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Defining Component Environments and Margin Through Zemblanic Consideration of Function Spaces

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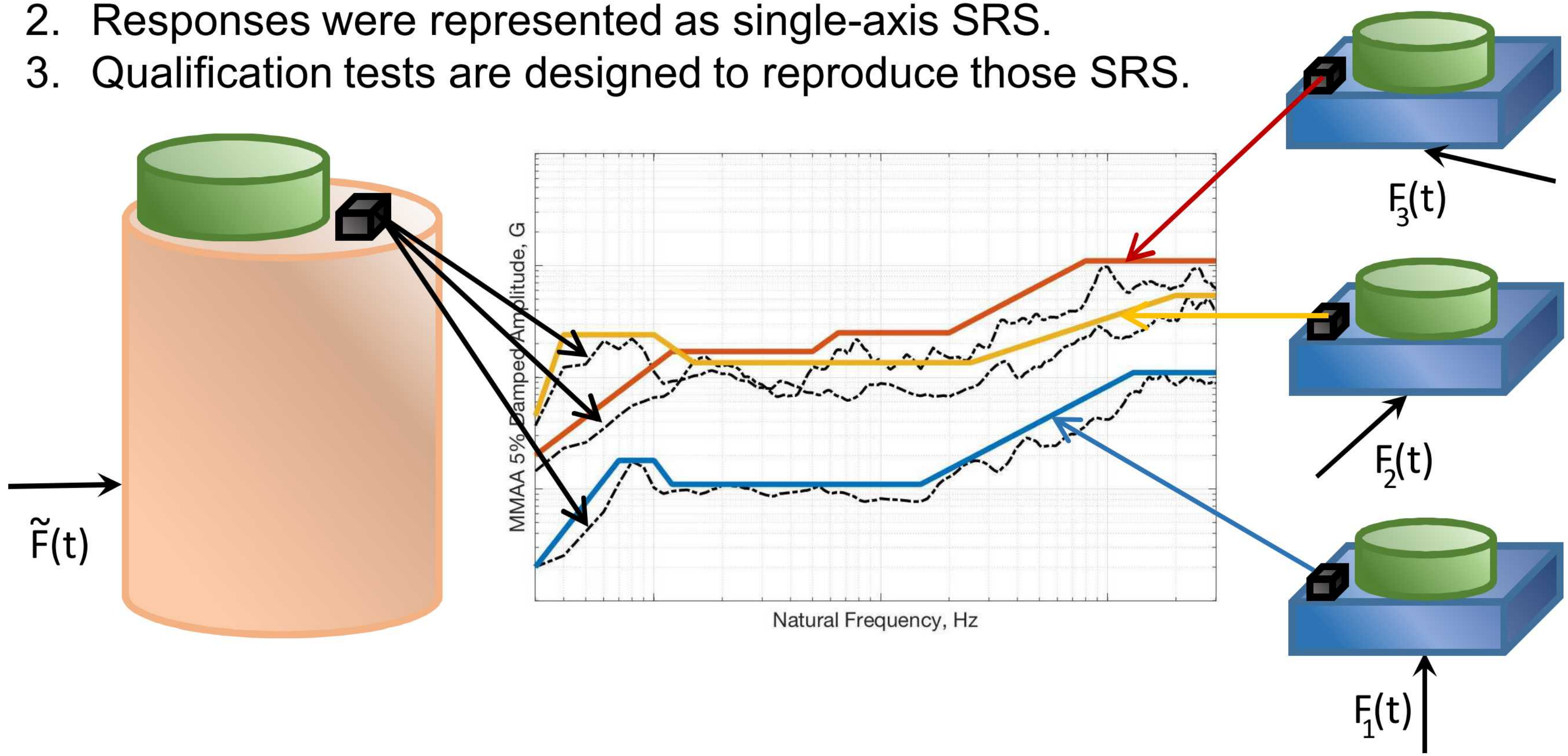
Idealized Description of Designing Qualification Specifications

1. An assembly experienced a field environment and responses were measured at or near the component of interest.
2. Responses were represented as single-axis SRS.
3. Qualification tests are designed to reproduce those SRS.



It is typically assumed that the manner of derivation of component-level inputs is a conservative characterization of the field environment.

The Problem with SRS

There are well-know deficiencies in Shock Response Spectrum (SRS) as a basis for qualification of components, among them:

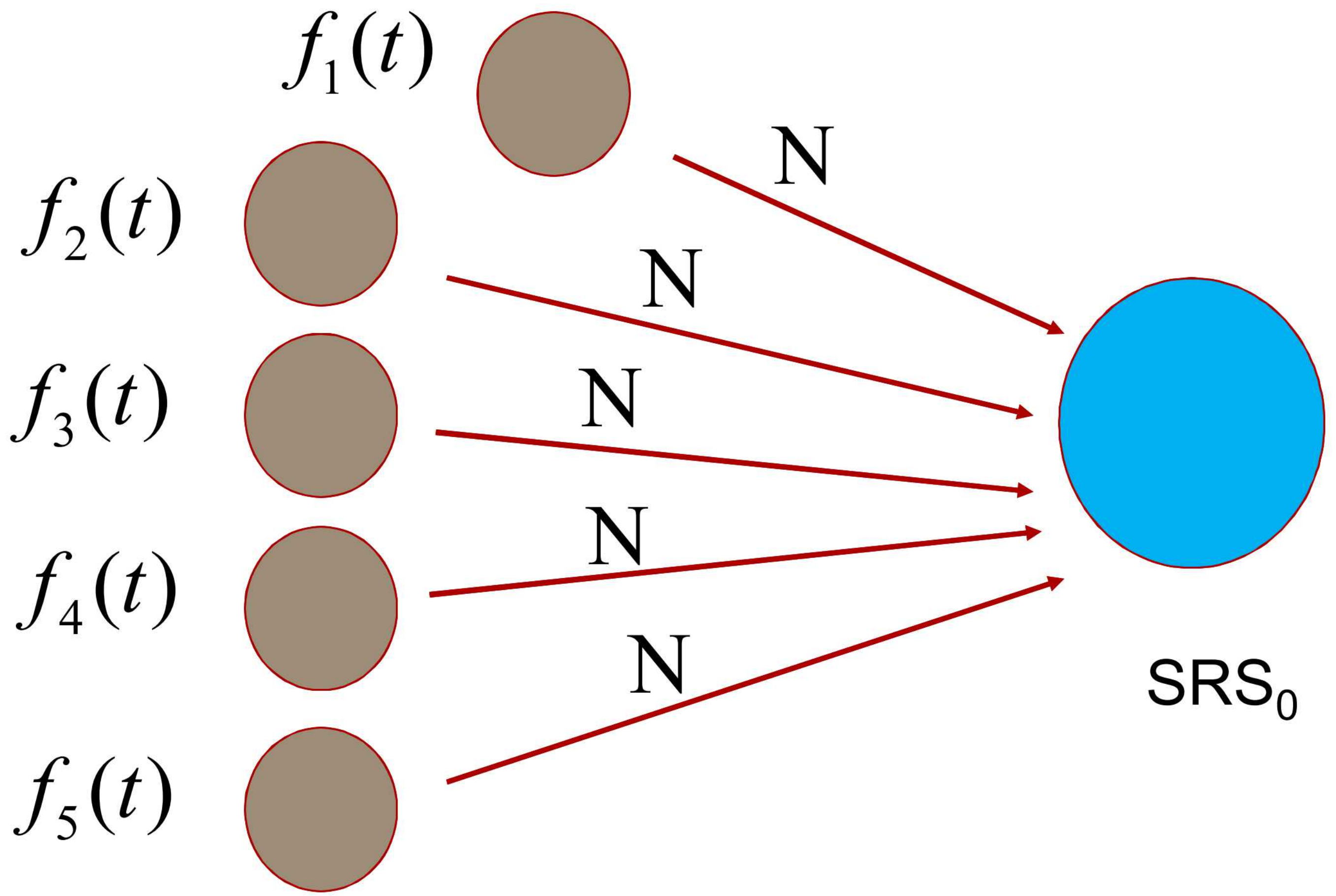
- Very different acceleration histories → same SRS.
- Conventionally, qualification test design is done without any consideration of the details of structural response or the nature of anticipated failure of its components.
- Advances since 1960s – particularly in material failure and simulation – are ignored.
- Over-testing occasionally happens, even on components that had previously qualified.
- This approach may not even be conservative.

On the Other Hand

We are somewhat married to SRS:

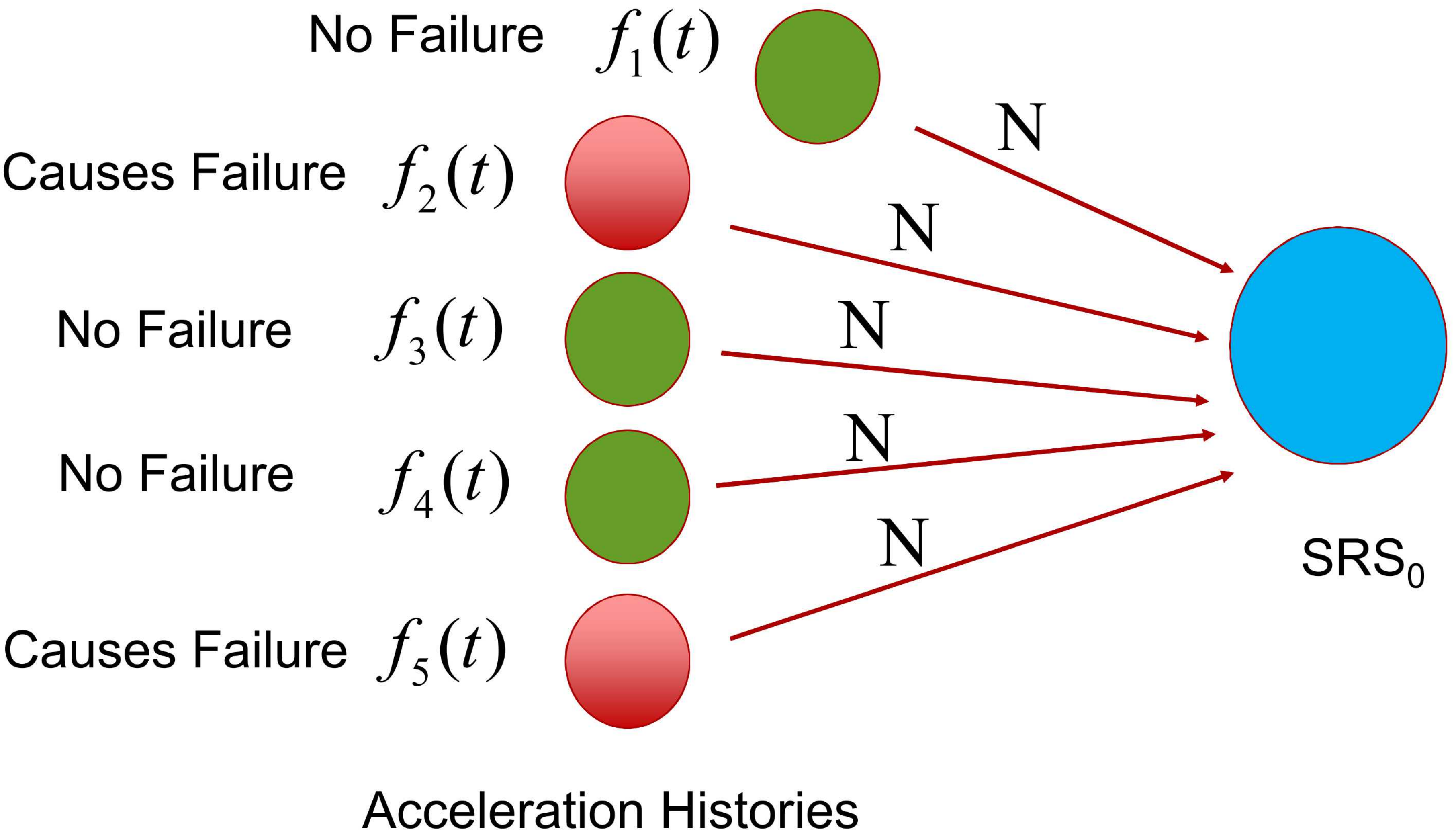
- SRS is often the only data still available from past system tests and hence the only basis on which to devise qualification tests.
- Much of the current environmental procedures are built around the legacy process.
- It is a process with which practitioners have become very comfortable.
- Despite an acknowledgment of the limitations and non-rigorous character of the current system, no more physics-based approach has been proposed.

Root Problem: Non-Uniqueness Issue



Acceleration Histories

Root Problem: Non-Uniqueness Issue



Mathematically

- Note that SRS process maps acceleration history to a frequency space function, but the mapping is not invertible.
  - An infinite number of acceleration histories map to each SRS
  - Per Smallwood the following is plausible

$$\text{Given } N\big(f_1(t)\big) = SRS_1(\omega) \text{ and } N\big(f_2(t)\big) = SRS_2(\omega)$$

$$SRS_1(\omega) < SRS_2(\omega) \text{ for all } \omega$$

$$\text{but } f_1(t) \text{ causes failure, while } f_2(t) \text{ does not}$$

  - An acceleration's SRS is a characteristic of that acceleration but does not adequately define it.

A Little More Detail

- Conservativism
  - As Smallwood showed, a test with an SRS that envelopes one that causes failure might itself not cause failure.
  - Only the Least Favorable Response is mathematically proven to be conservative, but that may not be experimentally feasible.
- More detail about experiments
  - Severe limitations on types of history achievable from some types of experiment
    - Drop table and light initiated explosive – both impulsive in nature
  - Even general test platforms – such as shakers – have limitations in peak acceleration, frequency bands, power-time trade offs.

Desirable Process for Qualification Testing

- Uses what is known experimentally – generally SRS.
- Has clear line of physics (and mathematics) connecting what we know of anticipated loads (SRS), implementable experiments, and knowledge of component failure.
- Makes optimal use of experimental capabilities.
- Focuses on actual modes of component failure.
- Fully employs modern simulation tools to introduce physics between applied loads and resulting excitation on components.
- Provides tools for integrating SRS data from multiple directions.

Proposal: Solve the non-uniqueness problem by making test selection and design an optimization problem using the prescribed SRS as a constraint.

Our optimization will be an illustration of Zemblanity. Zemblanity is the opposite of serendipity, it is the faculty of making unhappy, unlucky and expected discoveries by design.

Mathematical Formulation in One Dimension

Assuming that we have a good structural model and a quantified failure criterion:

- In the following we assume a mapping from acceleration history to some failure measure of the component.

$$m = F\big(f(t)\big)$$

Think rupture stress at some critical location.

- Also for each test type, T_k, there will be a parameter set $\{\beta\}_k$. Let $\{B_k\}$ be the set of achievable experiments. We shall have to restrict our attention to parameter sets such that

$$\{\beta\}_k \in \{B\}_k$$

Such as tower height in drop test.

- The resulting achieved experimental acceleration history will be

$$f_k(t, \{\beta\}_k)$$

Use an Optimization Process to Identify An Appropriate Qualification Test

- Define $m_k^* = \max_{\beta_k \in B_k, N(f_k) < SRS} F(f_k)$

This is the best that can be done through test T_k to find a qualification exposure level using this test.

- Now consider all the tests available to us and select the one harshest with respect to known failure modes

$$m^* = \max_{T_k} m_k^*$$

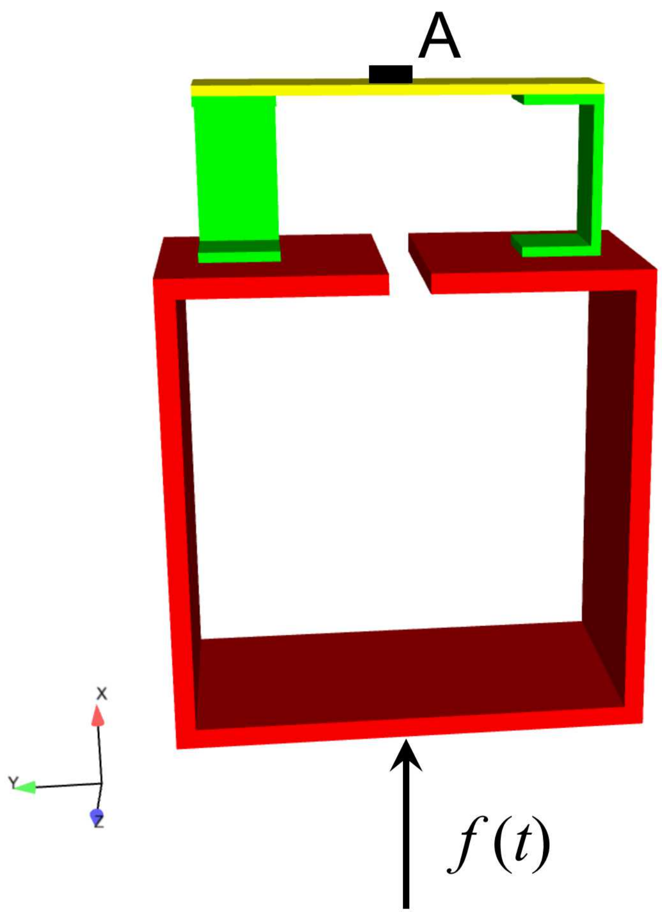
This is the most conservative test that can be performed with our available equipment.

Generalization of the Optimization to Multiple Axis Inputs

- Say that we are given SRS_1 and SRS_2 associated with accelerations in the x and y directions. These are what is postulated for some segment of a qualification specification.
- We consider available multiaxial tests T_k and the associated accelerations $f_{k,\beta_k} = f_{k,\beta_k}^{x}(t)\mathrm{i} + f_{k,\beta_k}^{y}(t)\mathrm{j}$
- Again, there are inherent constraints on achievable test parameters: $\beta_k \in B_k$
- We then extend the optimization problem to multiple dimensions

$$m_k^*(\omega) = \max_{\beta_k \in B_k, N\left(f_{k,\beta_k}^{x}(t)\right) \leq SRS_1, N\left(f_{k,\beta_k}^{y}(t)\right) \leq SRS_2} F\left(f_{k,\beta_k}(t)\right)$$

Illustrated with the Numerical Representation of the BARC Geometry

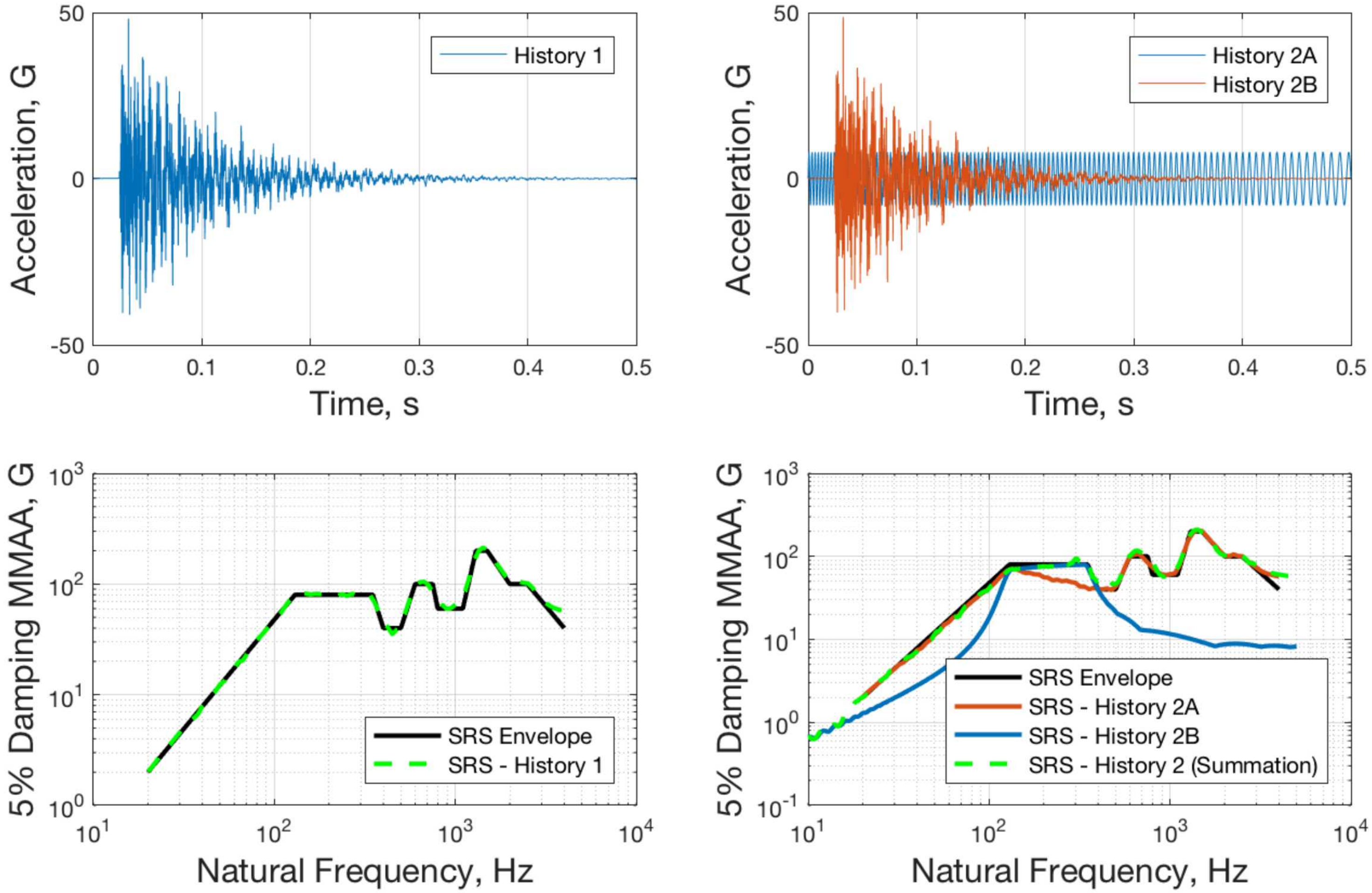


Simulate transient shock input, calculate plate curvature in vicinity of a critical component A

$$\kappa = \frac{\partial^2 x}{\partial y^2} \propto \sigma$$

Derive multiple realizations of single-axis inputs from families of SRS.

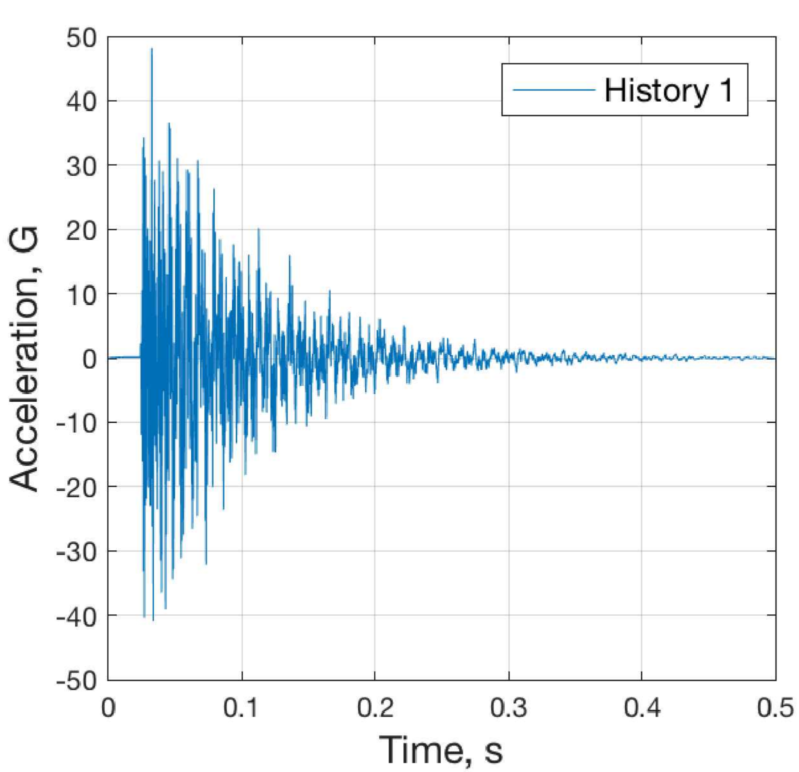
An Example Construction of Time Histories Which Preserve SRS

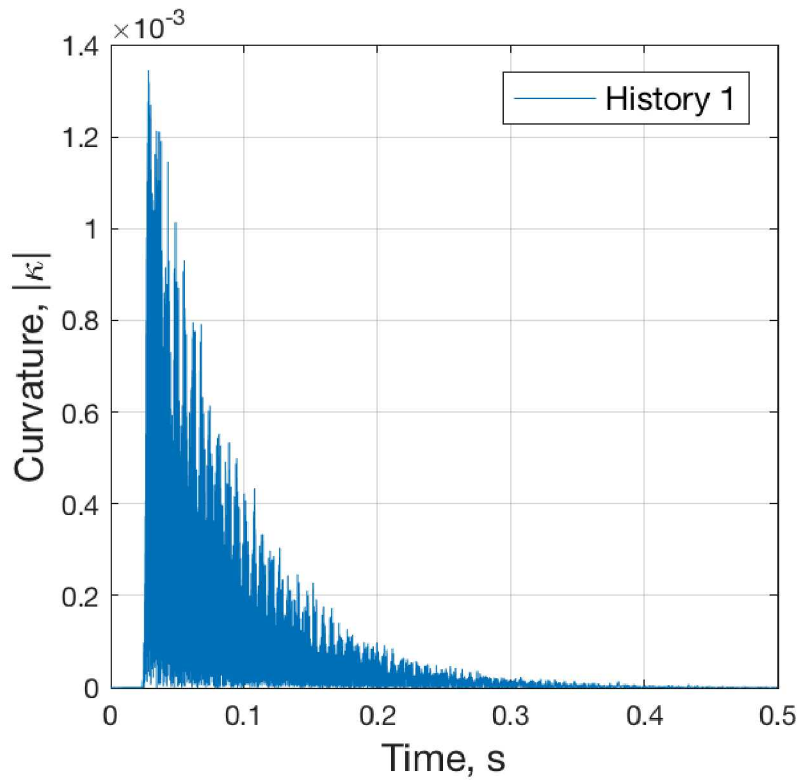


This and other constructions are used to develop equivalent testable time histories.

Let's Look at Predictions of Our Failure Measure

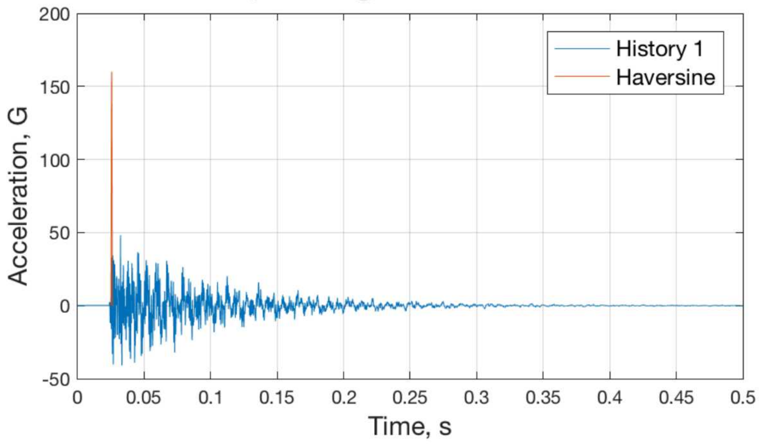
- For time history 1 (left), the curvature at Component A on the BARC structure is predicted (right).

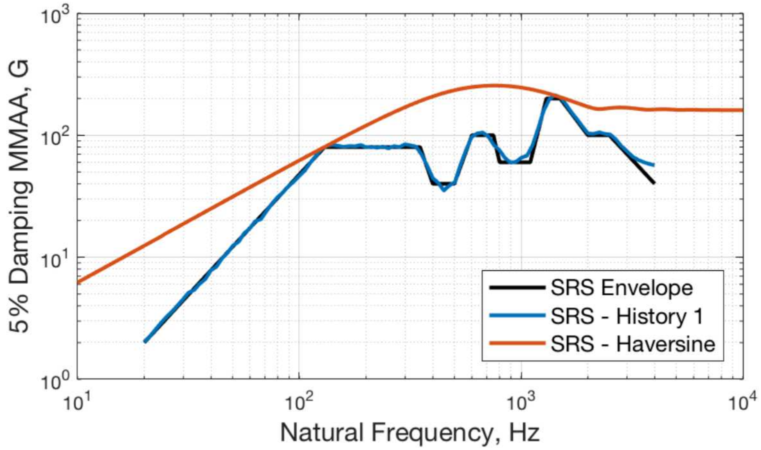




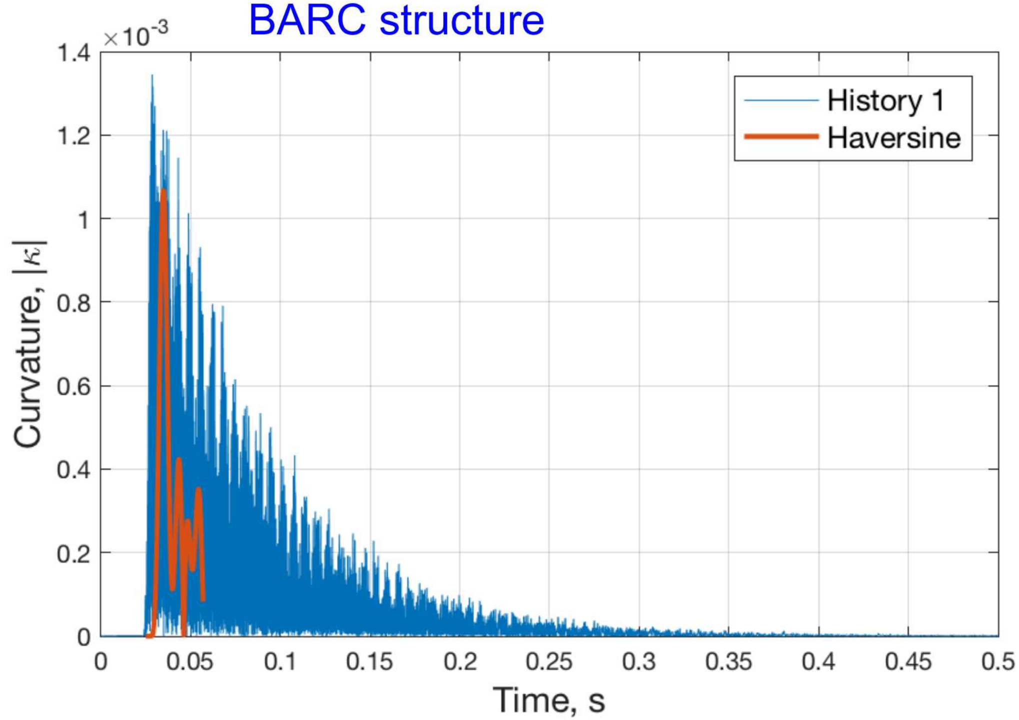
Failure may manifest as a single-passage stress-rupture failure, or perhaps as a low-cycle fatigue mechanism.

Aside: What if We Predict Response From an Enveloping Haversine?





Curvature at Component A on the BARC structure

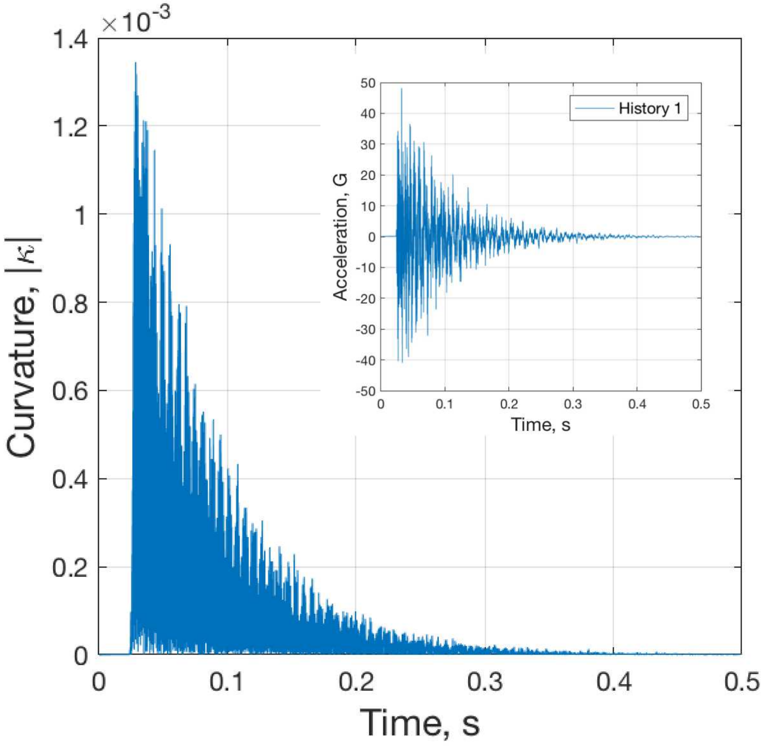


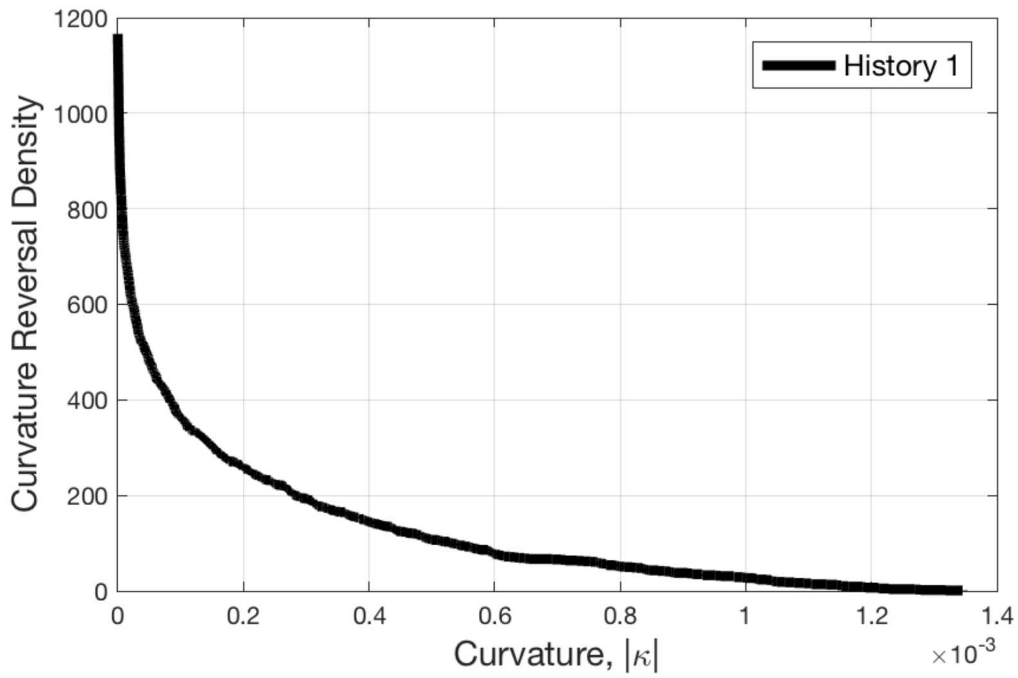
Note: time axis has been expanded for the haversine curve

The haversine is not conservative with respect to single-passage failure measure despite enveloping the SRS.

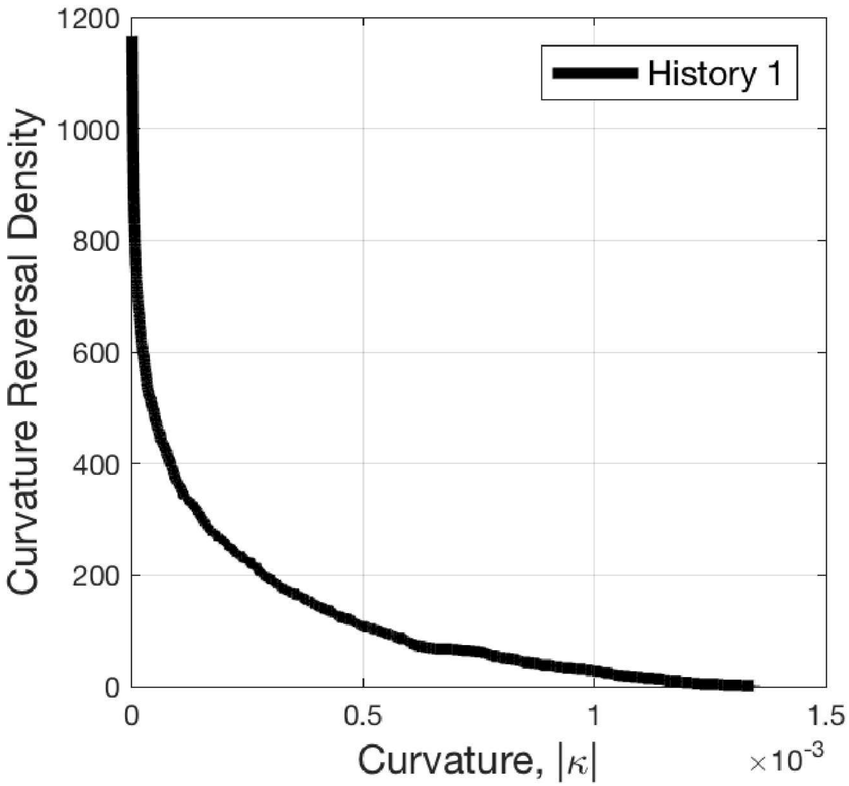
Consider the Number of Curvature Reversals for the Predicted Curvature

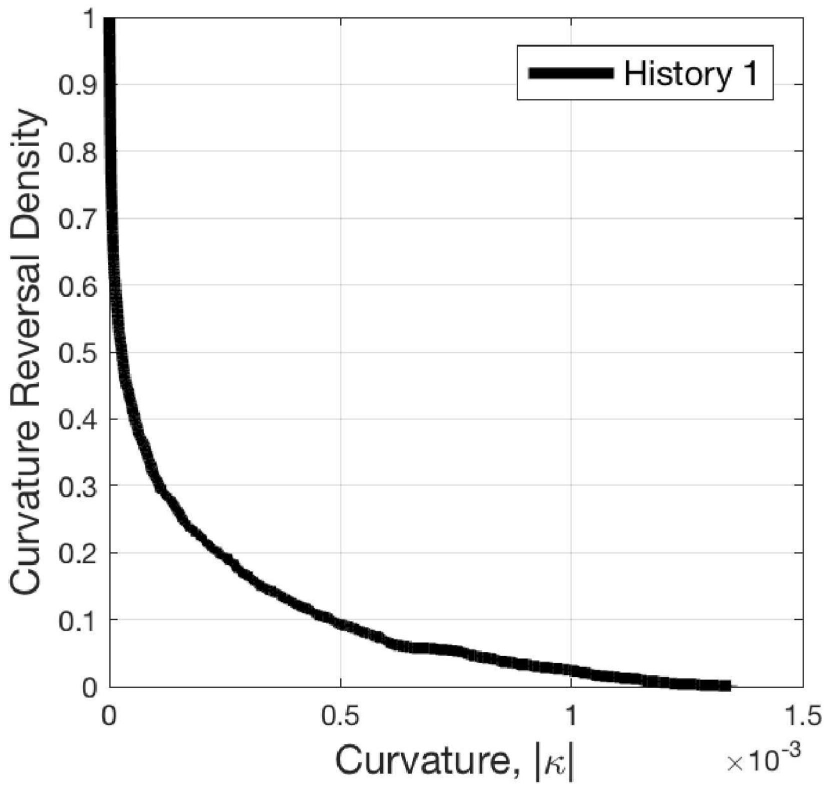
- The predicted curvature at Component A (left) on the BARC structure from time history 1 (left inset) leads to curvature reversal density (right).





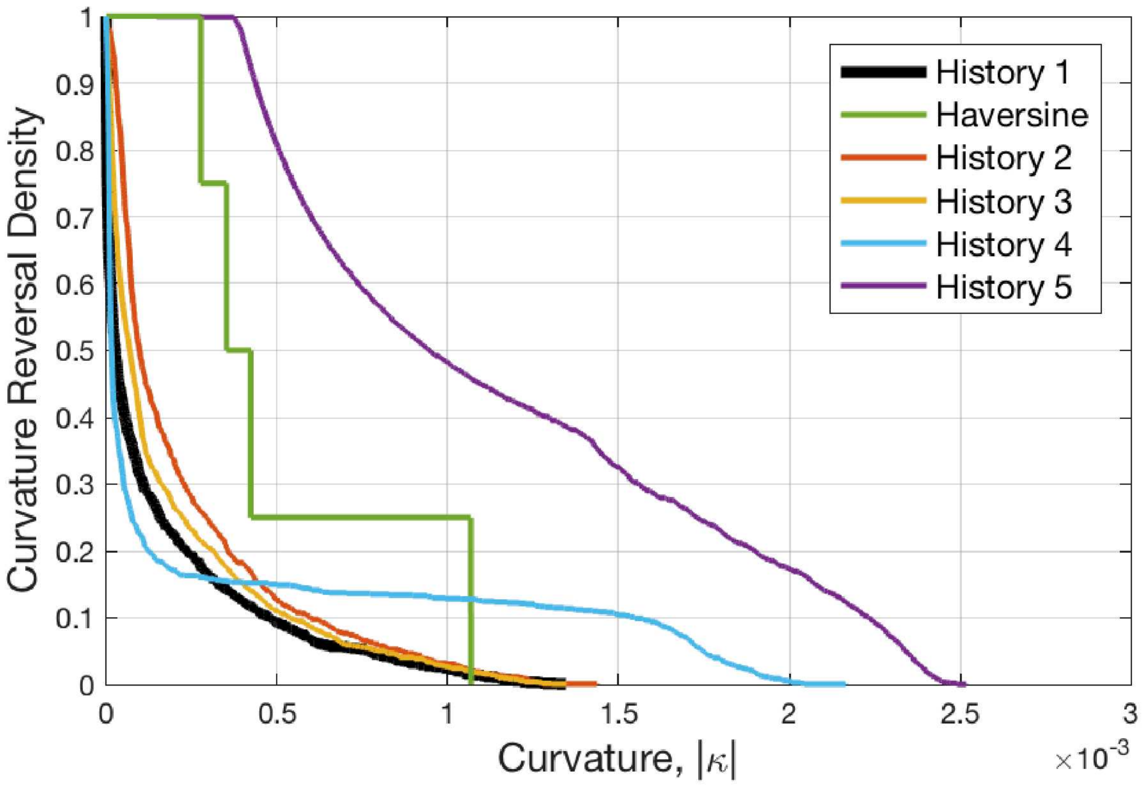
Consider a Simple Normalization to Visualize Histories With Different Underlying Character





Reversal density is a measure of frequency of exposure to a threshold curvature during the transient shock event.

Execution of an Optimization Process to Predict Reversal Density of Our Failure Measure



History 1 is that shown previously for the decayed sine synthesis of input transient. (Green curve is haversine).

Each of the synthesized time histories has the same input duration.

Optimization requires an explicit understanding of the mechanics and dynamics of the article under test.

Discussion

- Effective use of this approach requires high-level of understanding of component under investigation.
  - model calibrated to some experimental data (modal, strain, etc.)
  - location of component vulnerabilities
  - relationship between input, response, and damage metric

- Areas for further investigation include:
  - Automating the process of scanning and optimizing over candidate tests and test parameters.
  - Using this foundation to define and estimate margin

The point of all of this is selection and design of the most conservative test consistent with a given SRS.

Qualification requires actually performing that test.

Backup Slides

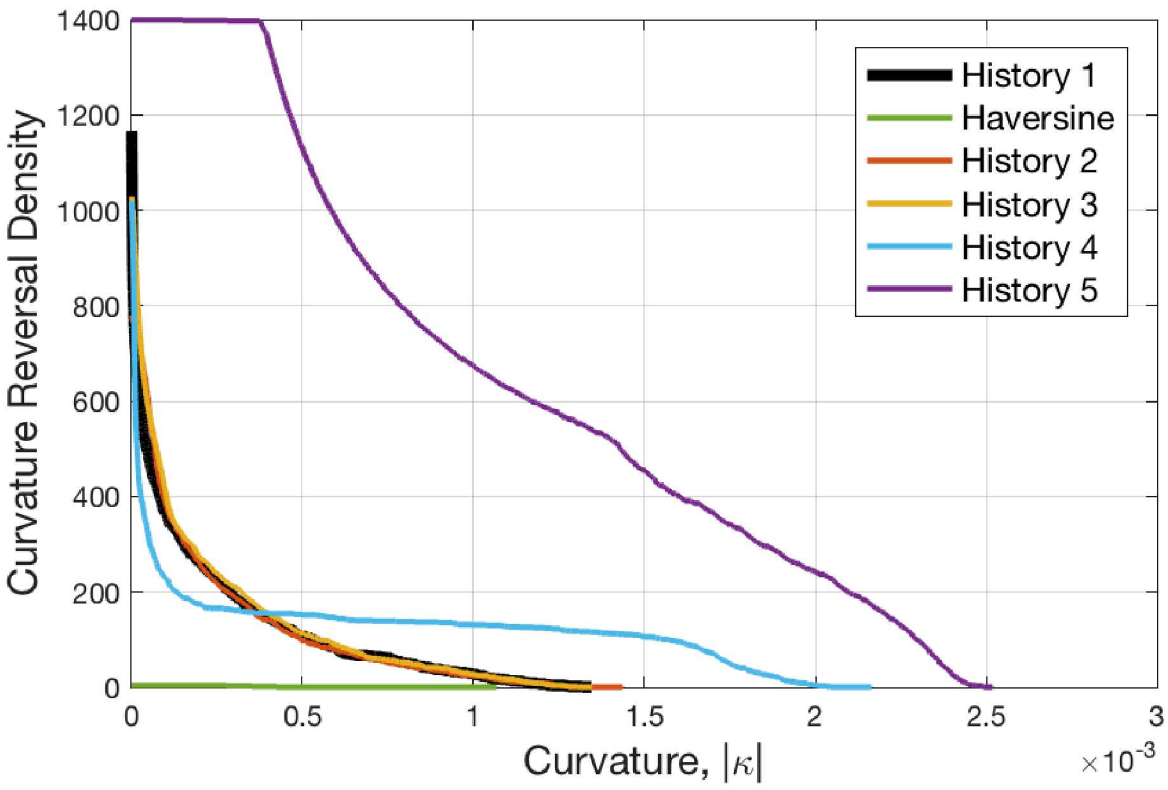
Current Practice

1. Component specifications are written in terms of Shock Response Spectrum (SRS). *(These often legacy quantities, but we do not dispute their provenance here.)*
2. An experimentalist selects a test that will reproduce that SRS.
3. The experiment is performed and the component qualifies or not.

What Do We Know About SRS?

- SRS is a nonlinear mapping from acceleration history to the frequency domain, but there is no assertion that histories with the same SRS are in any other way equivalent.
- Presumption of conservativism is unfounded.
- There is an intuitive basis, but no physics basis for this process.
- Modern experimental, and particularly modern simulation tools, are ignored.

Non-Normalized Comparison of Curvature Reversals



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