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Impact Dynamics Research at Sandia National Laboratories

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Component Science and Mechanics
Sandia National Laboratories

Sandia National Laboratories

Outline

- **Introduction to Sandia National Laboratories**
  - Broad Research Overview – The Four Mission Areas of Sandia
    - Nuclear Weapons
    - Defense Systems
    - Energy Resources
    - Homeland Security
- **Overview of Nonlinear Dynamics Research**
  - Center and Departmental Research
- **Impact Dynamics Research**
  - Constitutive Relationships
    - Understanding the Physical Processes
    - Experimental Validation
  - Exact and Approximate Solution Methods
    - Application to Analytical and Numerical Models

Sandia National Laboratories

Sandia National Laboratories

Four Mission Areas:

- **Nuclear Weapons**
- Defense Systems
- Energy Resources
- Homeland Security

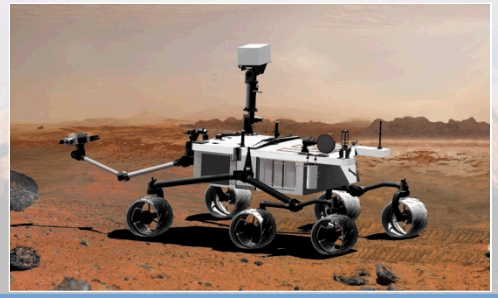
- Research, Design, and Development of Non-Nuclear Components (96% of Total NW Parts)
- Life Extension of Nuclear Weapons
- Neutron Generator (NG) Manufacturing
- Stockpile Support – maintenance, military liaison, surveillance, dismantlement, logistics
- Nuclear Materials Protection

Sandia National Laboratories

Four Mission Areas:

- Nuclear Weapons
- **Defense Systems**
- Energy Resources
- Homeland Security

- Science & Technology Products
- Surveillance & Reconnaissance
- Integrated Military Systems
- Remote Sensing and Verification
- Information Operations
- Proliferation Assessment



Sandia National Laboratories

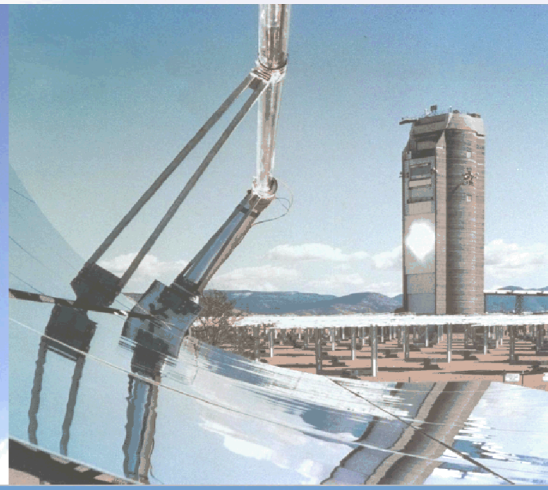
Four Mission Areas:

- Nuclear Weapons
- Defense Systems
- **Energy Resources**
- Homeland Security

Energy and Fuels:

Institutions Ranked by Citations

Rank	Institution	Citation ('98-'08)
1	**Sandia National Laboratories**	**4,147**
2	National Renewable Energy Lab	3,773
3	CSIC (Spain)	3,678
4	Chinese Academy of Sciences	3,541
5	Indian Institutes of Technology	3,166



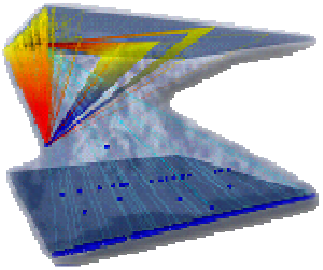
Sandia National Laboratories

Four Mission Areas:

- Nuclear Weapons
- Defense Systems
- Energy Resources
- **Homeland Security**

- We're the specialists that solve national, engineering emergencies:
  - Gulf Oil Spill
  - Challenger Disaster
  - Anthrax Mailings
  - …

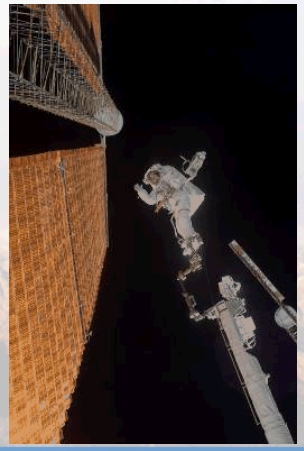
Cyber Security



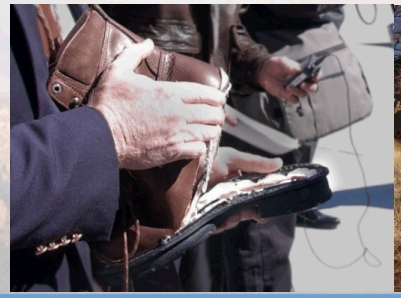
Analysis of the I-35 Bridge Collapse

Synthetic Aperture Radars

Laser Dynamic Range Imager Orbiter Inspection System (LOIS)



Unabomber and Shoe Bomber Investigations

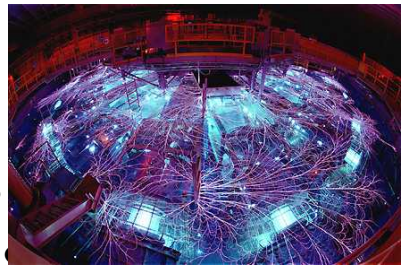


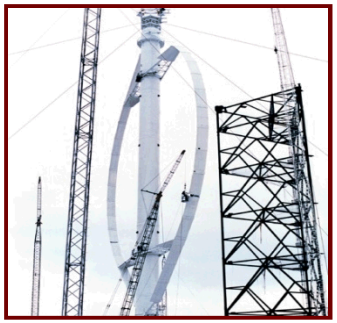
Engineering Sciences: Solid Mechanics/Structural Dynamics

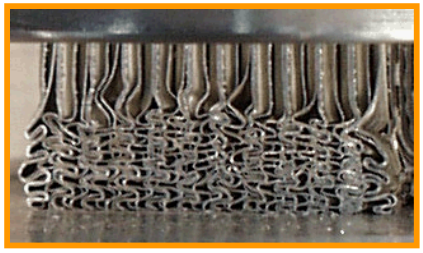
Mission: Provide the research, development, and applications expertise in solid mechanics and structural dynamics required for Sandia to accomplish its mission in nuclear weapons and other national security areas

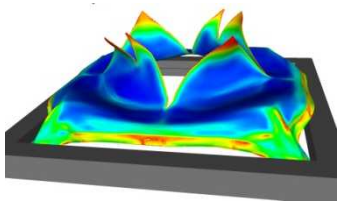
Solid Mechanics

- Nonlinear Computational Mechanics
- Experimental Solid Mechanics
  - Diagnostic Development & Application
  - Production Testing
  - Certification & Failure Margin Testing & Discovery
- Material Response



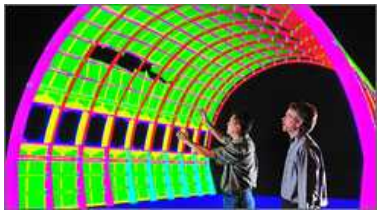


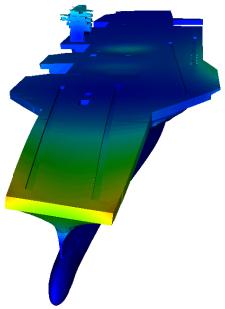


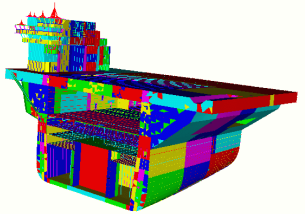


Structural Dynamics

- Modal, Shock & Vibration, acoustics
  - Computational
  - Experimental
- Nonlinear Structural Dynamics
- Smart Structures & Controls
- Nondeterministic Methods & Optimization







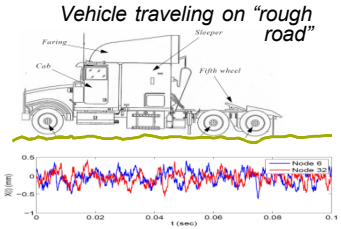
Component Science and Mechanics

Mission: To conduct frontier research in mechanics and provide technical solutions to accomplish Sandia's goals in Micro- and Nano-systems vision and Science-Based Engineering process.

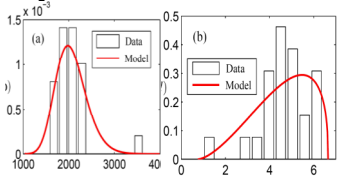
Probabilistic Mechanics **Micro- and Nano-Mechanics**

Scientific Knowledge and Technology Development

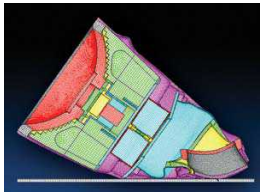
Safety and Critical Components



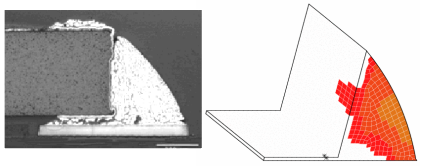
Dynamic Environment



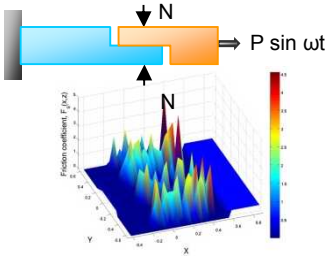
Parameter Uncertainty



Component Modeling

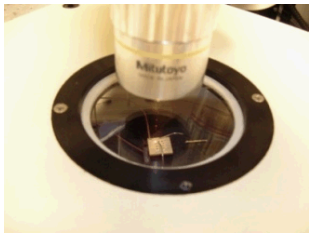


Coarsening leading to Cracks

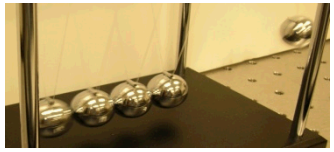


Energy Dissipation in Joints

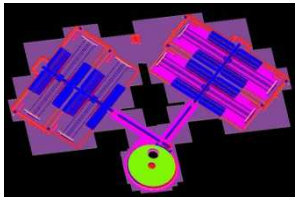
Solder Joints



Micro-Diagnostics

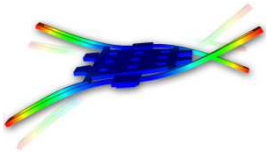


Elastodynamics of Rebound

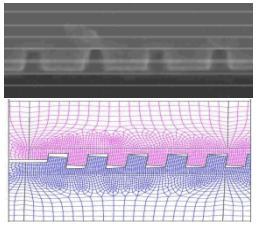


MEMS Switch

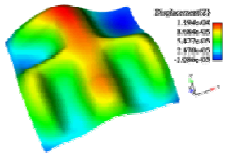
RF MEMS



Coupled-physics



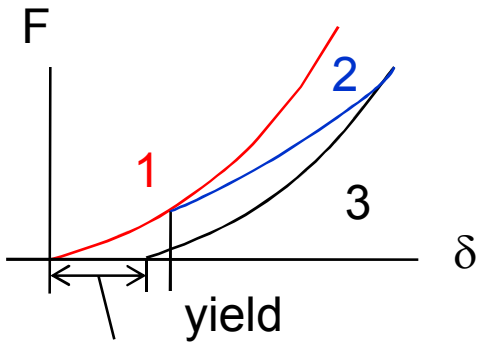
Nano-Patterning



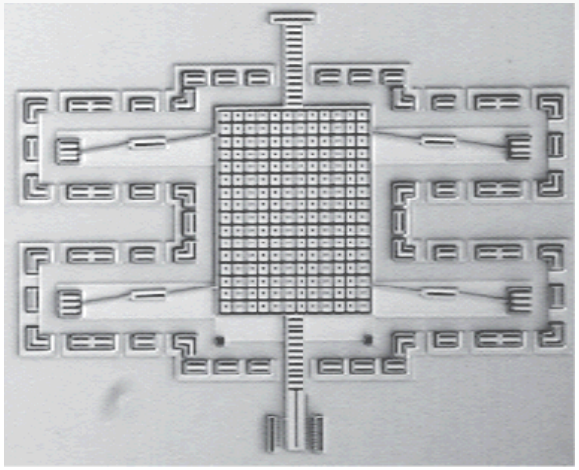
Adaptive Surface

My Research Areas

Elastic-Plastic Modeling for Rebound Dynamics



plastic deformation



Bistable Mechanisms

Analytical Nonlinear Dynamics

$$\mathcal{L}(w(\mathbf{x},t)) = f(\mathbf{x},t) + \mathcal{N}(w(\mathbf{l},t))$$

$$\|\mathrm{L}_2(\widehat{\eta}_n^{(j)})\| = \sqrt{\int_0^L \left(\widehat{\eta}_n^{(j)}\phi_n^{(j)}(\mathbf{x}) + \sum_{m=1}^{n-1} \widehat{\eta}_m^{(j)}\phi_n^{(j)}(\mathbf{x}) + y^{(j)}(\mathbf{x},t) - y^{(i)}(\mathbf{x},t) - \sum_{m=1}^{N} \eta_m^{(i)}(t_0)\phi_m^{(i)}(\mathbf{x}) \right)^2 \mathrm{d}\mathbf{x}}$$

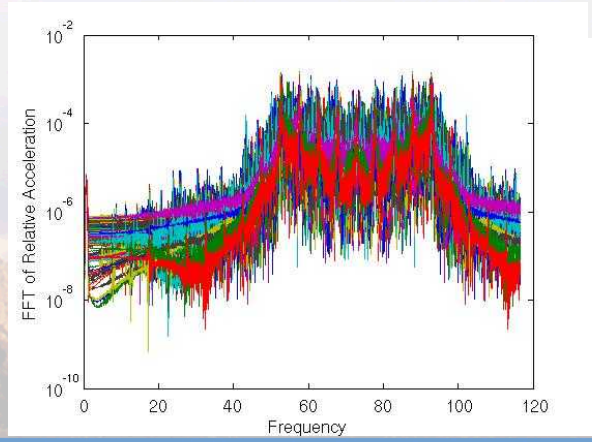
$$\frac{d\boldsymbol{\chi}_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0))}{d\boldsymbol{\eta}^{(j)}(t_0)} = \begin{bmatrix} \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);1)}{d\eta_1^{(j)}(t_0)} & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);2)}{d\eta_1^{(j)}(t_0)} & \cdots & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);N)}{d\eta_1^{(j)}(t_0)} \\ \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);1)}{d\eta_2^{(j)}(t_0)} & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);2)}{d\eta_2^{(j)}(t_0)} & & \vdots \\ \vdots & & \ddots & \\ \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);1)}{d\eta_N^{(j)}(t_0)} & \cdots & & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);N)}{d\eta_N^{(j)}(t_0)} \end{bmatrix}$$

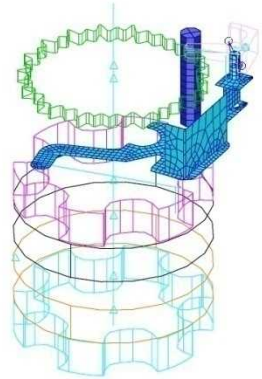
$$\eta_n^{(j)}(t) = \widehat{\eta}_n^{(j)} e^{\lambda_n^{(j)}(t-t_0)} + \int_{t_0}^{t} e^{\lambda_n^{(j)}(t-\tau)} q_n^{(j)}(\tau) d\tau$$

$$\Xi = \left\{ \frac{d\boldsymbol{\chi}_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0))}{d\boldsymbol{\eta}^{(j)}(t_0)} \right\}^T \frac{d\boldsymbol{\chi}_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0))}{d\boldsymbol{\eta}^{(j)}(t_0)}$$

Model Reduction for Probabilistic Analysis

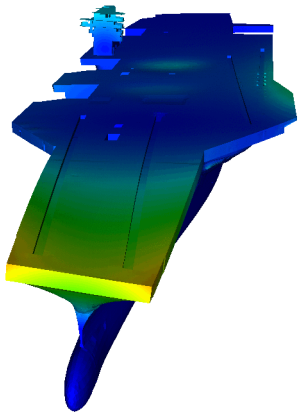
Fluid-Structure Interaction



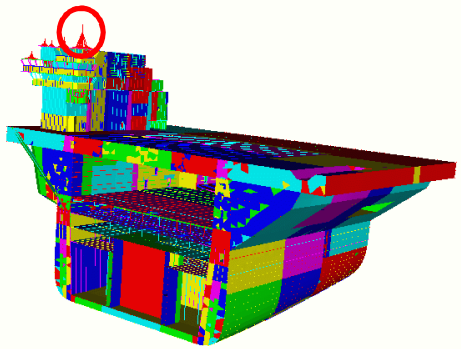


Motivation: Nonlinearities Can Lead to Unexpected System Responses

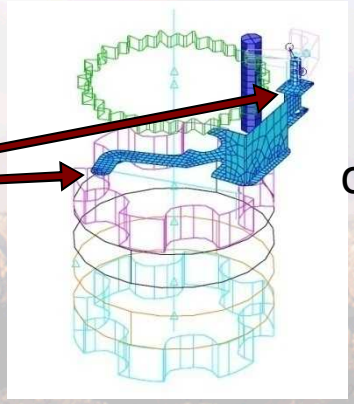
- Detailed modeling of subcomponents highlights unexpected responses due to nonlinearities (impact dynamics)
- High fidelity models can be used to calibrate efficient models for parametric studies



System analysis results are used as input to submodels



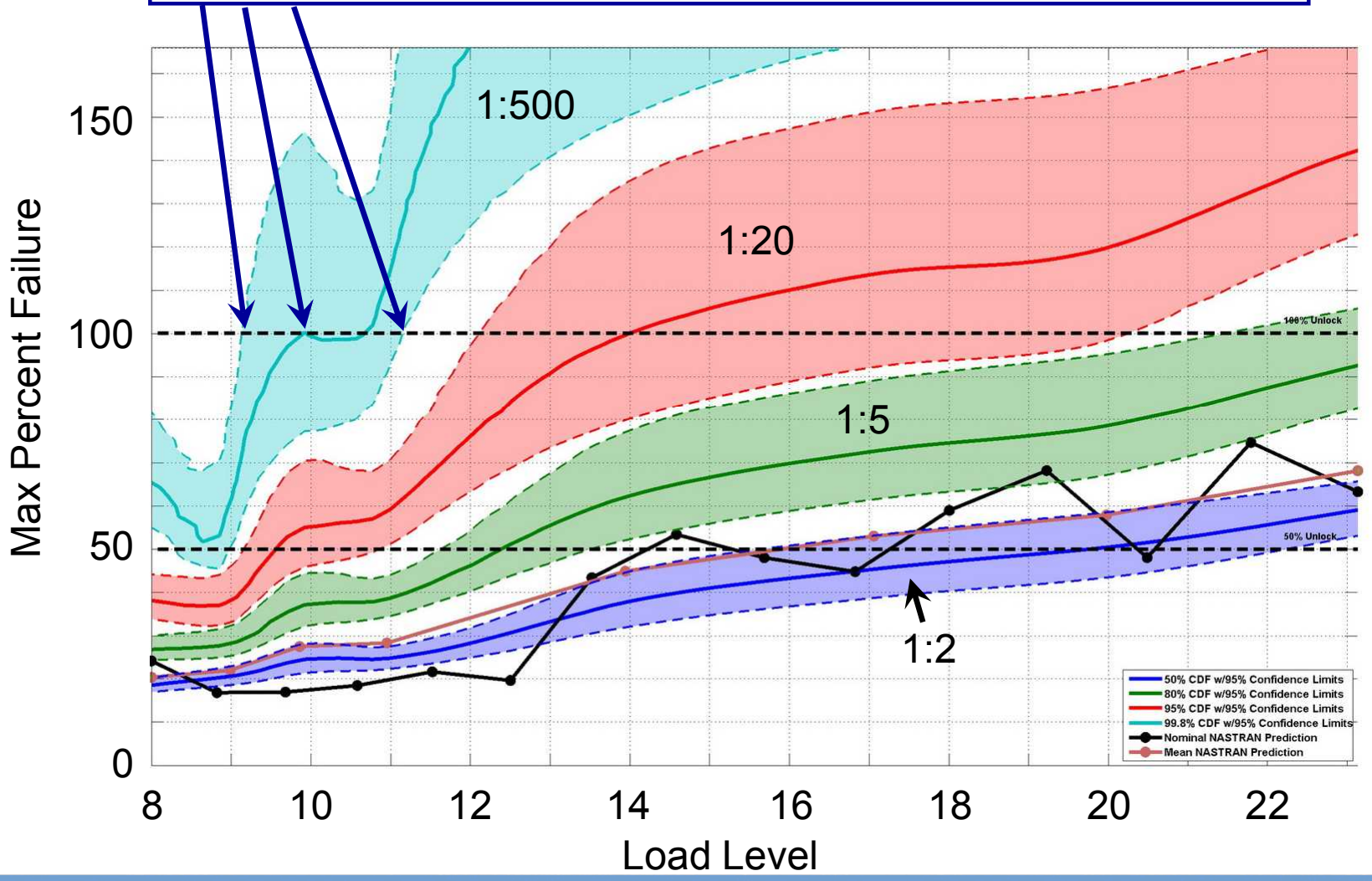
Crucial impact phenomena



Essential dynamics captured in an efficient model for parametric studies

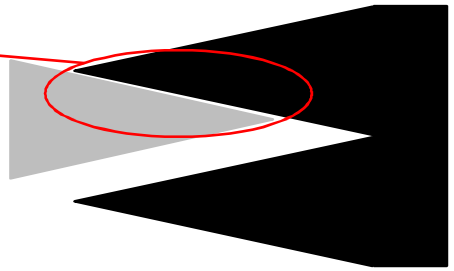
Probabilistic Analysis of Failure Criterion

Expectation: 1 out of 500 tests will fail at a load level of 9.9
(9.1 < Failure Level < 11.1, with 95% Confidence)

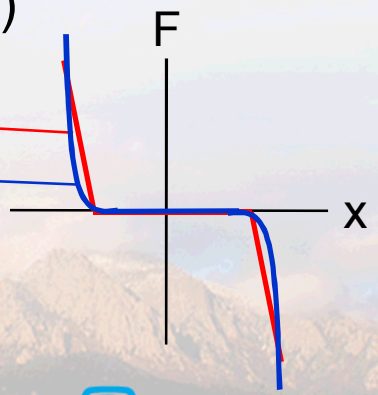


Impact Dynamics: Constitutive Modeling

- **Physical process**
  - Plasticity
  - Localized yielding
  - Energy dissipation
  - etc.

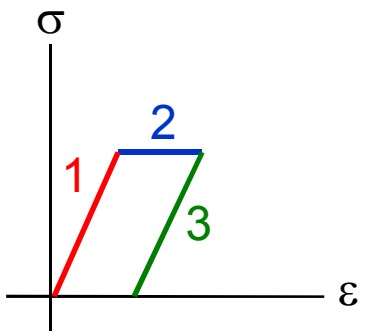


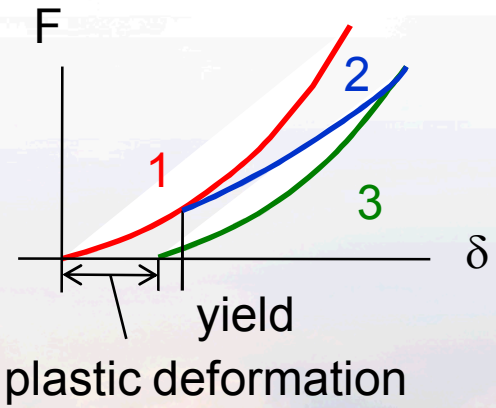
- **Methods of simplified impact dynamics modeling**
  - Iwan-type models (bolts, joints, frictional interfaces)
  - Penalty stiffness
  - Hertzian contact
  - Coefficient of restitution
  - Elastic-Plastic models



Simplified Elastic-Perfectly Plastic Impact Modeling

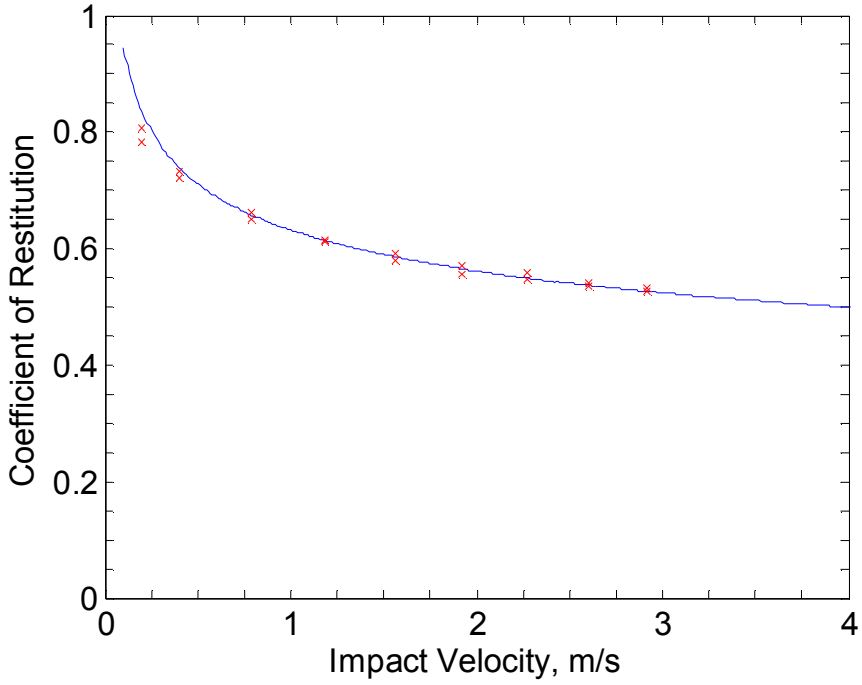
- **Deflection divided into three phases:**
  - Elastic loading (1)
    - Hertzian force-deflection relationship
    - Spans from the initial contact until the onset of yielding
  - Plastic loading (2)
    - Transition regime from elastic to unconstrained (plastic) flow defined using hardness properties
    - Linear force-deflection relationship in fully plastic regime (elastic-perfectly plastic behavior only…)
  - Elastic unloading (3)
    - Hertzian, but with a different contact radius than for loading
    - A portion of the plastic deflection is unrecoverable



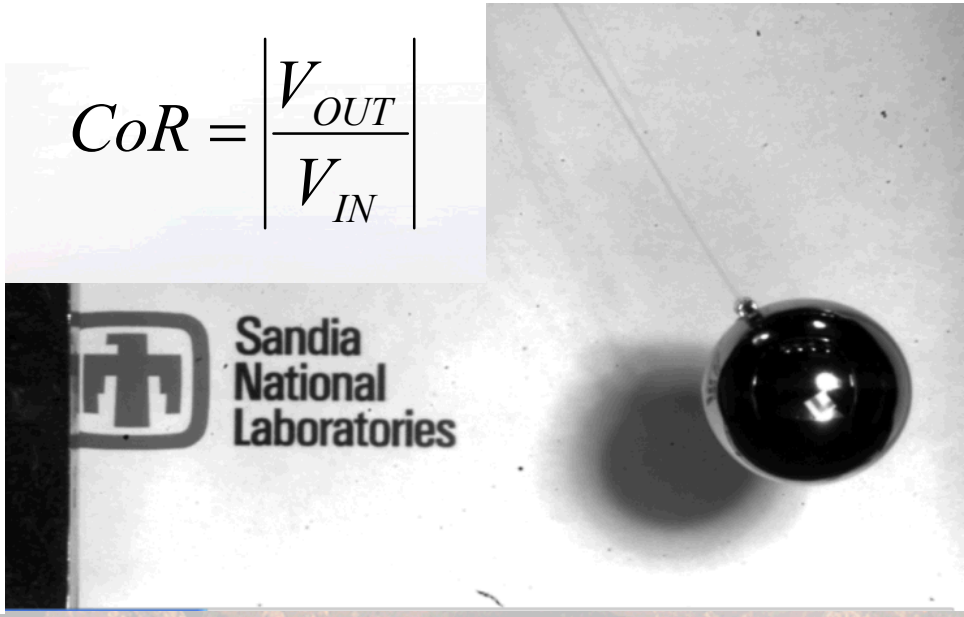


Experimental Efforts to Validate

- Elastic-plastic impact model based on material properties (hardness, yield stress, etc.)
- Experimental validation includes pendulum impact studies
- The measured coefficient of restitution is compared to the predicted results from a simulation of the system:

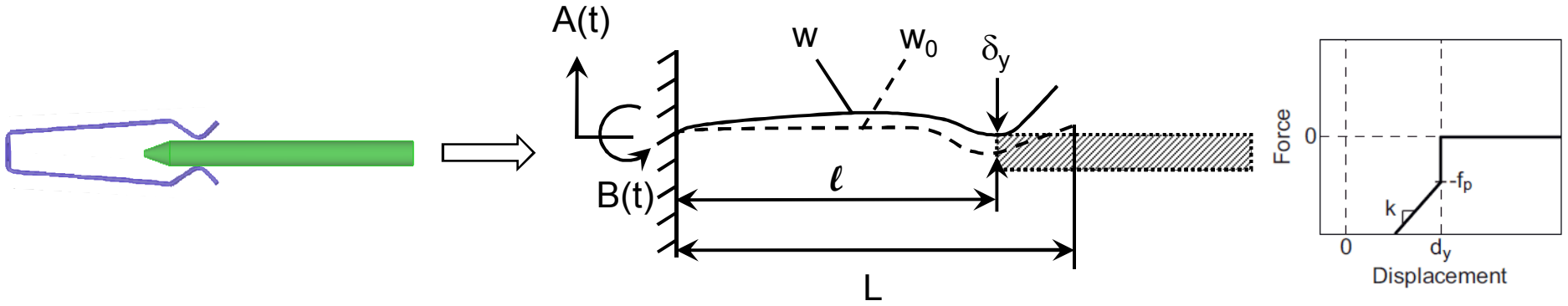


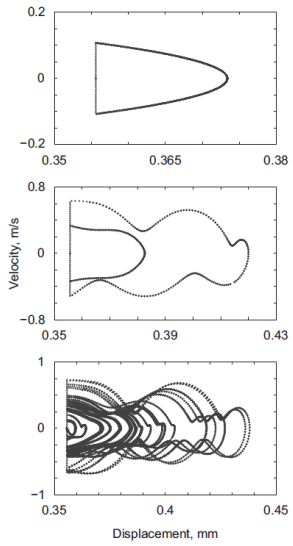
$$CoR = \left| \frac{V_{OUT}}{V_{IN}} \right|$$

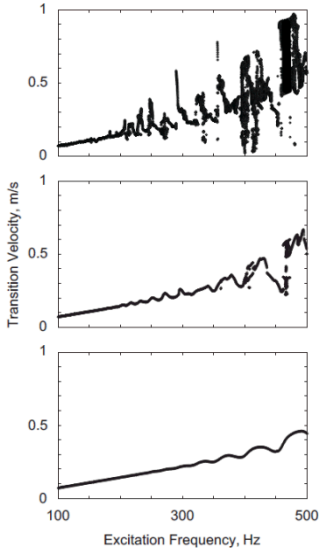


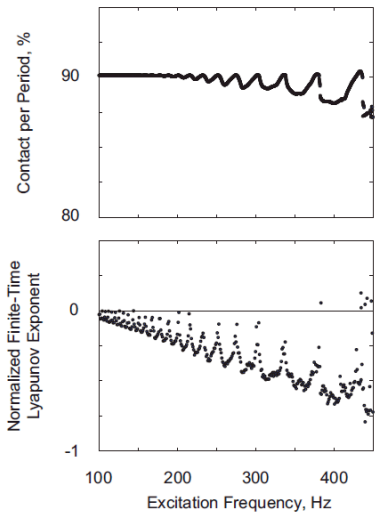
“Exact” Methods to Account for Nonlinearities

- Well suited to reduced/efficient models
- Nonlinearities handled via modal mapping techniques
- Limited to piecewise-linear constitutive models









$$\mathcal{L}(w(\mathbf{x},t)) = f(\mathbf{x},t) + \mathcal{N}(w(\mathbf{l},t))$$

$$\|\mathrm{L}_2(\widehat{\eta}_n^{(j)})\| = \sqrt{\int_0^L \left(\widehat{\eta}_m^{(j)} \phi_n^{(j)}(\mathbf{x}) + \sum_{m=1}^{n-1} \widehat{\eta}_m^{(j)} \phi_n^{(j)}(\mathbf{x}) + y^{(j)}(\mathbf{x},t) - y^{(i)}(\mathbf{x},t) - \sum_{m=1}^{N} \eta_m^{(i)}(t_0) \phi_m^{(i)}(\mathbf{x}) \right)^2 \mathrm{dx}}$$

$$\frac{d\boldsymbol{\chi}_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0))}{d\boldsymbol{\eta}^{(j)}(t_0)} = \begin{bmatrix} \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);1)}{d\eta_1^{(j)}(t_0)} & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);2)}{d\eta_1^{(j)}(t_0)} & \cdots & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);N)}{d\eta_1^{(j)}(t_0)} \\ \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);1)}{d\eta_2^{(j)}(t_0)} & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);2)}{d\eta_2^{(j)}(t_0)} & & \vdots \\ \vdots & & \ddots & \\ \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);1)}{d\eta_N^{(j)}(t_0)} & \cdots & & \frac{d\chi_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0);N)}{d\eta_N^{(j)}(t_0)} \end{bmatrix}$$

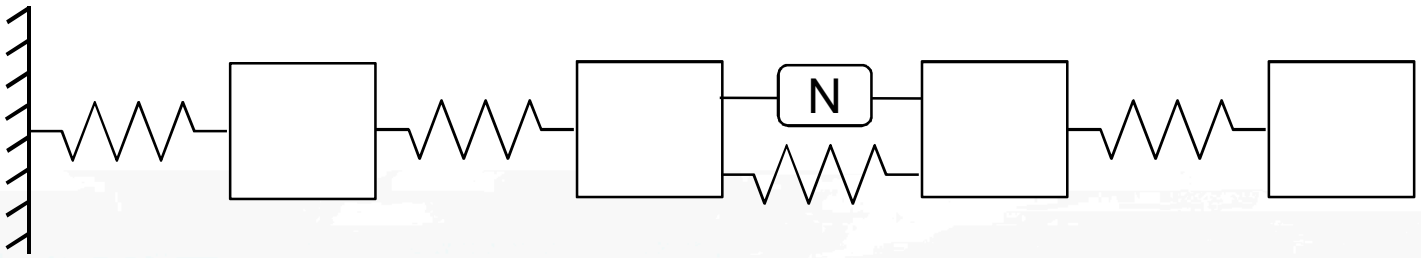
$$\eta_n^{(j)}(t) = \widehat{\eta}_n^{(j)} e^{\lambda_n^{(j)}(t-t_0)} + \int_{t_0}^{t} e^{\lambda_n^{(j)}(t-\tau)} q_n^{(j)}(\tau) d\tau$$

$$\Xi = \left\{ \frac{d\boldsymbol{\chi}_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0))}{d\boldsymbol{\eta}^{(j)}(t_0)} \right\}^T \frac{d\boldsymbol{\chi}_{t_0}^{t_0+\tau}(\boldsymbol{\eta}^{(j)}(t_0))}{d\boldsymbol{\eta}^{(j)}(t_0)}$$

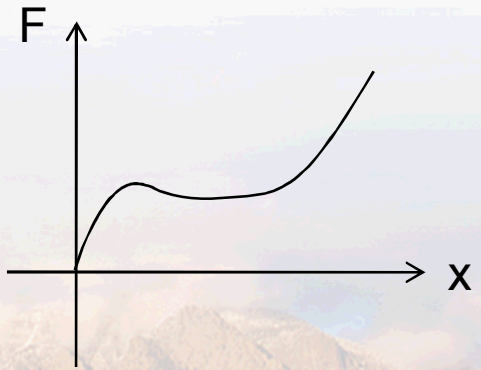
Approximate Methods to Account for Nonlinearities

Method of discontinuous basis functions:

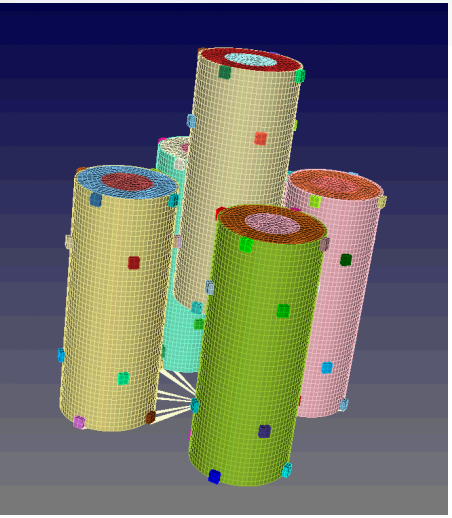
- **Well suited for large finite element models**
- **Component mode synthesis based approach supplemented with discontinuous basis functions**



- **How can we assess the accuracy?**
- **What is the impact?**
  - Decrease in computation time
  - No constraints on type of nonlinearity

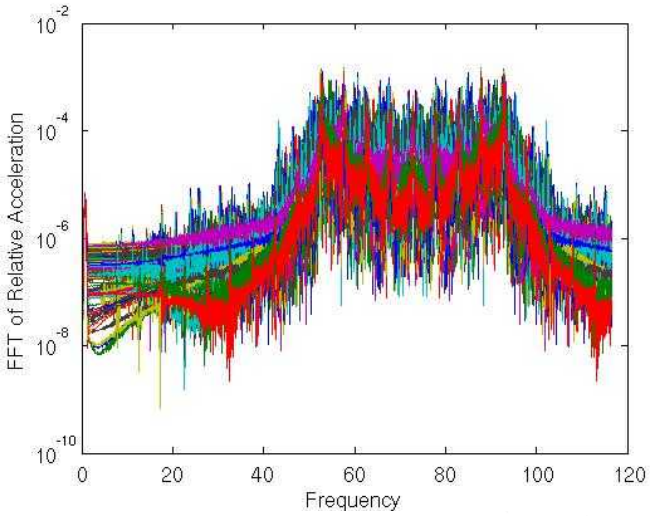


Model Reduction of Large Dynamic Systems with Localized Nonlinearities



Large Problems with Sharp Nonlinearities Require tiny time steps and long compute times.
Many simulations are necessary for qualifying uncertainties.

MDBF: Basis functions consisting of enough Eigen functions for frequency resolution augmented by other functions with discontinuities at locations of nonlinearity.



Time Step	Salinas	Reduced Order Model
1e-4	Still running	312 minutes
2e-4	Still running	156 minutes
4e-4	7347 minutes	79 minutes
8e-4	Unstable	39 minutes
2e-3	Unstable	19.5 minutes
4e-3	Unstable	Unstable

Observe:

- **For equal time steps, the full model requires 93 times more computational time**
- **For simulations that include less of the ringdown following the initial event, the full model requires 126 times more computational time**

Note:

- **Heavy reliance on MP computing to set up problems, though transient analysis may be scalar.**
- **Absolutely necessary to capture nonlinearities of joints.**

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Method of Discontinuous Basis Functions Applied to Analytical Systems

- **Similar approach as for discrete/numerical systems:**

Full System Equation

$$\mathcal{L}(w) + \sum_{j=1}^{N_L} \mathcal{N}_j(w(\underset{\sim}{\ell}_j, t)) = f$$

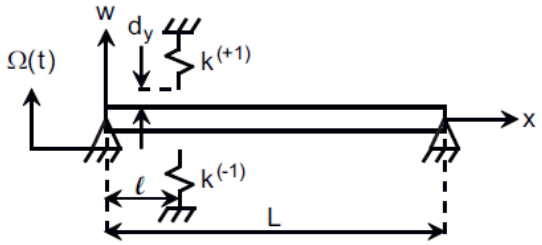
Ordinary Basis Functions:

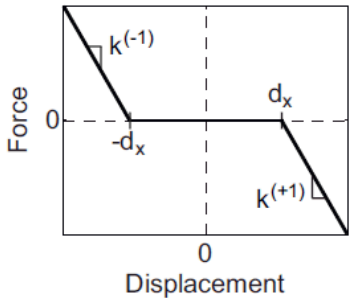
$$\mathcal{L}(w) = 0$$

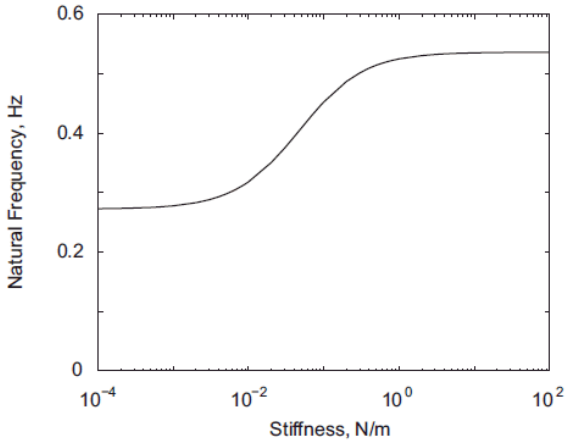
Discontinuous Basis Functions:

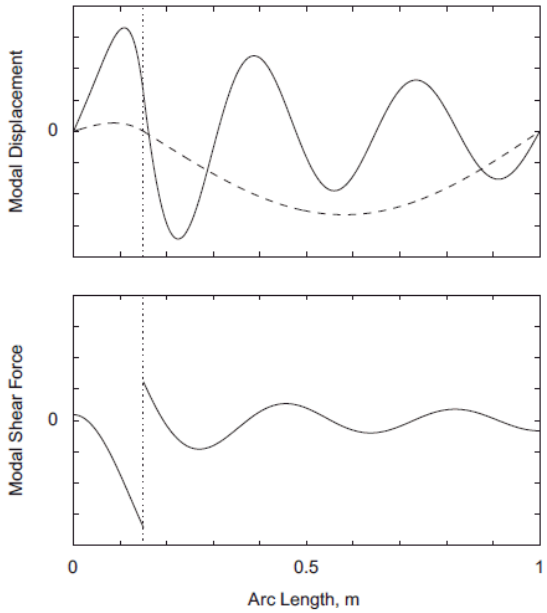
$$\mathcal{L}(w) + kw(\underset{\sim}{\ell}_j, t)\delta(\underset{\sim}{x} - \underset{\sim}{\ell}_j) = 0$$

Derivatives taken for the resulting basis functions with respect to *k*



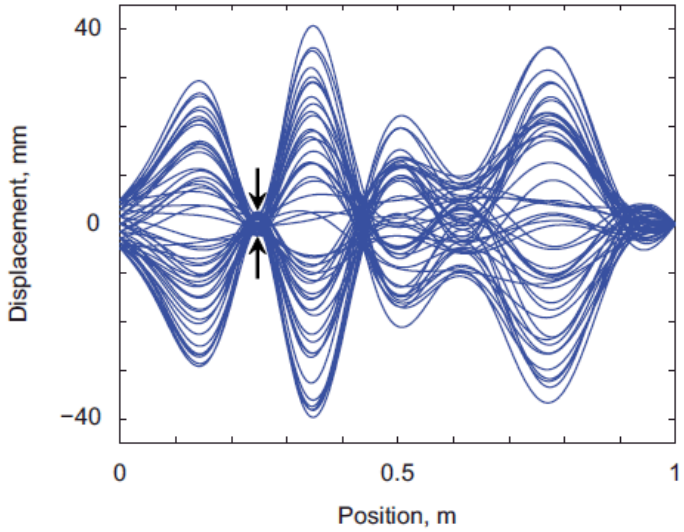


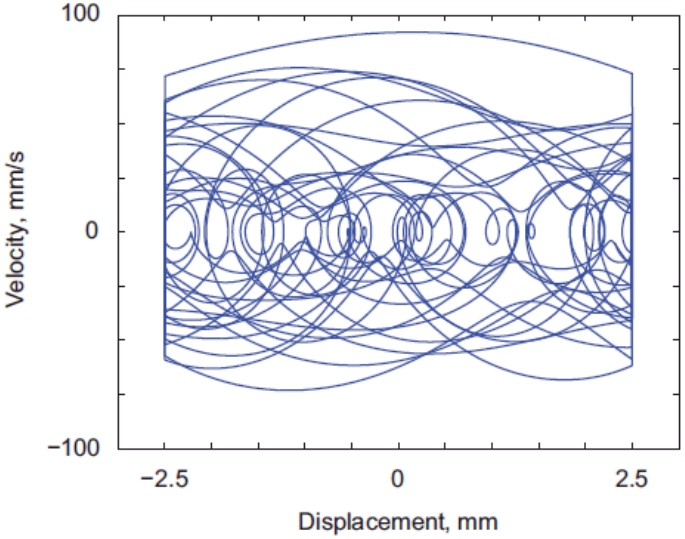




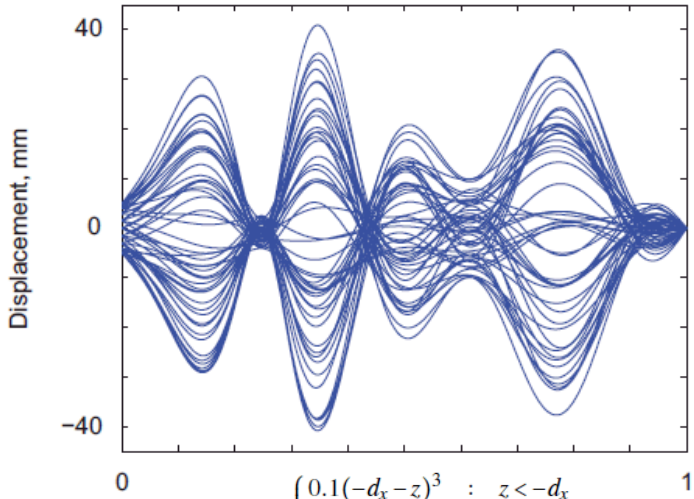
Method of Discontinuous Basis Functions Applied to Analytical Systems

One Piecewise Linear Constraint

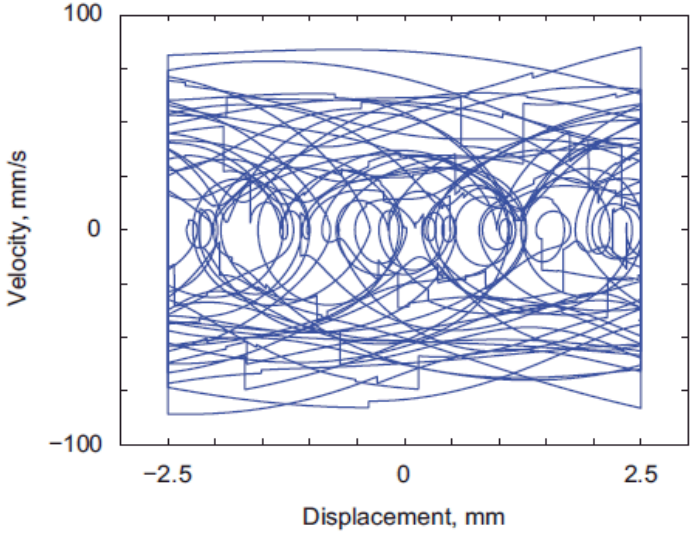




One Piecewise Nonlinear Constraint



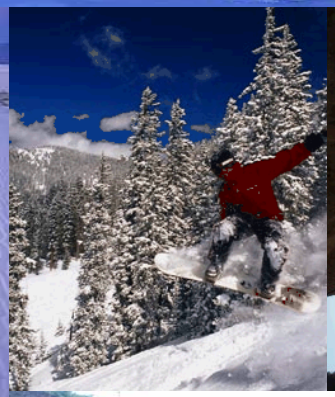
$$\mathcal{N}(z) = \begin{cases} 0.1(-d_x - z)^3 & : \quad z < -d_x \\ 0 & : \quad -d_x \le z \le d_x \\ 10^6(d_x - z) & : \quad d_x < z. \end{cases}$$

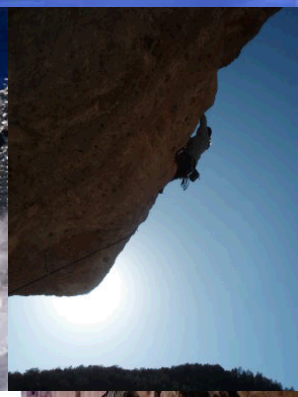


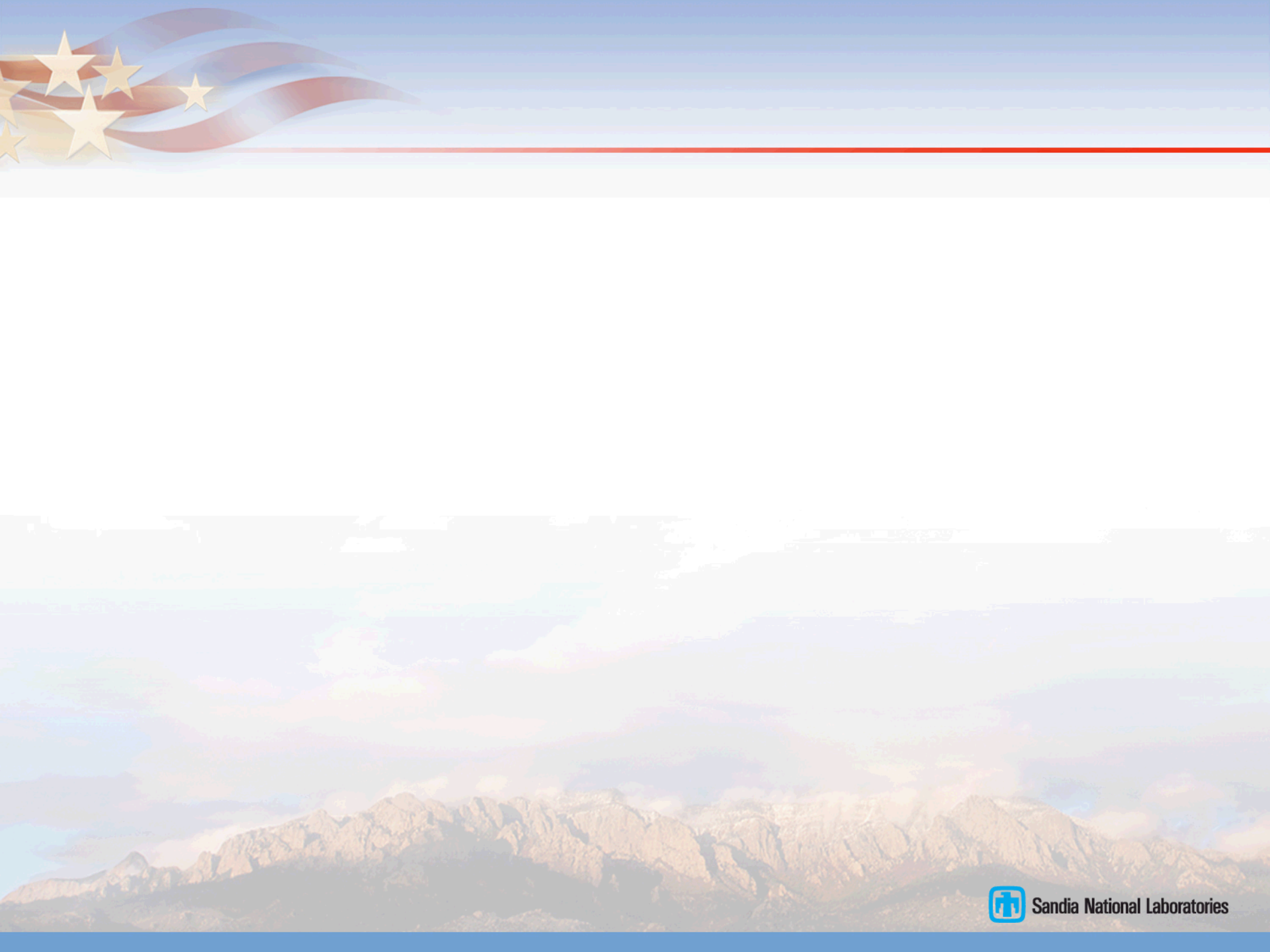
Summary

- Nonlinearities, such as impacts, can lead to unexpected (and chaotic) system responses
- In order to probabilistically explore design spaces to quantify performance, efficient simulation methods are required
- Exact methods are available, but are limited to piecewise linear contact laws and are more time consuming (computationally and programming)
- Different contact laws can produce qualitatively similar results away from the point of contact…
- A new elastic-plastic contact law has been developed that shows very good agreement with test results, and requires no calibration

Sandia National Laboratories in Albuquerque, New Mexico



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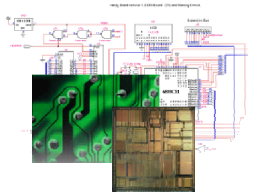
Backup Slides/Job Opportunities

Full Time Job Opportunities

- I personally know several managers that are looking to hire many Mechanical Engineers this year:
  - Advanced microsystems packaging design engineer (ME or ECE, masters, hardware and modeling)
  - ECE systems engineers
  - Thermal, fluid, and aero sciences – theory, modeling, code development, experimentation, and diagnostic development
  - Coupled thermal/fluid or fluid/structure code development
  - Development and implementation of advanced diagnostics (laser based or other) with a background in ME, ChemE, or a related field
  - Large finite element thermal analyst
  - Structural dynamics and solid mechanics theoreticians and experimentalists
  - Dynamics and vibration modeling (see me for both full time and internships)
- If any of these positions sounds like a good fit, let me know, and I'll take your resume/CV directly to the hiring manager

Active Recruiting Areas

- **Computational Science and Engineering**



Architectures

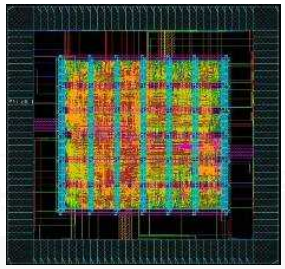
Algorithms

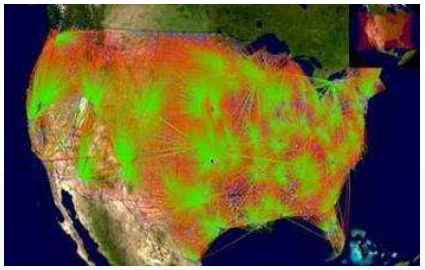
Applications

One 1994 computer day ≈
One 2006 computer minute

1997: 1 Teraflop in a *room*.
2007: 1 Teraflop on a *chip*.

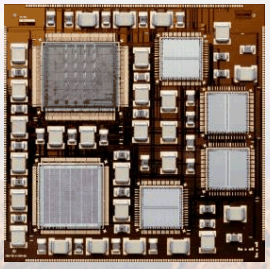
- **Cyber Security**
  - Includes Infrastructure Modeling, Cryptographic Chips, and Microelectronic Development



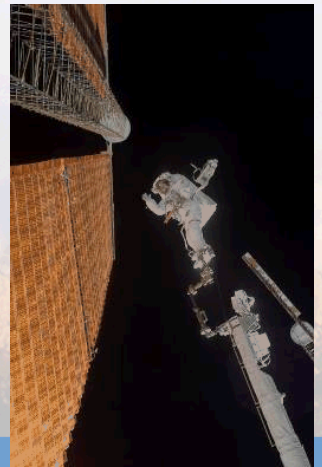


- **Space Systems**

Galileo Spacecraft



Rad-hard chips
& MEMS devices



Laser Dynamic Range Imager Orbiter Inspection System (LOIS)

Student Internships

Institutes

- National Institute for Nanoscale Engineering (NINE)
- Physical Sciences Institute
- Computer Science Research Institute
- Center for Cyber Defenders
- Enabling Predictive Simulation Research Institute
- Sandia Institute for Modeling and Simulation
- National Security Engineering Institute

Internships and Co-ops

- Year-round and summer
- Must be a U.S. citizen with full-time enrollment status
- Minimum cumulative GPA of 3.2/4.0 for undergraduates or 3.5/4.0 for graduate students
- STEM and business disciplines
- Apply online at Sandia's website: www.sandia.gov
- Pay based on job classification and the number of academic credit hours completed prior to internship

Master Program Fellowships

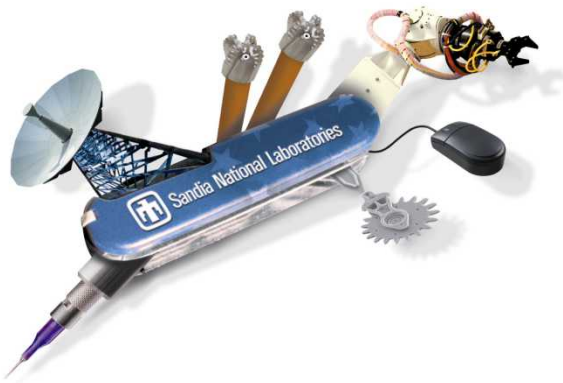
- The Critical Skills Master's Program (CSMP)
  - For engineering and computer science degrees
  - Aiming to hire 30 candidates this fiscal year

- Masters Fellowship Program (MFP)
  - For minority applicants
  - Aiming to hire 20 candidates this fiscal year

- Specifics for both programs:
  - For engineering and computer science degrees
  - Minimum GPA of 3.2
  - Pursue a graduate degree while on an annual stipend
  - Upon completion, return to Sandia as a member of the technical staff
  - Must apply to the program specific job posting at the Sandia website

PhD Research Opportunities

- Postdoctoral Fellowships
  - Pay is one of the highest for engineering post docs in the country
  - Special opportunities exist as:
    - Truman Fellowship (high-risk, high-value research in the national interest)
    - Alexander Hollaender Fellowship (biology and environmental research)
    - John Von Neuman Fellowship (computational science)

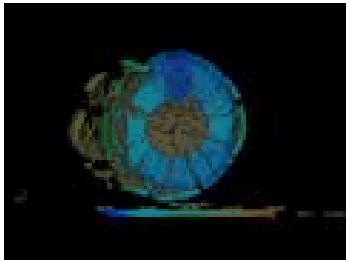


- Early Career R&D
  - Conduct your own research that is funded by Laboratory Directed Research & Development (LDRD) for up to 2/3 of your time

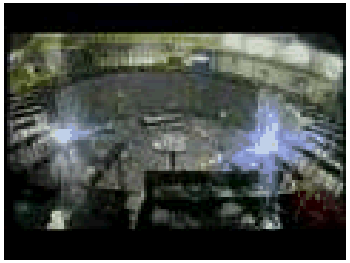
Stay Connected

www.youtube.com/user/SandiaLabs

Top viewed videos:



Apophis destruction simulation
140,800+ views



Z Machine at Sandia Labs
64,200+ views

Rocket Powered Train Impact Test
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