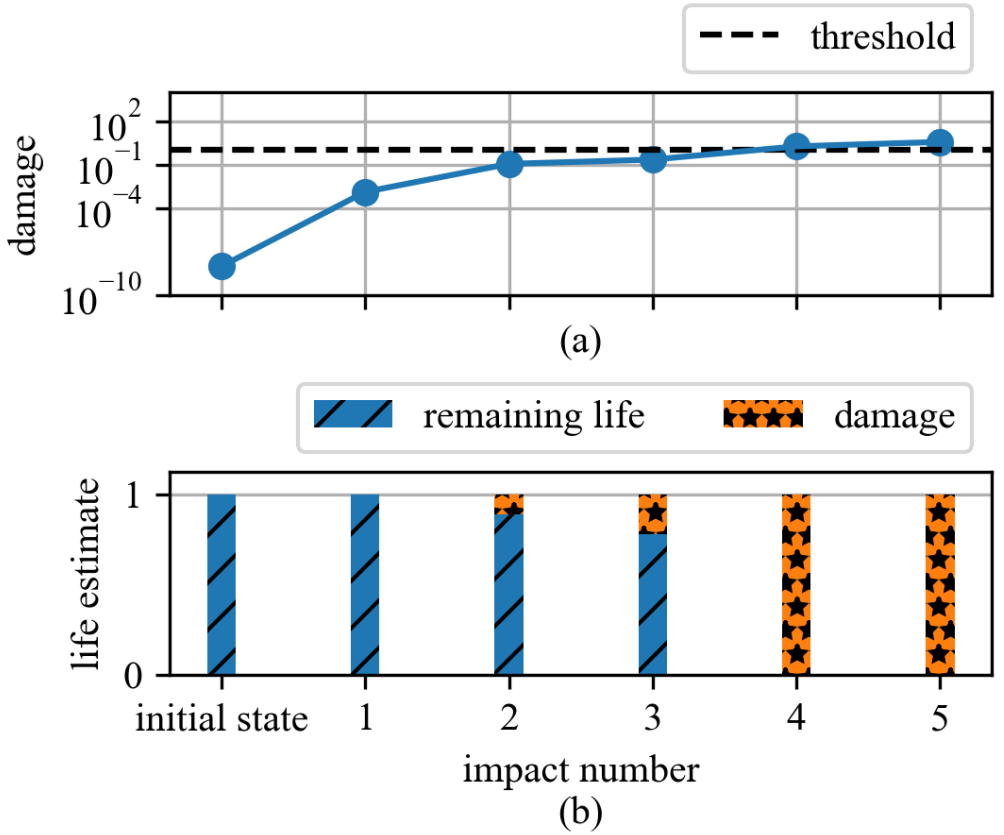
RESULTS – SET 3

- Third impact set
  - Failed after five impacts
  - Damage estimate changed 0->100%
  - Survived one more impact than expected



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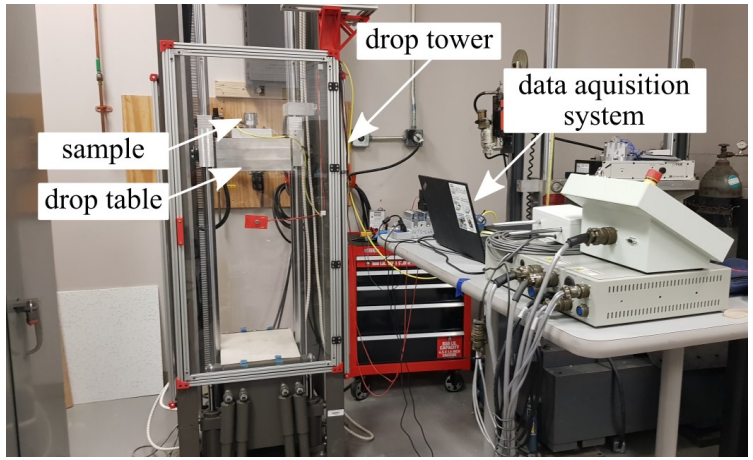
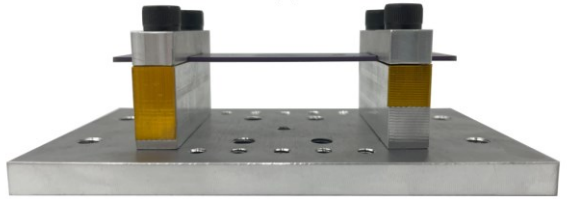
CONCLUSIONS AND FUTURE WORK

- Algorithm for predicting remaining useful life in solder joints
- Future work
  - Incorporating fatigue from creep[3]
  - Verifying algorithm predictions
  - Generating with varying structural configurations



(a)

(b)



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THANKS!

Open-source Data Set

https://github.com/High-Rate-SHM-Working-Group/Dataset-9-repeated-impact-testing-of-rectangular-electronic-assembly [4]

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REFERENCES

[1] Dodson, Jacob, Downey, Austin, Laflamme, Simon, Todd, Michael D., Moura, Adriane G., Wang, Yang, Mao, Zhu, Avitabile, Peter and Blasch, Erik. High-Rate Structural Health Monitoring and Prognostics: An Overview. Springer International Publishing (2021): pp. 213–217. DOI 10.1007/978-3-030-76004-5_23.

[2] Barsom, John M and Rolfe, S. T. (eds.). Fracture and fatigue control in structures, 3rd ed. No. MNL 41-3RD in ASTM manual series, ASTM, West Conshohocken, PA (1999). In: Knovel library. - Dateiformat Volltext: PDF. - Includes bibliographical references and index. - Print version record.

[3] Wong, E.H., van Driel, W.D., Dasgupta, A. and Pecht, M. “Creep fatigue models of solder joints: A critical review.” Microelectronics Reliability Vol. 59 (2016): pp. 1–12. DOI 10.1016/j.microrel.2016.01.013.

[4] Yount, Ryan, Dodson, Jacob and Moura, Adriane. “Dataset 9 Repeated Impact Testing of Rectangular Electronic Assembly.” URL https://github.com/High-Rate-SHM-Worki ng-Group/Dataset-9-repeated-impact-testing-of-rectangul ar-electronic-assembly.

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