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Sandia National Laboratories

Mechanical Shock Failure Predictions Using Energy Response Spectra Methods

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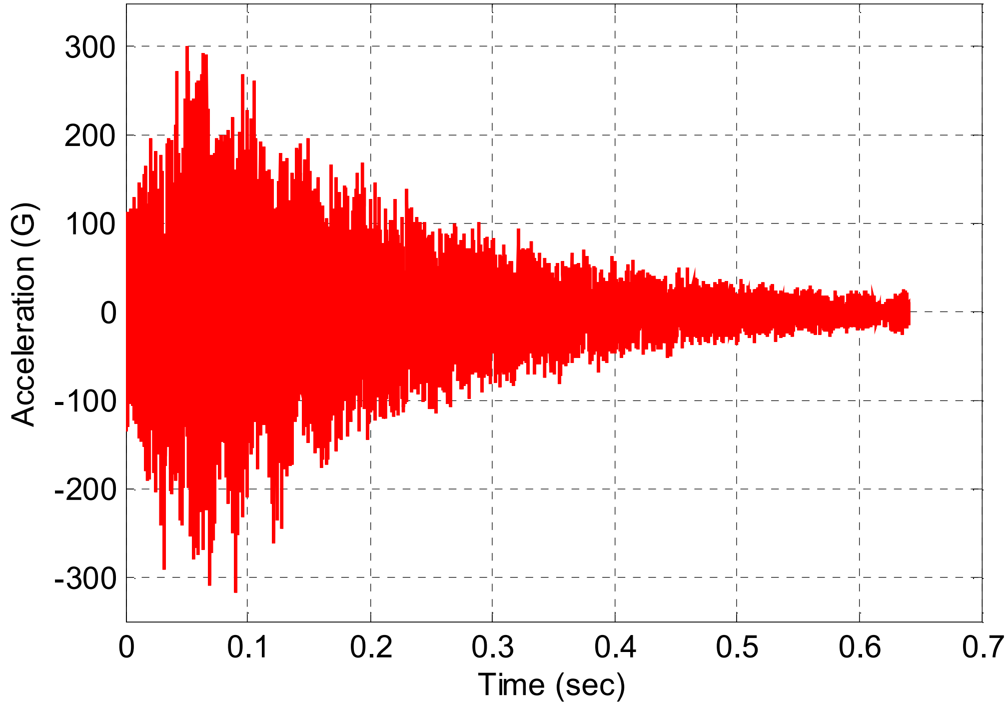
Outline

- Shock Response Spectra
- Project Introduction and Motivation
- Test Structure
  - Test Fixture & Cantilever Beams
- Shock Testing
  - Types of Failures
- Test Results
  - Shock Failure
  - Low Cycle Fatigue Failure
- Conclusions and Future Work

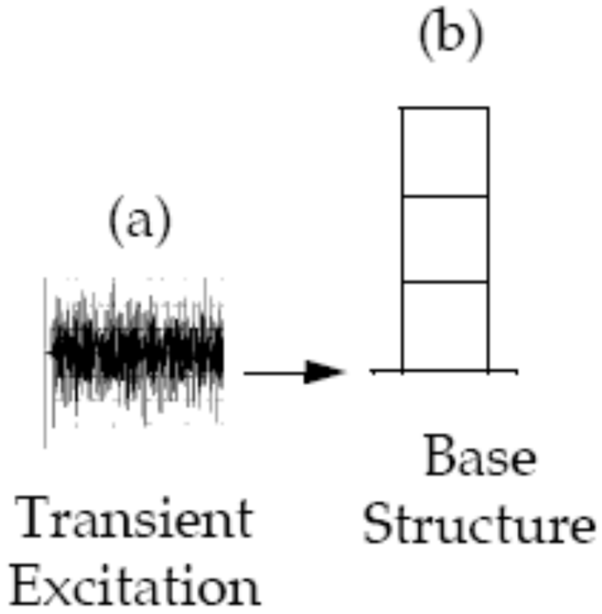
What is a Shock?

- A shock is a transient excitation
- The duration is less than the fundamental period of the system to which it is applied
  - Usually 10’s to 100’s milli-secs
- Usually high amplitude and high frequency



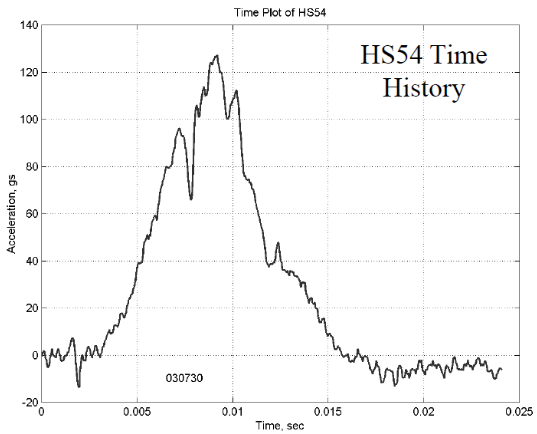
What is a Shock?

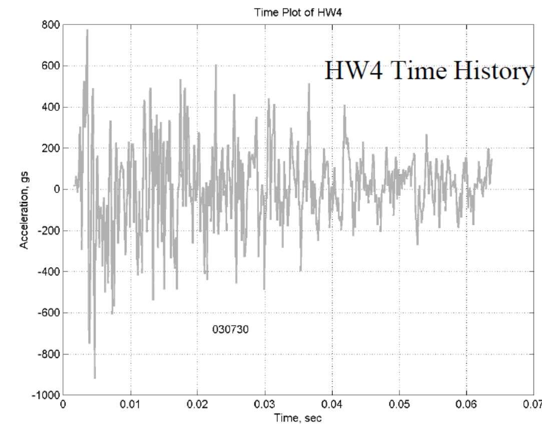
- A shock can be a short duration force
  - Classic impulsive load
  - Example: Baseball bat hitting a baseball
- A shock can be an enforced motion
  - Displacement or acceleration
  - Example: Earthquake shakes the base of a building
  - Non-zero initial conditions can be considered a shock

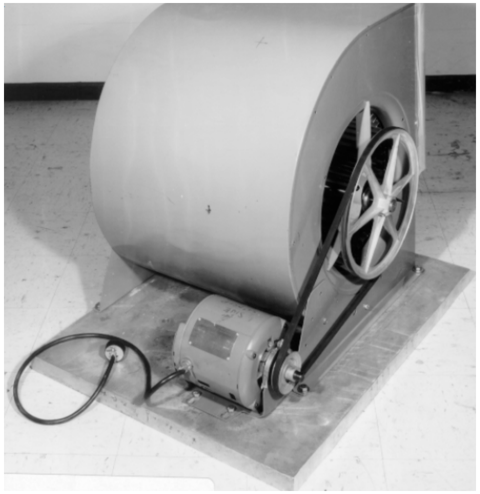


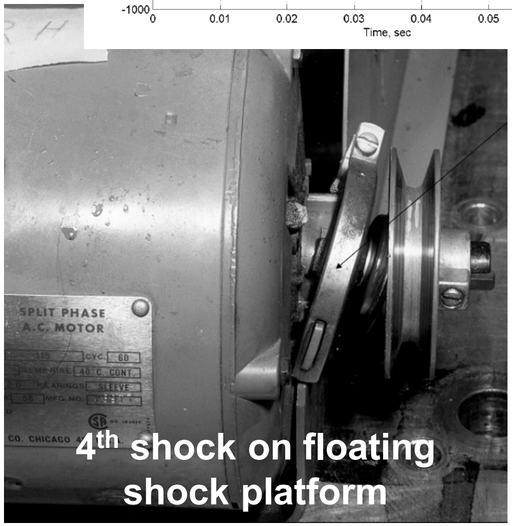
What Damage Can Shock Do?

- Shock can cause a wide range of damage





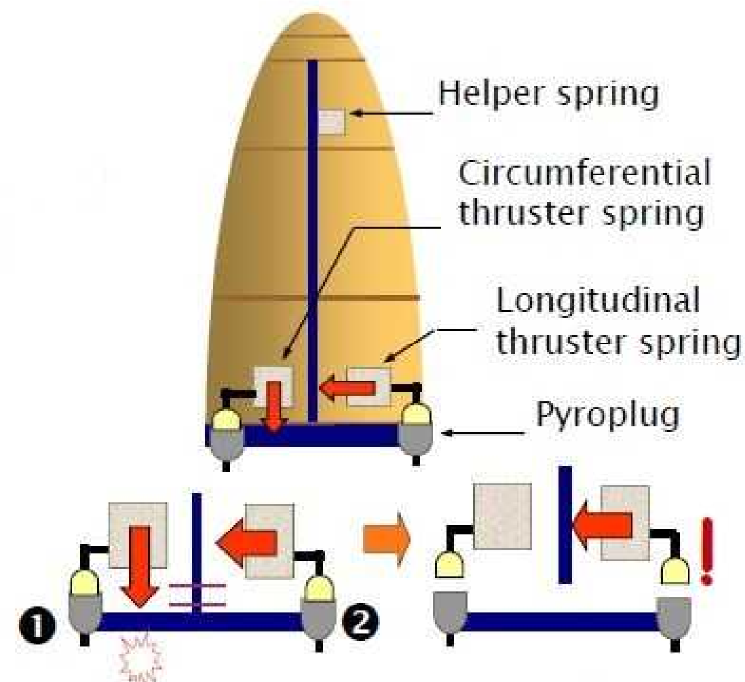




Navy shock tests of furnace squirrel cage blower motors

What Damage Can Shock Do?

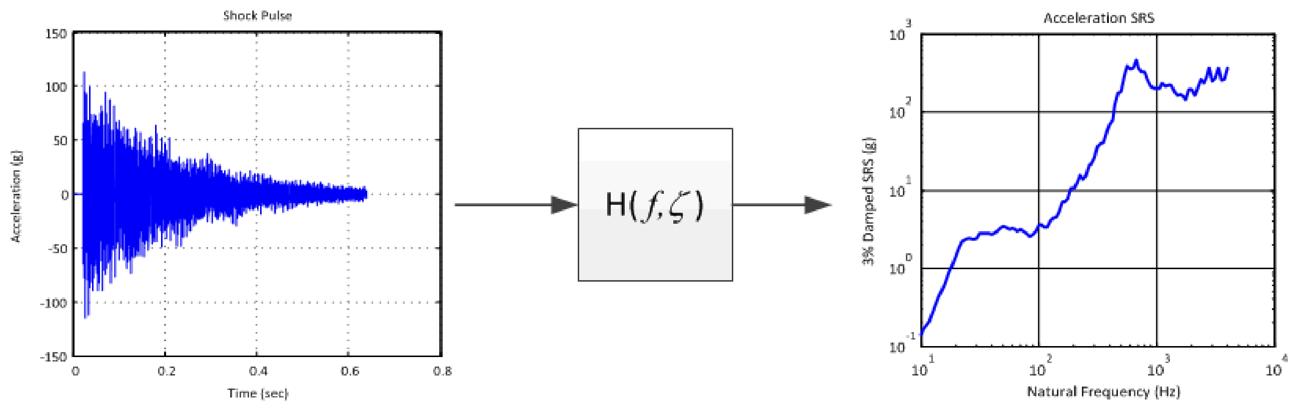
- Shock damage can be subtle too
  - Functional failure
  - Latent damage
  - Mechanism failure
- Pyro devices impart large shocks that can cause mechanism failures
  - A launch vehicle fairing failed to open because the shock from 1 set of squibs disconnected another



Shock from circumferential cut ❶ pulled the longitudinal firing plug ❷ apart

What is a Response Spectrum?

- SRS = Shock Response Spectrum
  - A plot of the maximum response of SDOF systems to a specific (transient) input
  - The output of a non-linear operator applied to a time history



- The SRS has been around for a long time (since the 1930's)
  - Ubiquitous in the shock community

SRS Fundamentals

- SRS correlates to damage potential
  - Two excitation sequences (i.e., environments) with the same SRS have the same damage potential
  - The damage mode is overstress due to peak stress
- The SRS does not apply to repeated shocks
  - Not applicable to damage from a train of shocks
  - The SRS of a sequence that has 2 identical shocks is the same as the SRS of a sequence with 1 shock
- Must also specify the duration of the shock

We are interested in response spectra methods for repeated shocks

SRS Characteristics

- The SRS operator is non-invertible and smoothing
  - Mapping from time to SRS frequency space is one way
    - This is both a curse and a blessing
  - Eliminates the “wiggles” in a time sequence
  - Response does not affect the input (force or motion) – no back driving
- Some information is sacrificed
  - Only the peak response per individual oscillator is computed
    - No phase information (i.e., time of peak response)
    - No interaction of the oscillator responses

Shock Response Spectra – The Movie

Energy Response Spectra

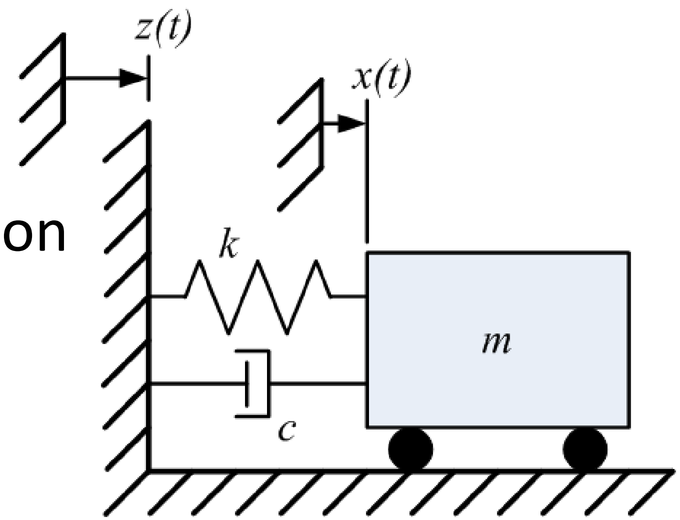
- SDOF Oscillator Equation of Motion

$$m\ddot{x}(t) + c\big(\dot{x}(t) - \dot{z}(t)\big) + \ k(x(t) - z(t)) = 0$$

- Relative displacement equation of motion

$$w(t) = x(t) - z(t)$$

$$\ddot{w}(t) + 2\zeta\omega_n\dot{w}(t) + \ \omega_n^2 w(t) = -\ddot{z}(t)$$



- Energy Balance

$$\int_{w(t_0)}^{w(t_f)} \ddot{w}(t)dw + 2\zeta\omega_n \int_{w(t_0)}^{w(t_f)} \dot{w}(t)dw + \omega_n^2 \int_{w(t_0)0}^{w(t_f)} w(t)dw = -\int_{w(t_0)}^{w(t_f)} \ddot{y}(t)dw$$

$$\int_{t_0}^{t_f} \ddot{w}(t)\dot{w}(t)dt + 2\zeta\omega_n \int_{t_0}^{t_f} \dot{w}^2(t)dt + \omega_n^2 \int_{t_0}^{t_f} w(t)\dot{w}(t)dt = -\int_{t_0}^{t_f} \ddot{y}(t)\dot{w}(t)dt$$

$$\frac{1}{2}\dot{w}^2(t)\Big|_{t_0}^{t_f} + \qquad 2\zeta\omega_n \int_{t_0}^{t_f} \dot{w}^2(t)dt + \qquad \frac{1}{2}\omega_n^2 w^2(t)\Big|_{t_0}^{t_f} \quad = -\int_{t_0}^{t_f} \ddot{y}(t)\dot{w}(t)dt$$

Energy Response Spectra

- Energy Balance Equation

$$\frac{1}{2}\dot{w}^2(t)\Big|_{t_0}^{t_f} + 2\zeta\omega_n\int_{t_0}^{t_f}\dot{w}^2(t)dt + \frac{1}{2}\omega_n^2 w^2(t)\Big|_{t_0}^{t_f} = -\int_{t_0}^{t_f}\ddot{y}(t)\dot{w}(t)dt$$

Relative Kinetic Energy $E_K{}^R$

Viscously Dissipated Energy E_D

Absorbed or Potential Energy E_A

Input or Total Energy E_I

- Just like the SRS, the energy response spectrum is a plot of the maximum response (energy) of SDOF systems to a specific (transient) input
  - Also must specify duration

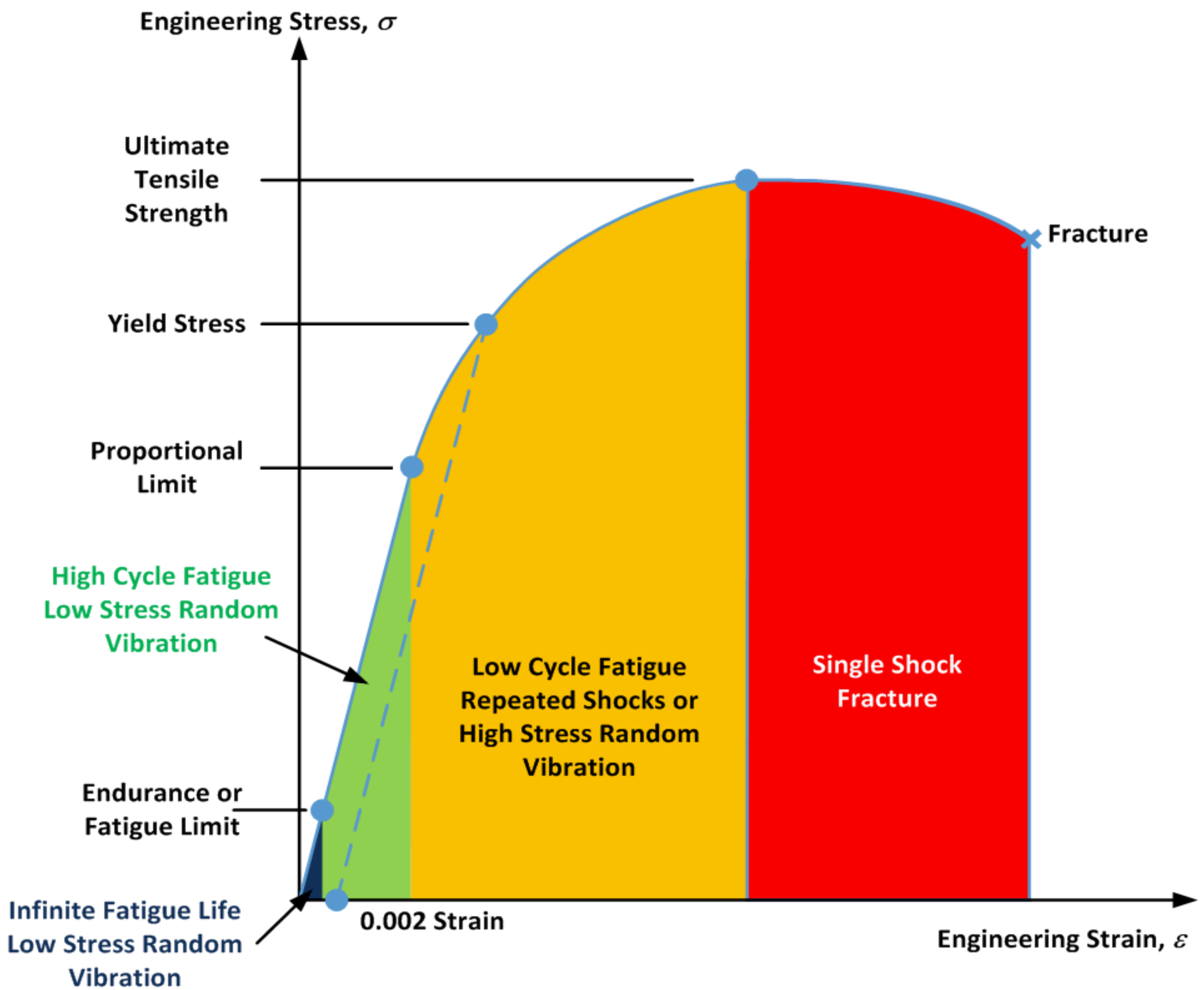
The integral means the ERS increases with multiple applied shocks

Introduction & Motivation

- Mechanical Shock Testing Margin Assessment
  - Sandia continually tests our systems to assess their structural integrity
    - Destructive and Evaluation testing
  - Some programs have adopted energy (dissipated and input) as a straightforward metric to relate the severity of mechanical insults to structural capacity
    - Margin assessment
  - The domain of applicability and implementation details are not fleshed out for our problems of interest
    - Failure criteria
    - Localized failures
    - Energy dissipation models
    - Relationship to design approaches

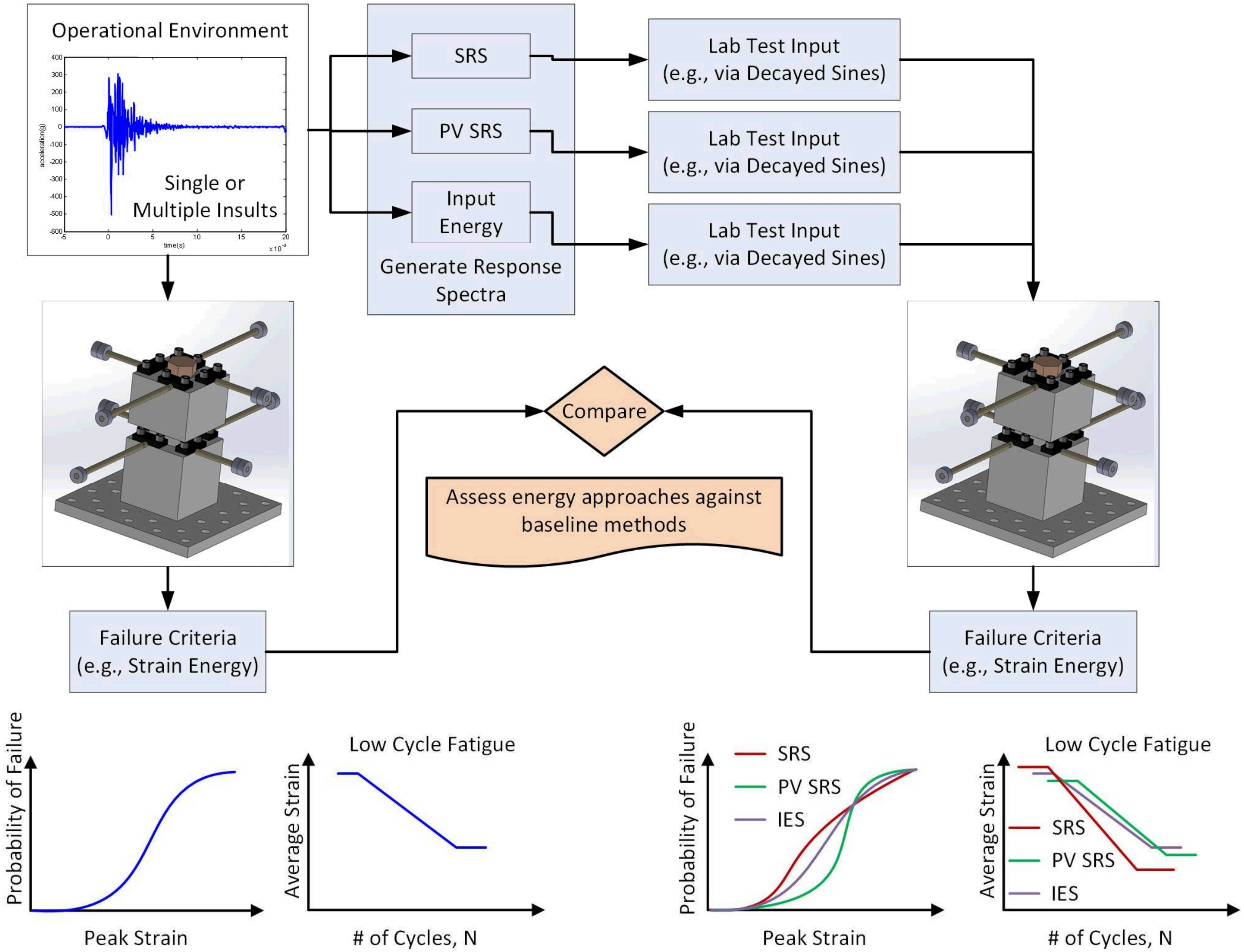
Characterize the effectiveness of energy-based methods for quantifying margins and uncertainties for shock environments

Loading and Damage Types



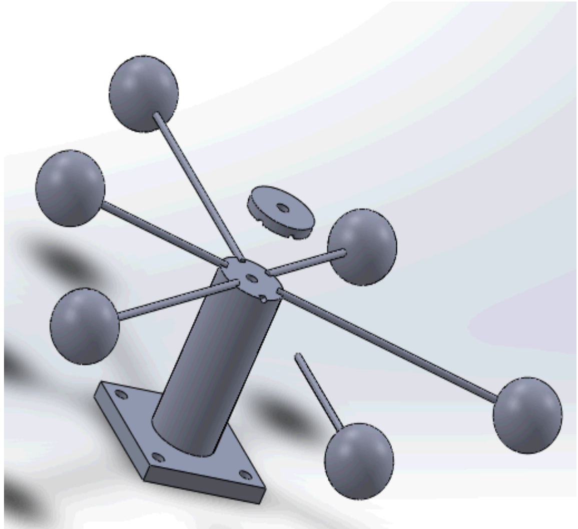
- In this project we are interested in the yellow and red regions
- If the part is not totally broken in the red zone, it is likely damaged and has no life left

Project Organization

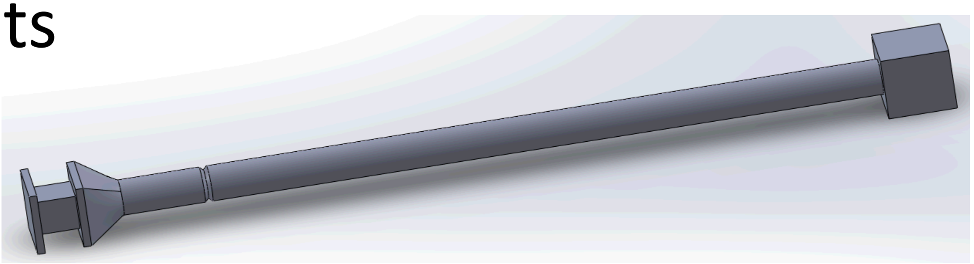


Test Structure

- Economical test fixture that can withstand rigorous amounts of testing
- Multiple test articles to facilitate testing
  - Use additive manufacturing to produce test articles
- After several iterations a fixture that met all requirements was designed



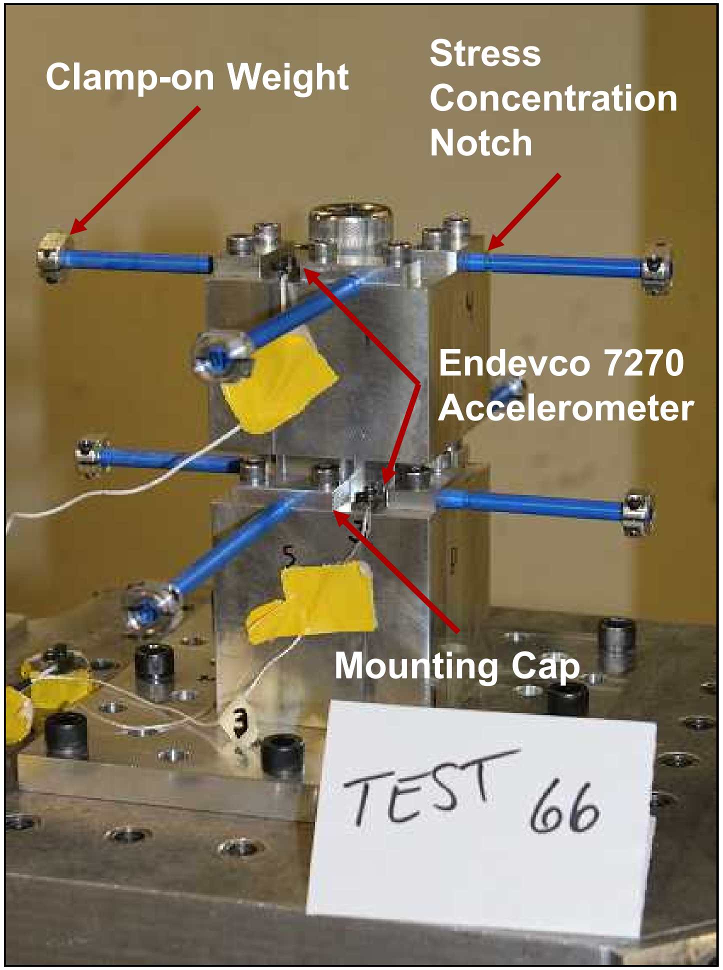
Early Concept of Test Structure



Early Version of Beam

Test Fixture

- Aluminum fixture compatible with drop table and shaker
- Each base section accommodates 4 beams (up to 8 total)
- 3D printed cantilever beams with stress concentration notches
  - Easily replaceable
  - Held in using caps that are bolted down to the structure
  - Clamp-on weights at beam ends
    - Used to tailor natural frequency and beam stress under shock
- Instrumentation
  - Endevco 7270 accelerometers on the base, middle, and upper tower levels
  - No instrumentation on beams for this round of testing

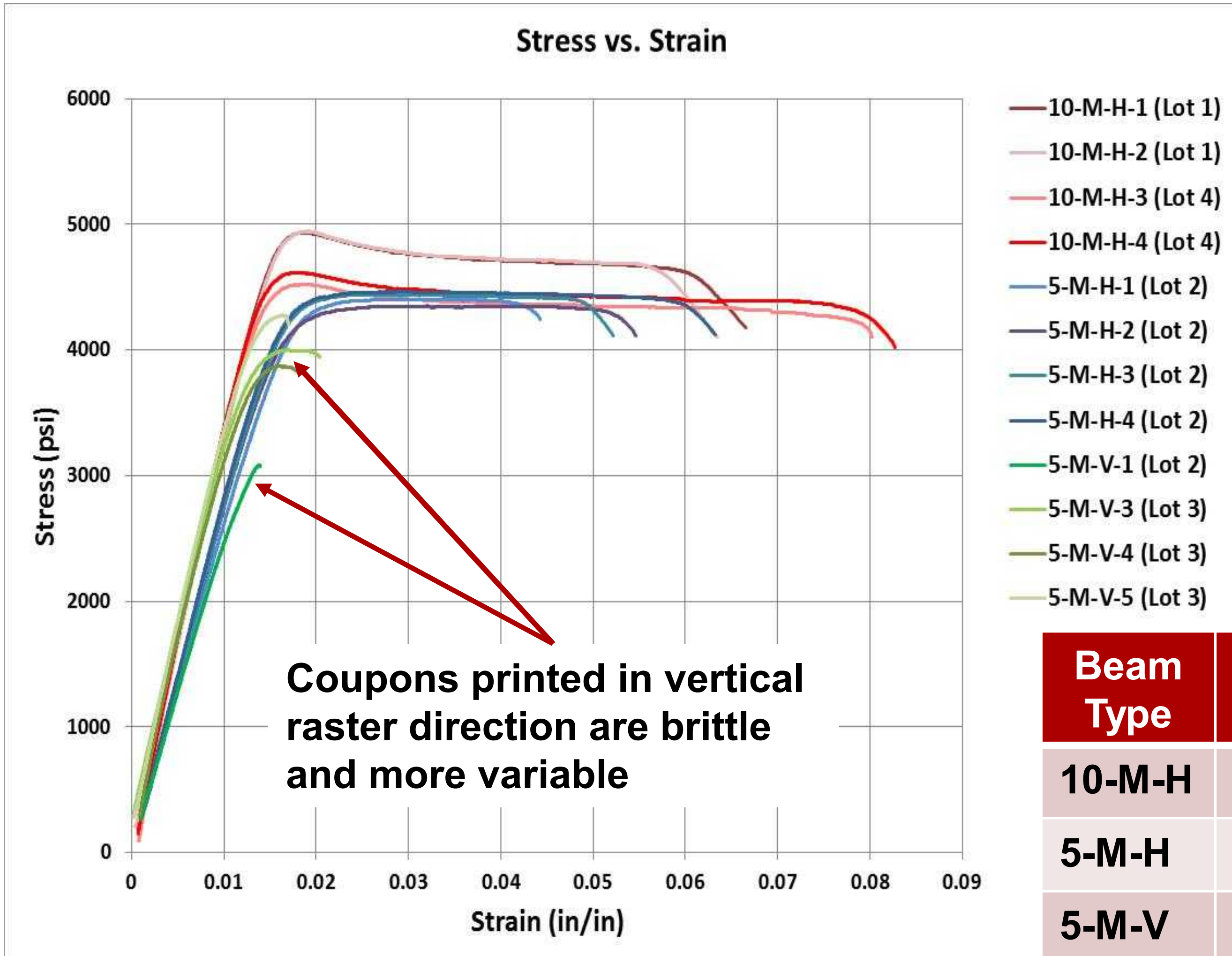


Cantilever Beam Description

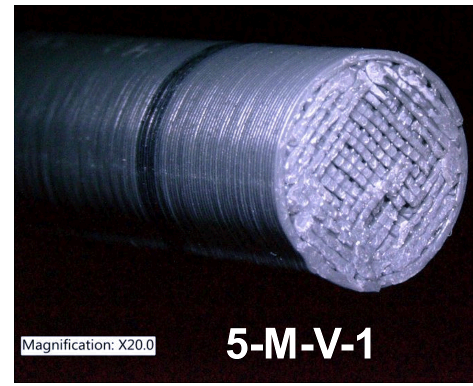
- SNL 3D Printing and Additive Manufacturing group made all beams
- All beams were made from ABS plastic
  - Cantilever beams were printed with layers oriented perpendicular to the beam axis
- Notched and Un-notched beams
  - Un-notched beams
  - 0.025 inch notch
  - 0.050 inch notch
- 3 inch and 5 inch lengths
  - 3 inch length needed to fit between uprights on the drop table

0.050” Notch 0.025” Notch

Elastic Properties of 3D Printed Beams



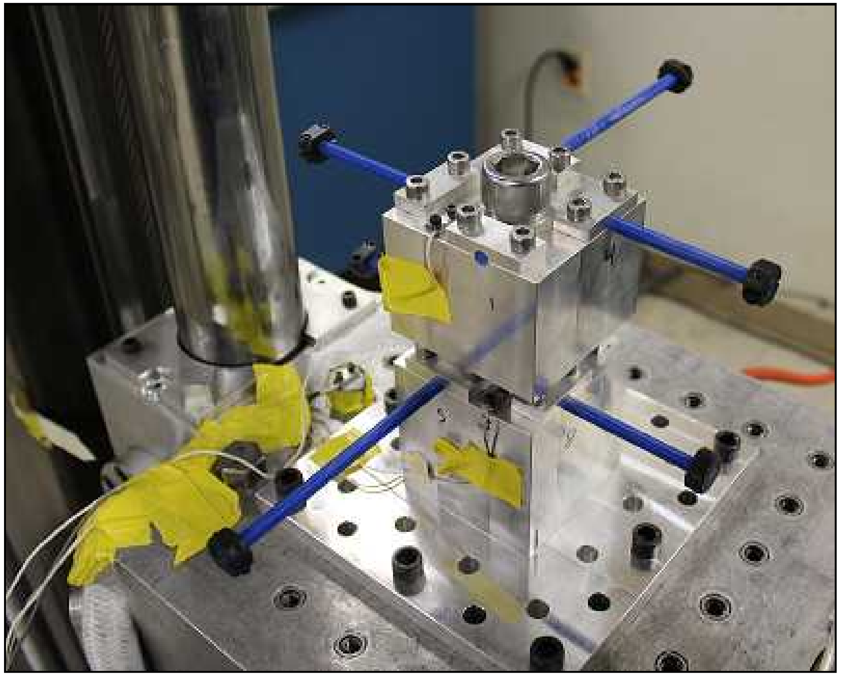
- **Static pull tests were performed on 3D printed coupons**



Beam Type	Avg Modulus (MPa)	Modulus CoV (%)
10-M-H	2342	1.9
5-M-H	1899	2.63
5-M-V	2026	8.94

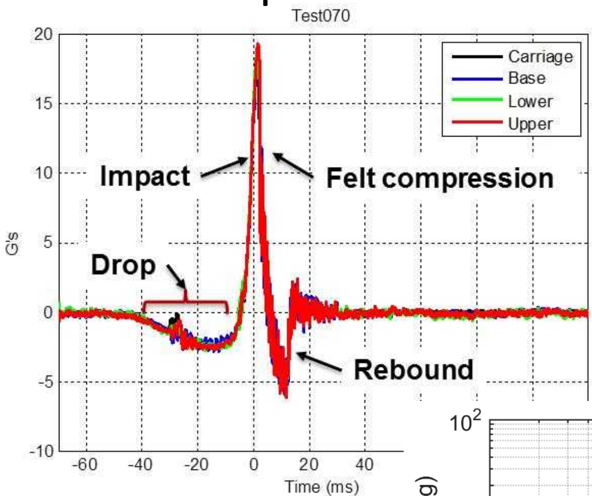
Shock Testing

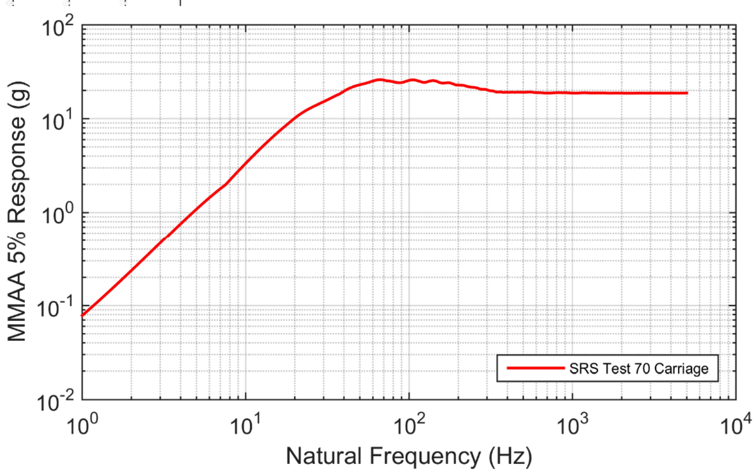
- Objective: Understand shock and low cycle fatigue failures of the 3D printed beams and related them to energy metrics
- Tested 72 cantilever beams on a drop table
  - Sets of 8 beams per test; four 5 inch and four 3 inch beams
- First passage failures
  - Stepped up input load incrementally until all beams failed
- Low-cycle fatigue failures
  - Repeated tests at input level well below failure levels until all beams failed
- Approximately 140 shocks

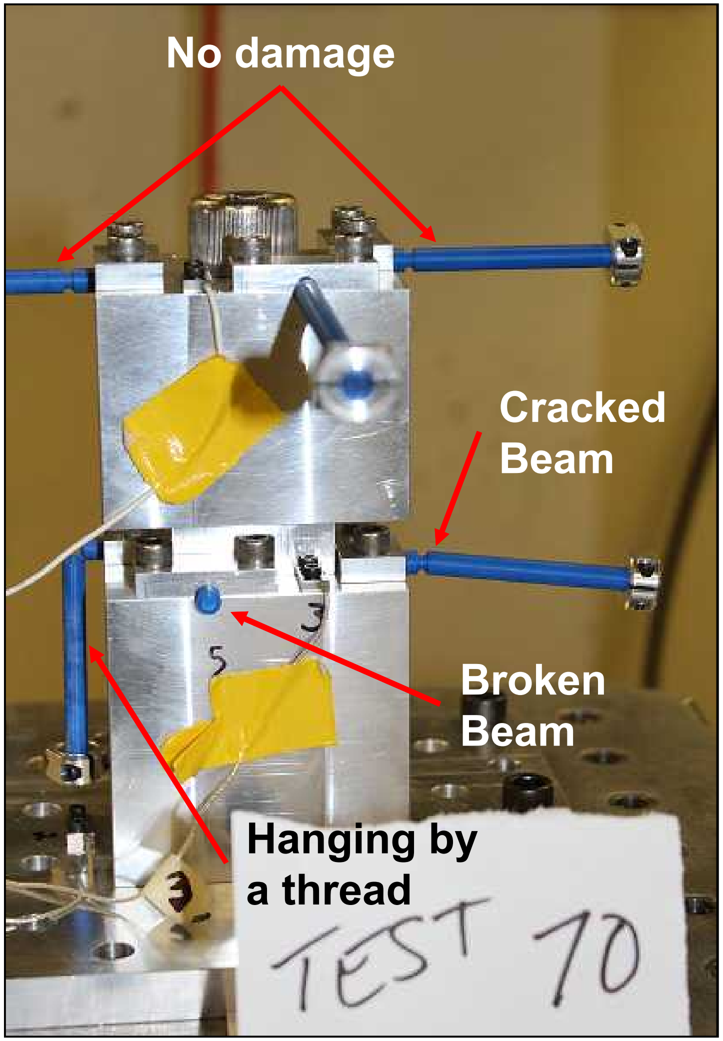


Shock Testing Failures

- All failures were brittle failures
  - Cantilever beams were intentionally printed to ensure brittle failure

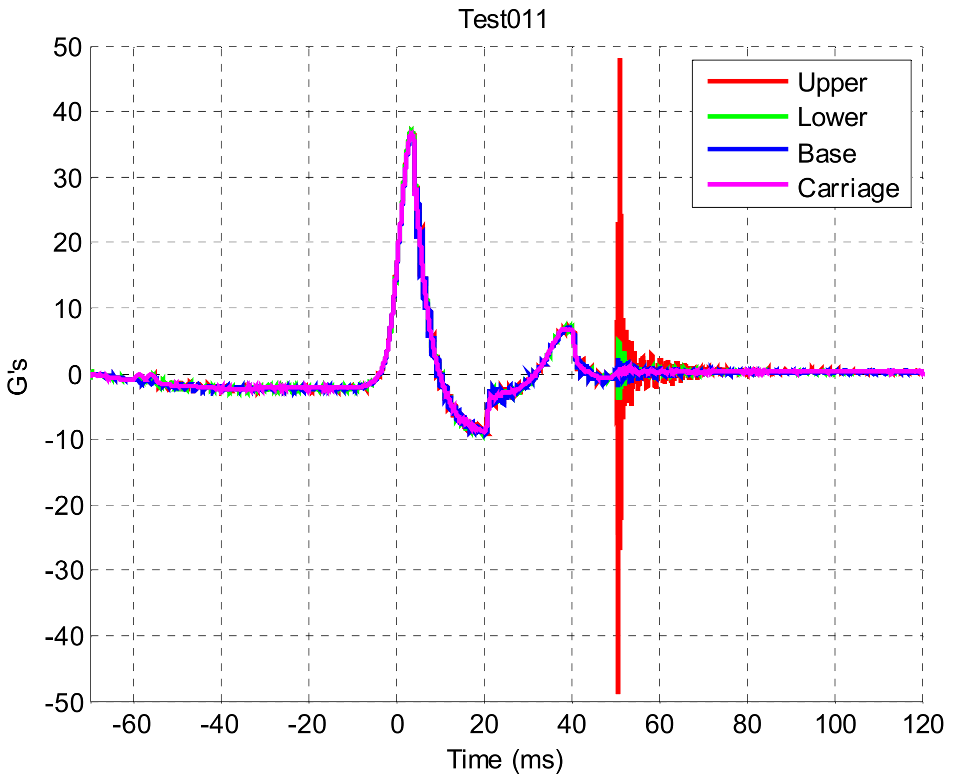






Typical Acceleration History

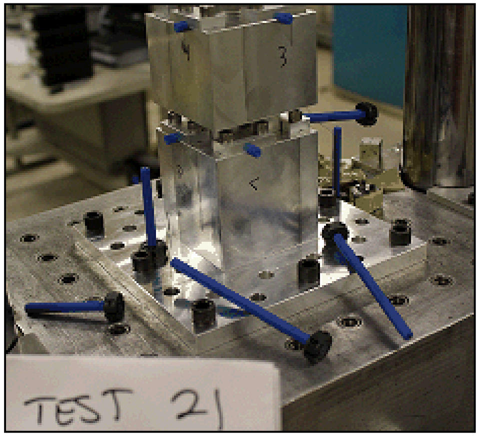
- Some time histories show multiple “shocks” per test
  - Some multiple shocks correlated to beams falling after breaking off



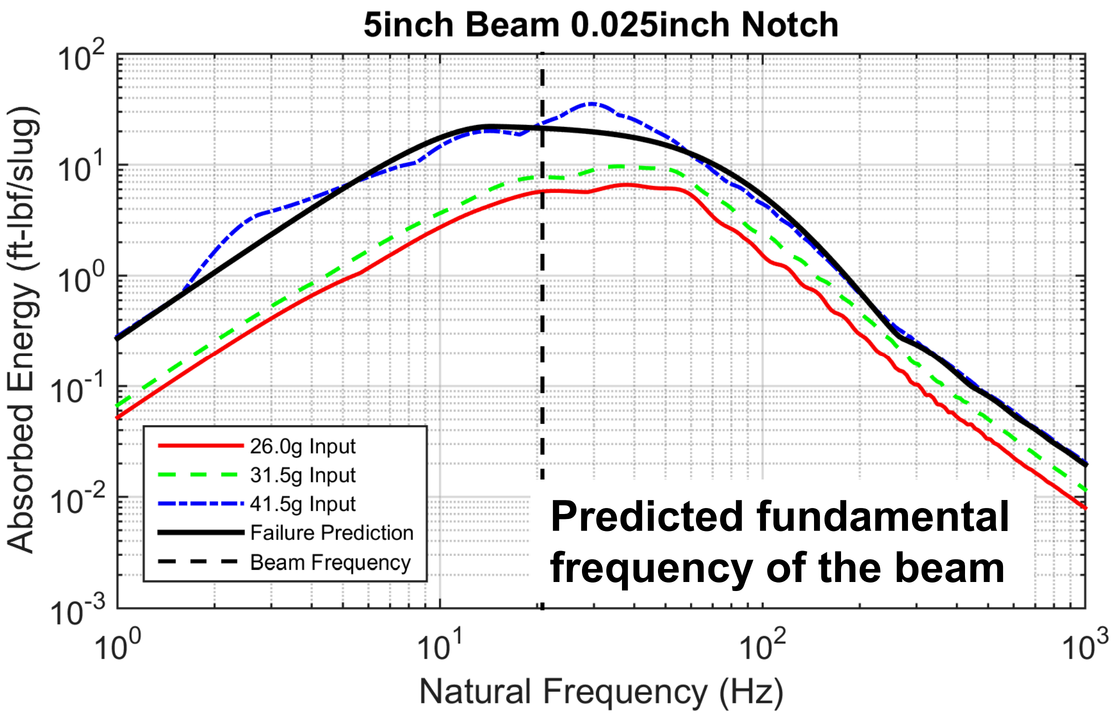
Shock Testing Results

- First tests were conducted to determine failure points of all beams and compare to FEA beam model predictions
  - Incremental nature of testing does not reveal the exact failure point
  - All tests were designed to achieve a nominal 90Hz Haversine pulse
  - Drop table was low end limited—unable to hit with less than ~21g
- Results generally show good agreement
  - Predictions for 5in un-notched beams were high

Length	Notch	Observed Test Failure	Predicted Failure
5 in	None	32.0g → 62.5g	64.5g
5 in	0.025 in	30.5g → 41.5g	38.5g
5 in	0.050 in	< 27.0g	18.8g
3 in	None	42.5g → 98.0g	58.8g
3 in	0.025 in	30.5g → 41.5g	37.4g
3 in	0.050 in	< 27g	20.4g



Overstress Shock Failure



- Test Series #3
- Pre-test prediction was pretty good for failure from a single shock

- Tested 4 beams to determine the input level for a single shock failure
- Found it on the 3rd try at 41.5 G
  - This might be conservative if the lower level inputs created some latent damage

Shock Testing Results

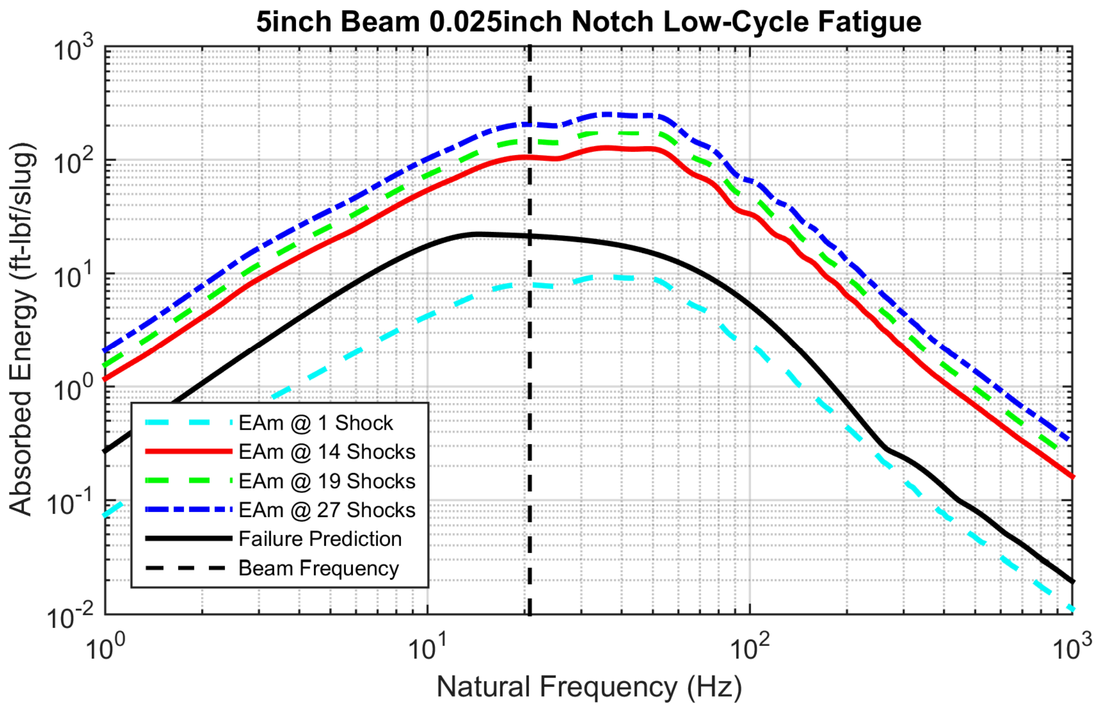
- Un-notched beams did not have a predictable failure location
  - Some failed inside the clamp
  - Others at various distances away
- Assume that failure occurs at locations of internal flaws or high porosity
- Notched beams showed significantly better predictability

Fatigue Testing Results

- One of the primary benefits of energy methods is their applicability to multiple shocks
- Simple low-cycle fatigue testing performed
  - Test level used was drop configuration one hit prior to first failure
  - Repeated shocks at nominally the same level until all beams failed

Beam Length	Notch	Tip Weight	Tested Shock Level	% of Strain Allowable	Average Hits to Fail	Range of Hits to Fail
5 in	None	0.028lbf	44.8g	61%	36	27 → 47
5 in	0.025 in	0.028lbf	31.7g	77%	19	14 → 27
5 in	0.050 in	0.010lbf	22.0g	61%	5	2 → 10
3 in	None	0.057lbf	38.8g	53%	3	1 → 6
3 in	0.025 in	0.028lbf	31.5g	78%	12	1 → 18
3 in	0.050 in	0.010lbf	21.7g	44%	13	4 → 33

Low Cycle Fatigue Results

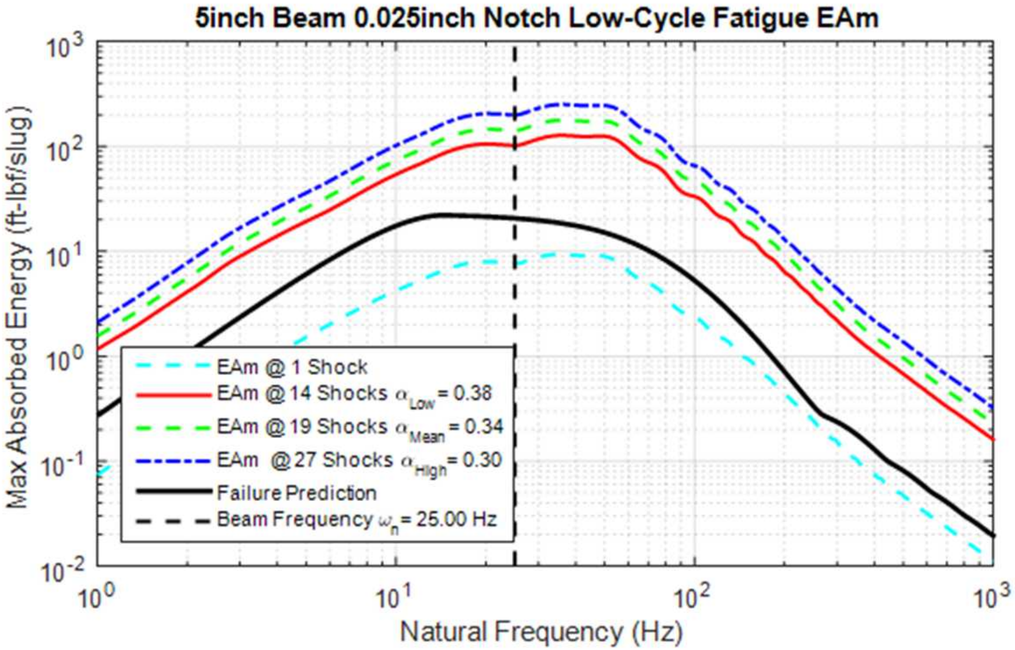


- Suggests the beam can absorb more energy from a series of small shocks than from one large amplitude shock

- Tested 4 beams with 31 g +/- 3 g 9 ms impacts to failure
- Beams had 1 steel collar
- Failure prediction is for a single impact
  - 41 G
- Absorbed energy lines are summed plots

Absorbed energy is not additive

Low Cycle Fatigue Energy Scaling



- Power law relationship is used in high-cycle fatigue S-N curves

- Consider the general power law form:

$$N^{\alpha} E_A = \widehat{E_A}$$

- If absorbed energy is additive, then $\alpha = 1$
- Figure suggests $\alpha = 0.34$ with

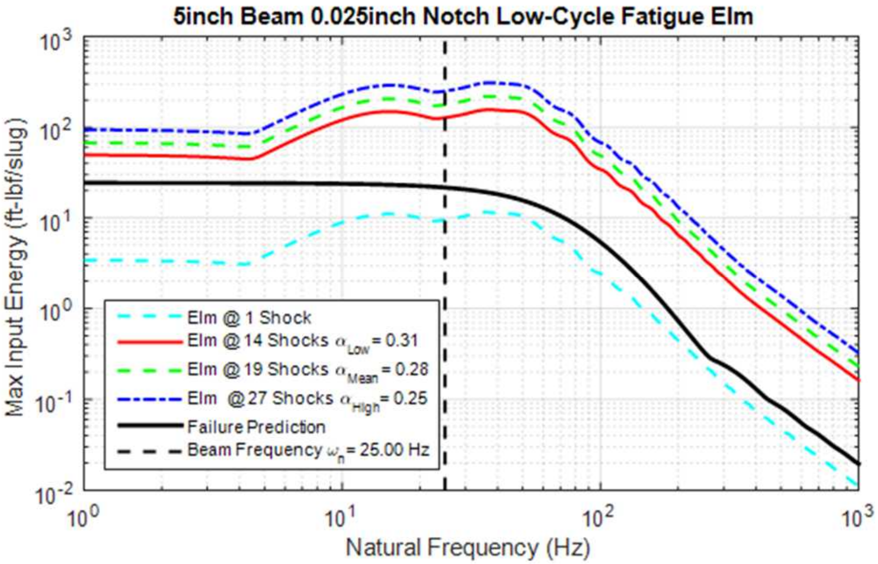
$$E_A = 8\ ft - lbf/slug$$

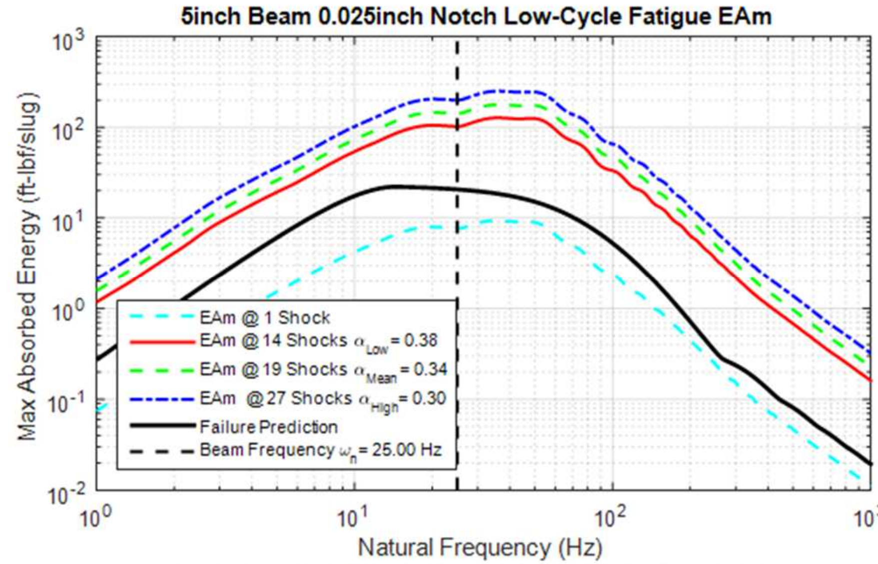
$$N = 19$$

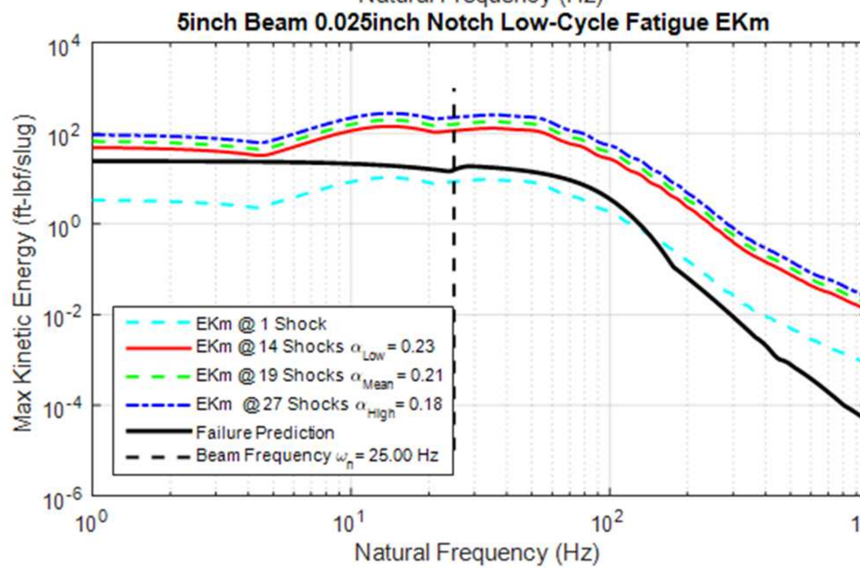
$$\widehat{E_A} = 20\ ft - lbf/slug$$

Power law relationship may apply to failure from multiple shock events

Low Cycle Fatigue Energy Scaling







	Total Energy	Absorbed Energy	Kinetic Energy
Min	0.31	0.38	0.23
Mean	0.28	0.34	0.21
Max	0.25	0.30	0.18

Conclusions and Future Work

- Conclusions
  - 3D printed ABS beams are remarkably consistent (best within a lot)
    - Print & test tensile coupons with each batch of beams
  - Test fixture functions as we expected
  - Predicted single shock failure levels reasonably well
  - Relationship of failure from accumulated shocks (low cycle fatigue) to single shock failure with absorbed energy needs to work
- Future Work
  - Perform shaker shock tests
    - Richer dynamic environment
  - Perform similar studies on realistic materials
    - Steel and Aluminum
  - Look at functional failures
    - Mechanisms and joints