Model Validation of Loose Bolted Joints in Damaged Structural Systems

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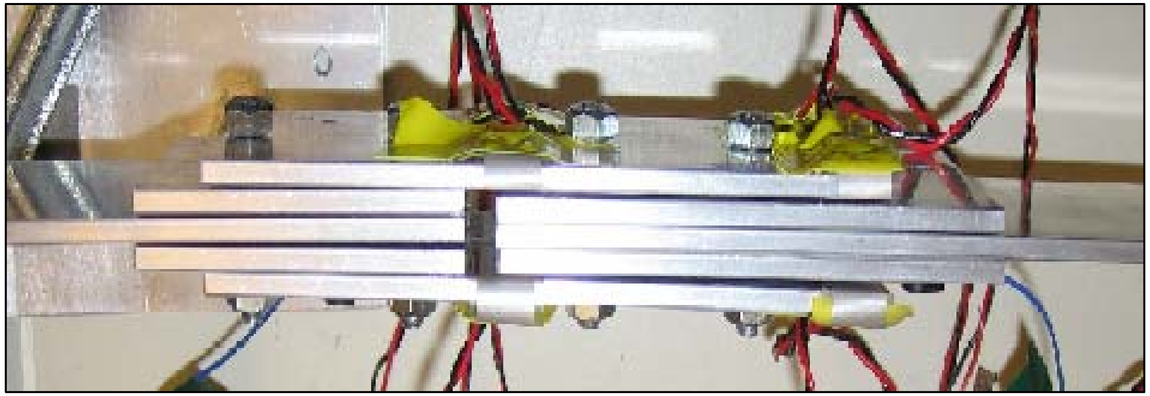

IMAC XXIV
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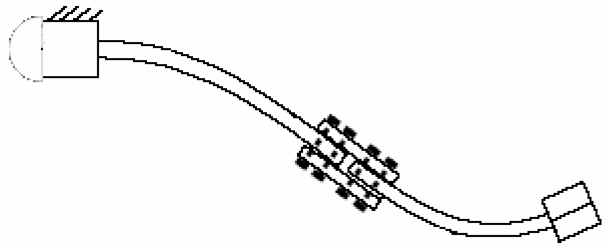
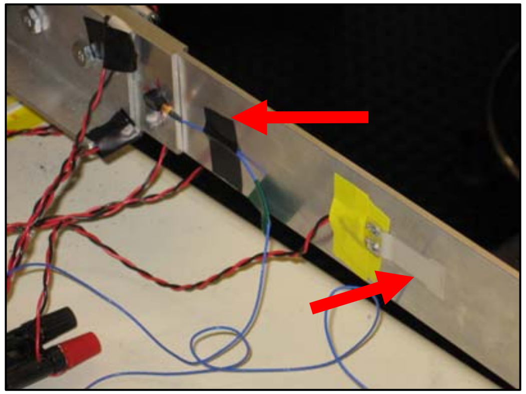
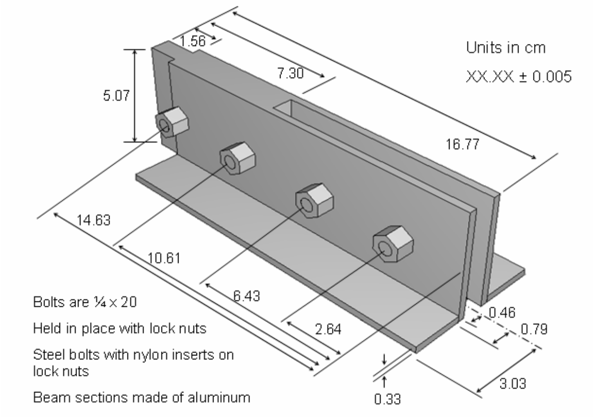
This presentation is a project summary concerning the model validation of a loose bolted joint



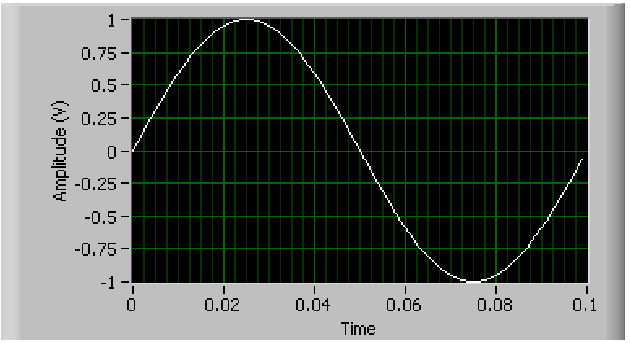
Modeling and simulation



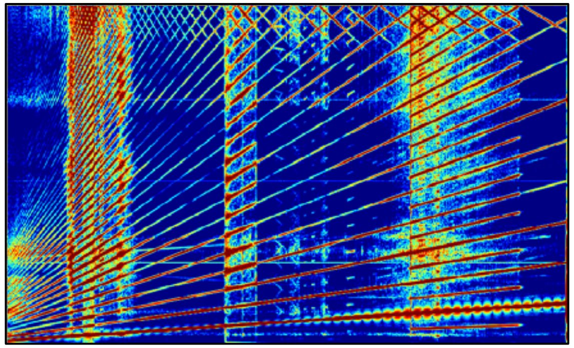
Experimental Setup



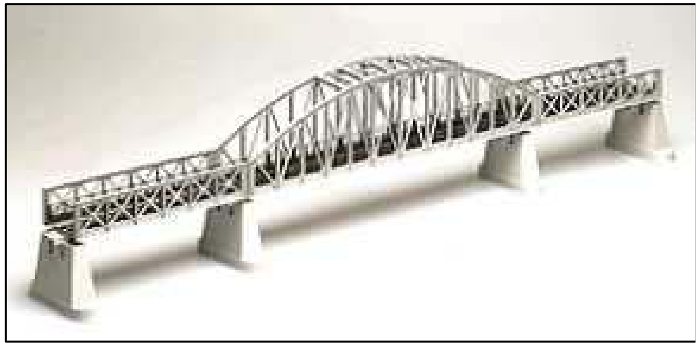
Parameter ID



Types of Tests



Data Comparison

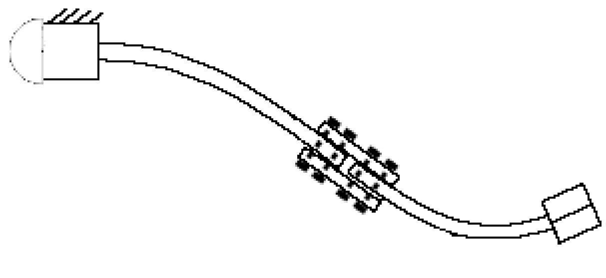


Future and Conclusions

The behavior of a damaged joint is difficult to model both accurately and quickly with current techniques

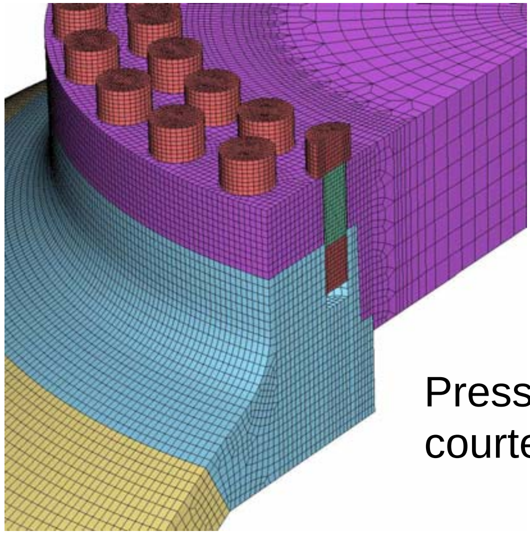
Over time, joints loosen in Buildings, Rockets, and other Structures

For real time analysis, a low order model is beneficial when compared to high order model

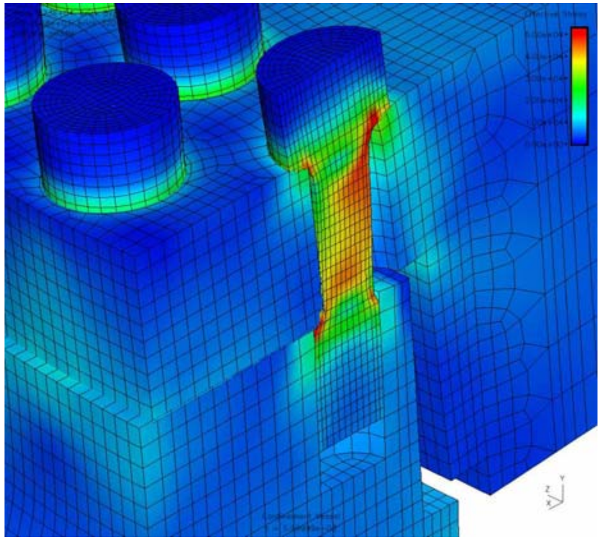


In the future, real time control, hazard mitigation, and extending the life of remote or dangerous to repair structures may be possible

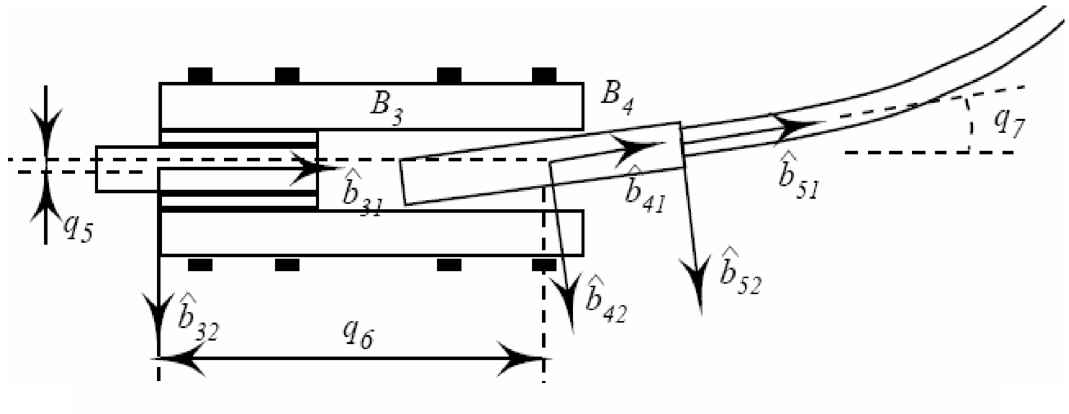
Using our model, the joint can be modeled as a nine d.o.f. system versus a FE model with millions of d.o.f.



Pressure vessel figures courtesy of R. Stevens, LANL



Each of the beam sections has a rotation, elongation, and deflection component for a maximum of nine degrees of freedom



Previous research on physics and dynamics of joint interactions has little application to this experiment

Joint motion → Microslip and Macroslip

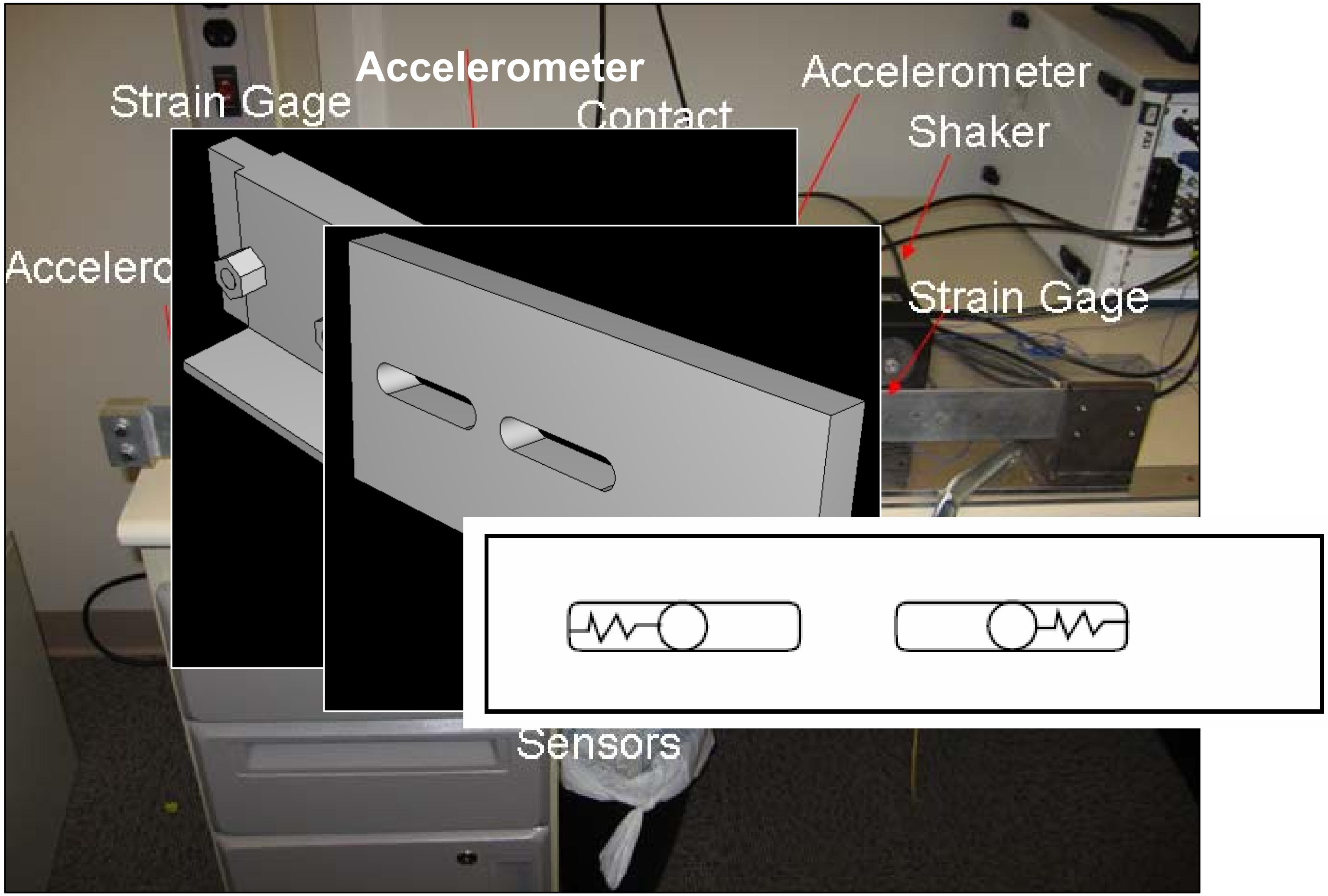
Previous research has been done concerning…

- Damping and energy dissipation on microslip conditions
  - Force Deflection Relationships
- Investigations into the physics at the joint interfaces

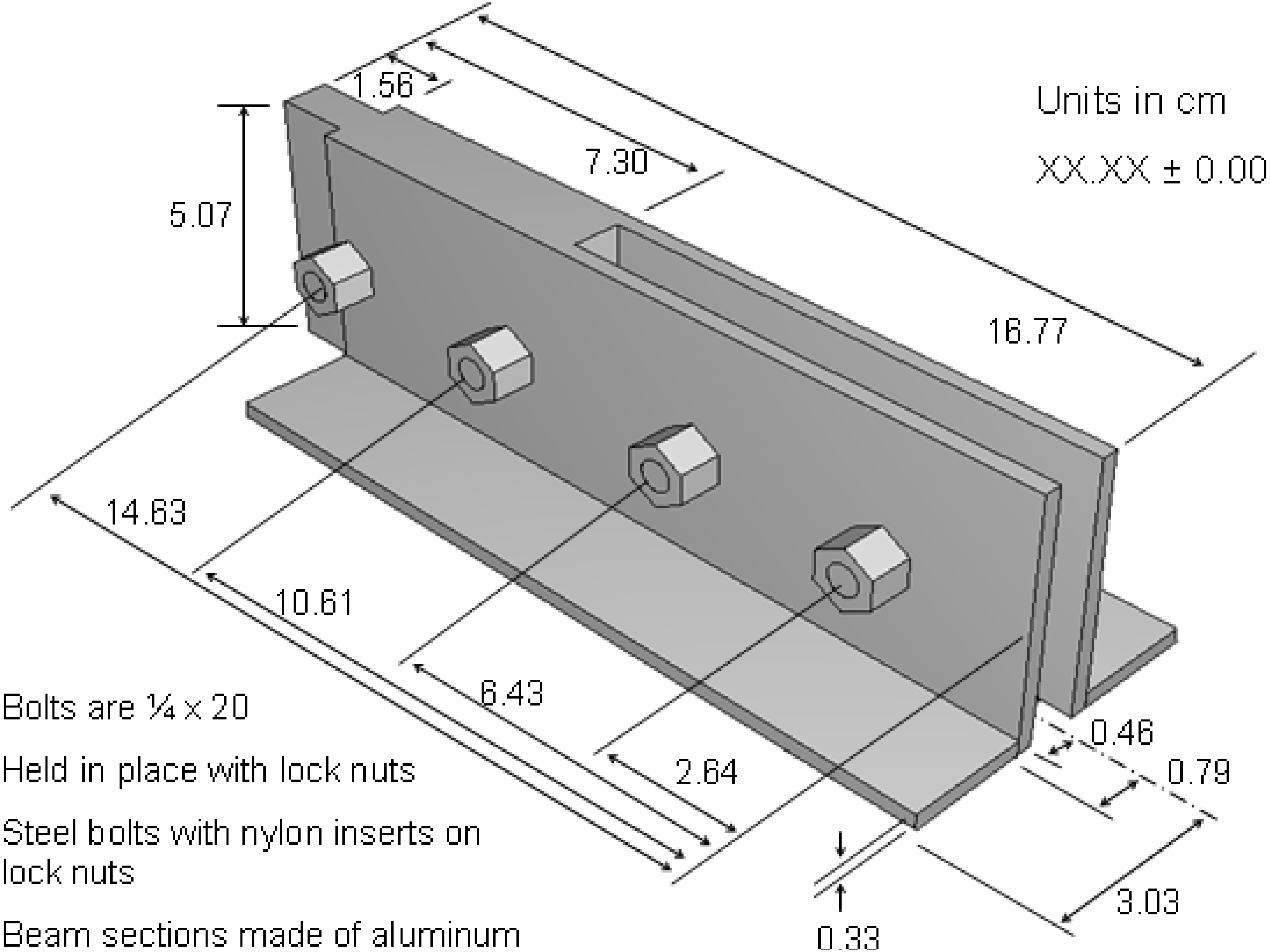
Iwan models – low-order model, based on a network of springs and sliders, that showed promise for identifying joint dynamics

All of the above investigations model joints in undamaged conditions

The experimental set-up is composed of several different components



The bolted lap joint, dimensioned



Units in cm

XX.XX ± 0.005

Bolts are ¼ x 20

Held in place with lock nuts

Steel bolts with nylon inserts on lock nuts

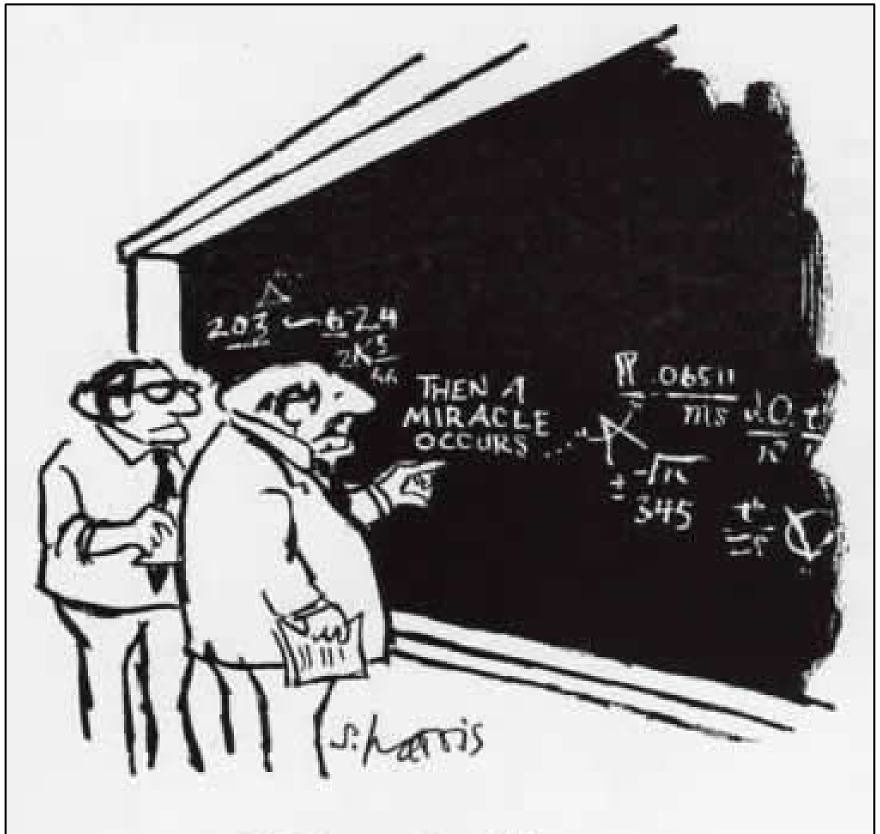
Beam sections made of aluminum

Several system parameters had to be identified for input into the model

Initial position	q1	q2	q3	q4	q5	…	q10
Initial velocity	s1	s2	s3	s4	s5	…	s10
Length	L1	L2	L3	L4	L5	L6	
Shaker Constants	As	Rs	Ks	Cs	Ms	Xs	
Sensors	accel1	accel2	accel3	strain1	strain2		
Elastic Constants	EI1	EA1	EI1	EA2			
Rigid body mass	m1	m3	m4	m5			
Mass inertia	I1	I3	I4	I6			
Damping Values	dv2	dv3	dv5	dv6			
Test parameters	F	Freq	Sfreq				
Gap	T	W					
Mass per unit Length	rho2	rho5					
Inertia per unit length	I2	I5					
Cork properties	Lk	Kk					
Time	ti	tf					
Integrator tolerance	rtol						
Gravity	g						
Contact Value							

Note that no coefficients of restitution or penalty-method based spring constants are required.

The model uses a Gibbs-Appell based approach applied to Hybrid Parameter Multiple Body Systems



"I think you should be more explicit here in step two."

No Lagrange Multipliers needed to implement constraints

Thus Differential Algebraic equations need not be solved

Which allow the “minimal” set of equations of motion to model the system

And the use of vector algebra eliminates tedious calculation

The simulation determines the switching, contact, strain, and acceleration of the system

Load System Parameters → Initialize contact in free state → Enter time step dependent loop

↓

Determine a value 1,2,3,4 which expresses the point in contact → Check to see if further contact occurs at the other 2 possible points

↓

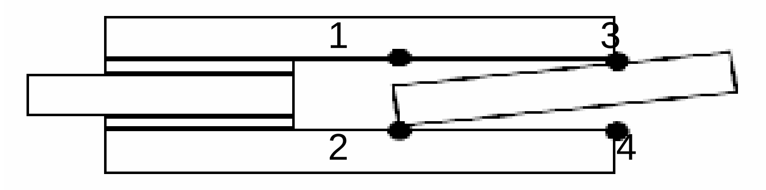
If dual contact, assign variable 2 digit value →23 corresponds to P2 and P3 → Based on variable value a stick or slip condition in the contact is determined and transfer momentum

↓

For every contact possibility, LSODA solves the appropriate equations of motion → Calculate Strain and Acceleration and increment time step

↓

Go back to Loop → (returns to "Determine a value 1,2,3,4 which expresses the point in contact")

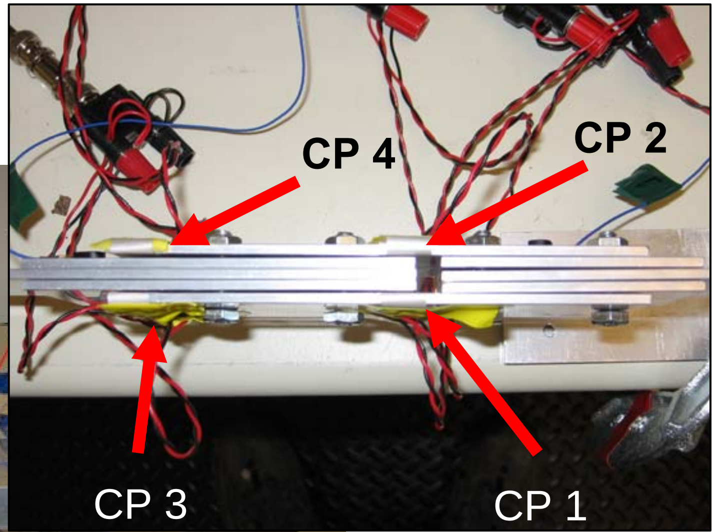


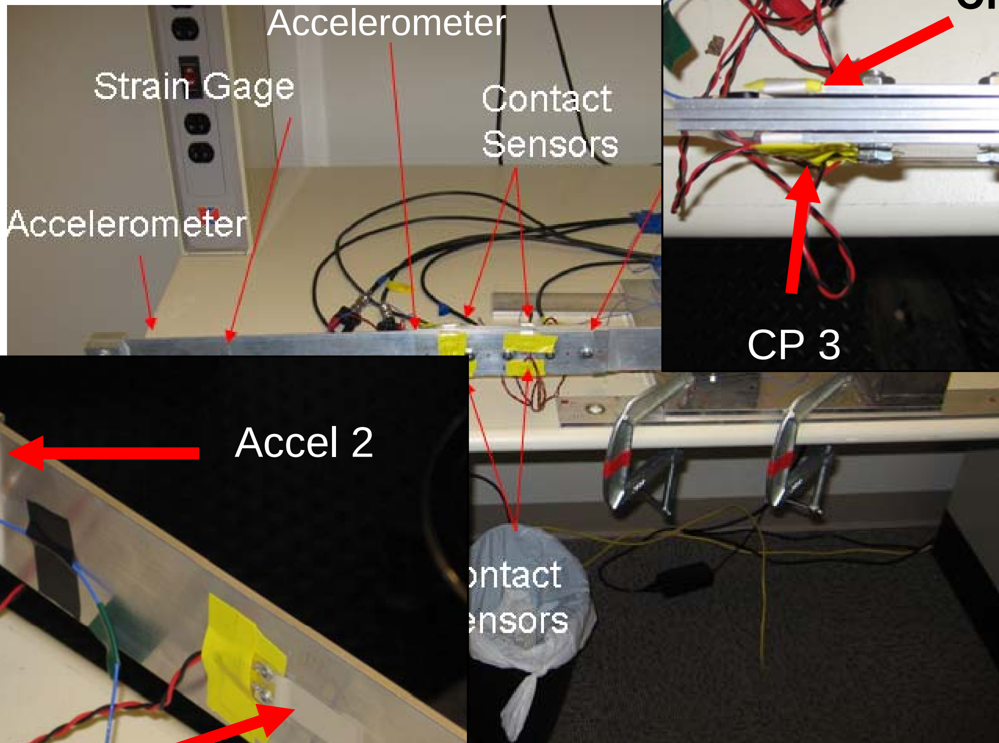
Possible Contact Regimes

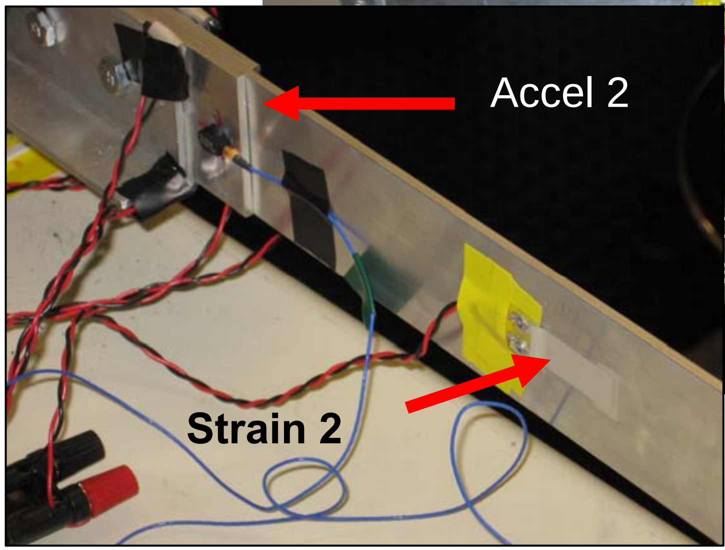
Contact 1	Contact 2
Free	Free
P1	Free
P1	P3
P1	P4
P2	Free
P2	P4
P2	P3
P3	Free
P4	Free

PVDF patches and accelerometers were used to collect the data for model validation

PVDF patches were also used for contact sensors







Two PVDF patches were utilized as Strain gages

Strain measurements are provided by calibrated PVDF patches

$$\delta_L = \frac{PL^3}{3EI}; \qquad \delta_x = \frac{Px^2}{6EI}(3L - x)$$

$$\therefore \frac{P}{EI} = \frac{3\delta_L}{L^3}$$

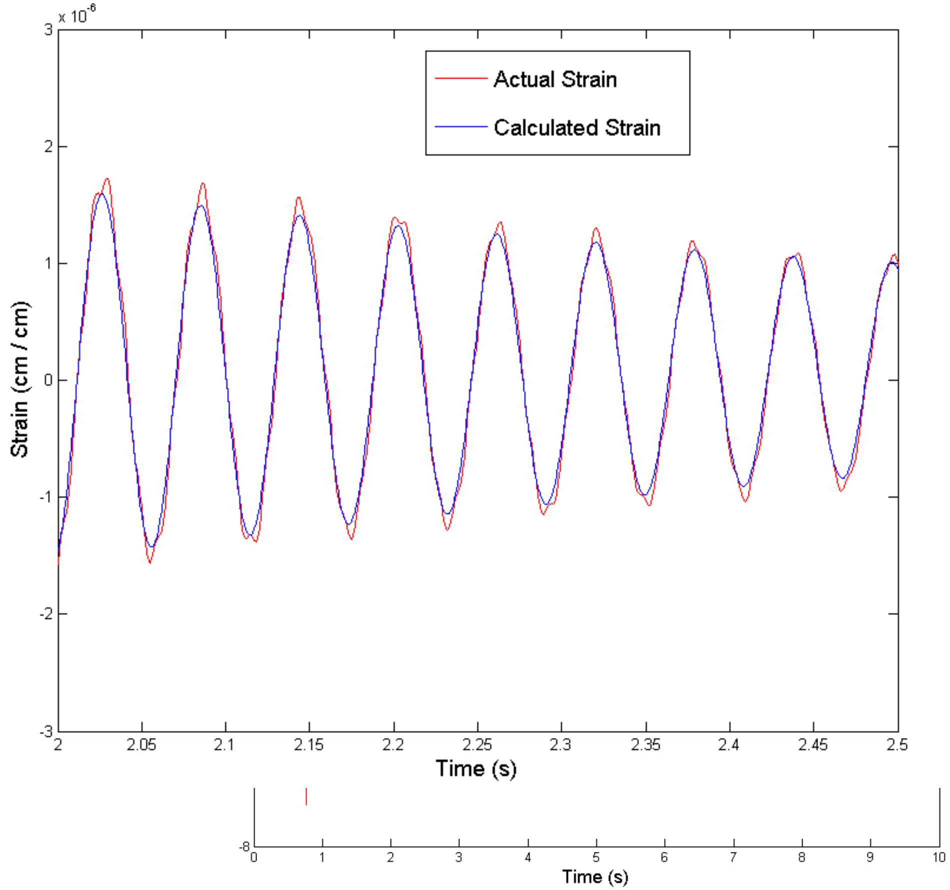
$$\therefore \delta_x = -\frac{\delta_L x^2}{2L^3}(3L - x)$$

$$M = EI\delta_x'' = \frac{3\delta_L EI}{L^2}\left(\frac{x}{L} - 1\right)$$

$$\sigma = \frac{Mc}{I} = \frac{3\delta_L Ec}{L^2}\left(\frac{x}{L} - 1\right)$$

$$\sigma = E\varepsilon; \qquad \boxed{\therefore \varepsilon = \frac{3\delta_L c}{L^2}\left[\frac{x}{L} - 1\right]}$$

Scaling factor = 0.0001



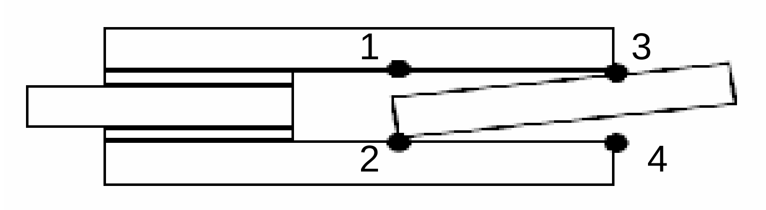
ABAQUS, LabVIEW, and MATLAB were utilized to collect and analyze data

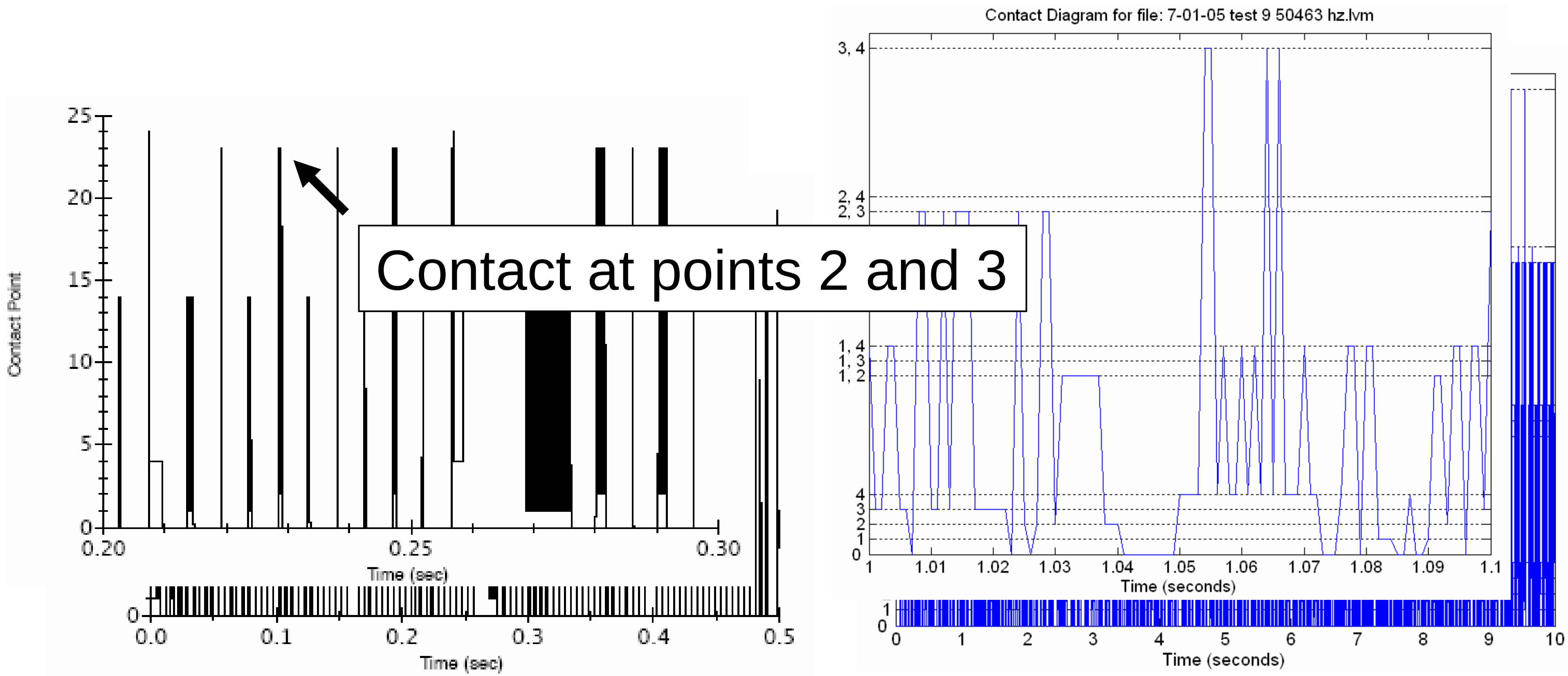
ABAQUS was used for parameter Identification

MATLAB was used for data analysis

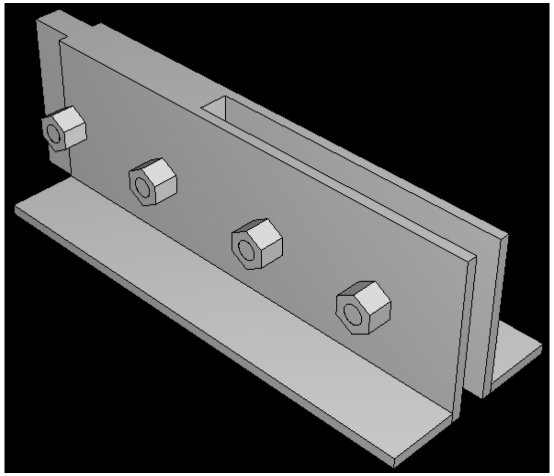
LabVIEW was the user interface and data acquisition system used

A MATLAB analysis program detects the switching behavior in the joint





Mass and Inertia properties of the rigid bodies were determined using ABAQUS

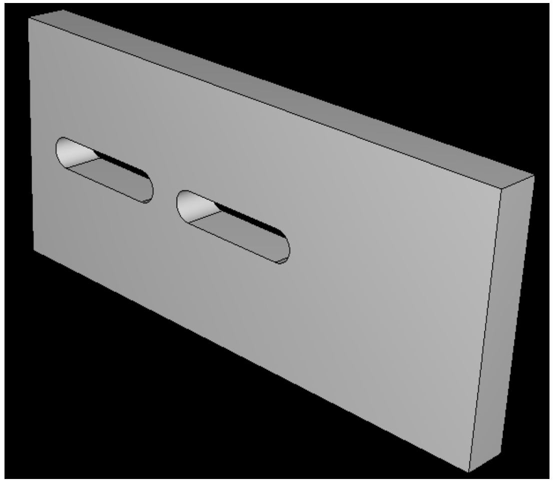


Section-3

Mass = 313.81 grams

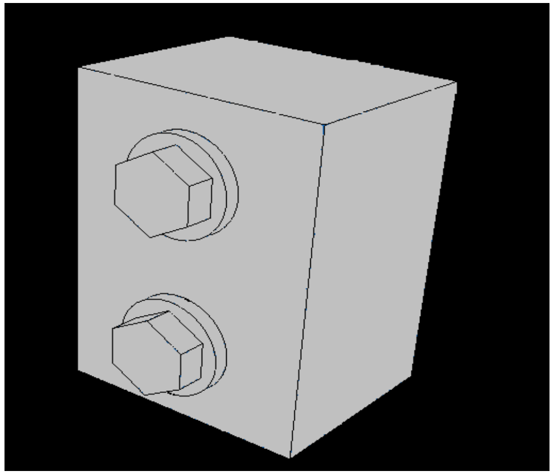
Mass moment of inertia = 24857 g*cm^2

Section-4



Mass = 123.33 grams

Mass moment of inertia = 301.55 g*cm^2

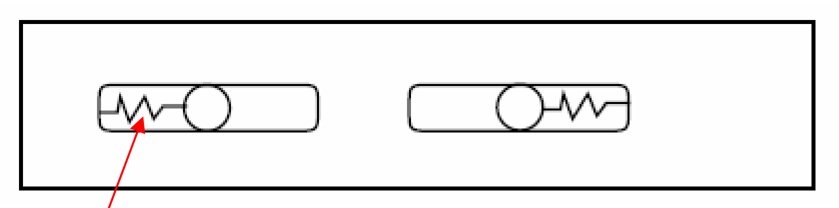


Section-6

Mass = 158.9 grams

Mass moment of inertia = 1398.6 g*cm^2

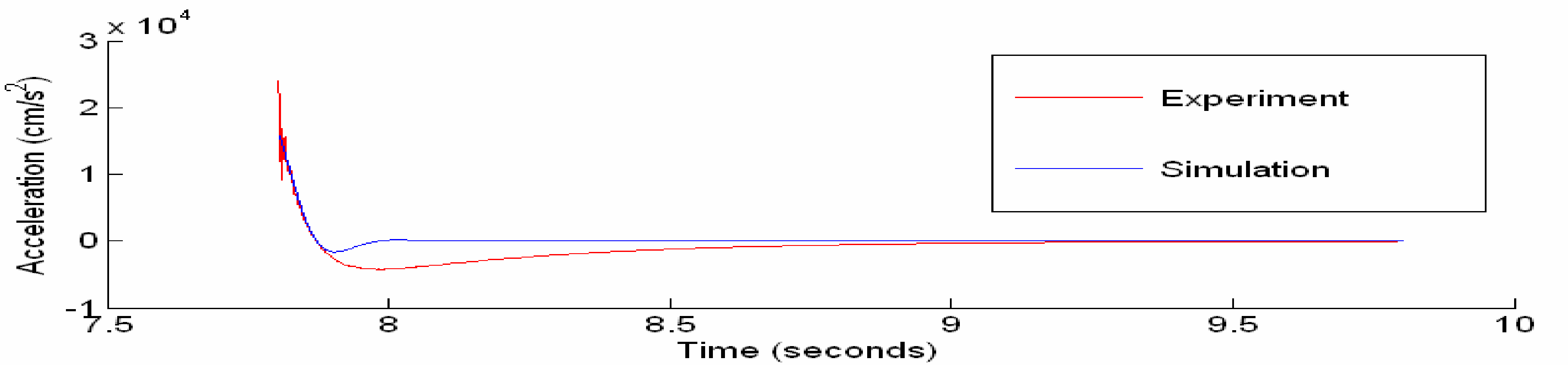
Determining the stiffness and damping properties of the cork filler is difficult



Cork Filler – Simulated by a spring-damper in the model

Static displacement to measure stiffness

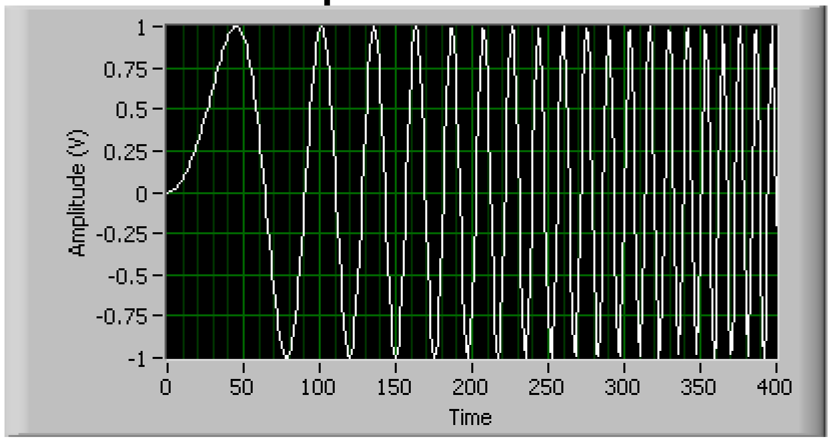
Applied Load (g*cm/s^2)	Pre-Load Gap (cm)	Load Gap (cm)	Stiffness (g/s^2)
3.14E+06	0.71	0.635	4.19E+07
4.12E+06	0.77	0.585	2.23E+07
3.92E+06	0.635	0.58	7.13E+07



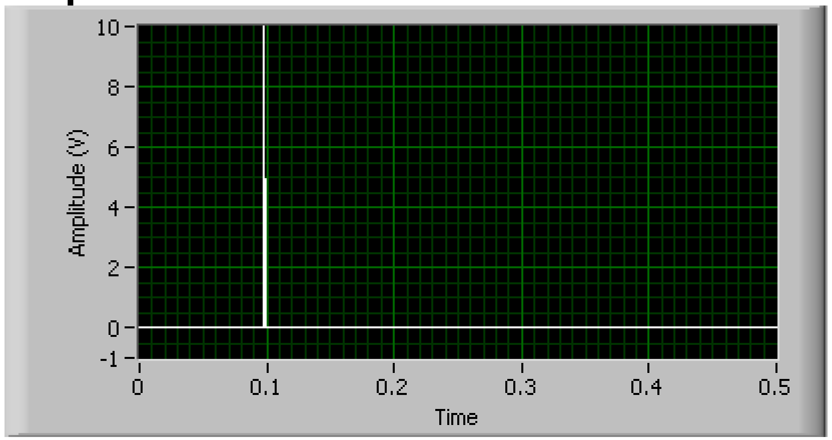
2nd order diff model using linear and nonlinear spring stiffness

Four sets of experiments, each with and without a tip mass, were performed on the beam

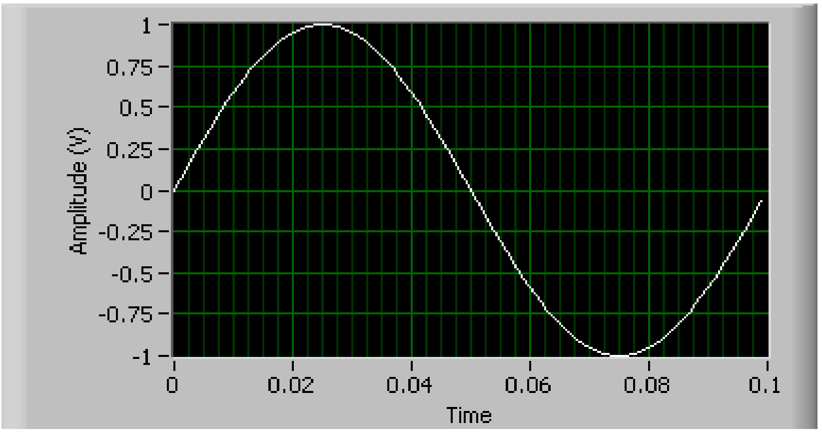
Sine Chirp



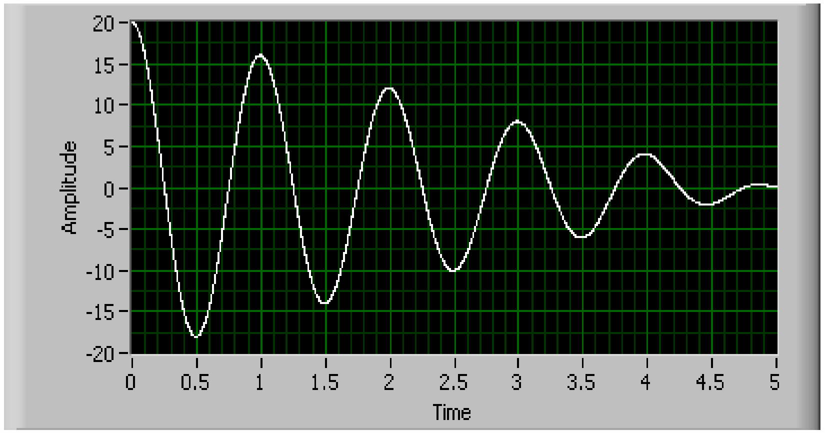
Impact



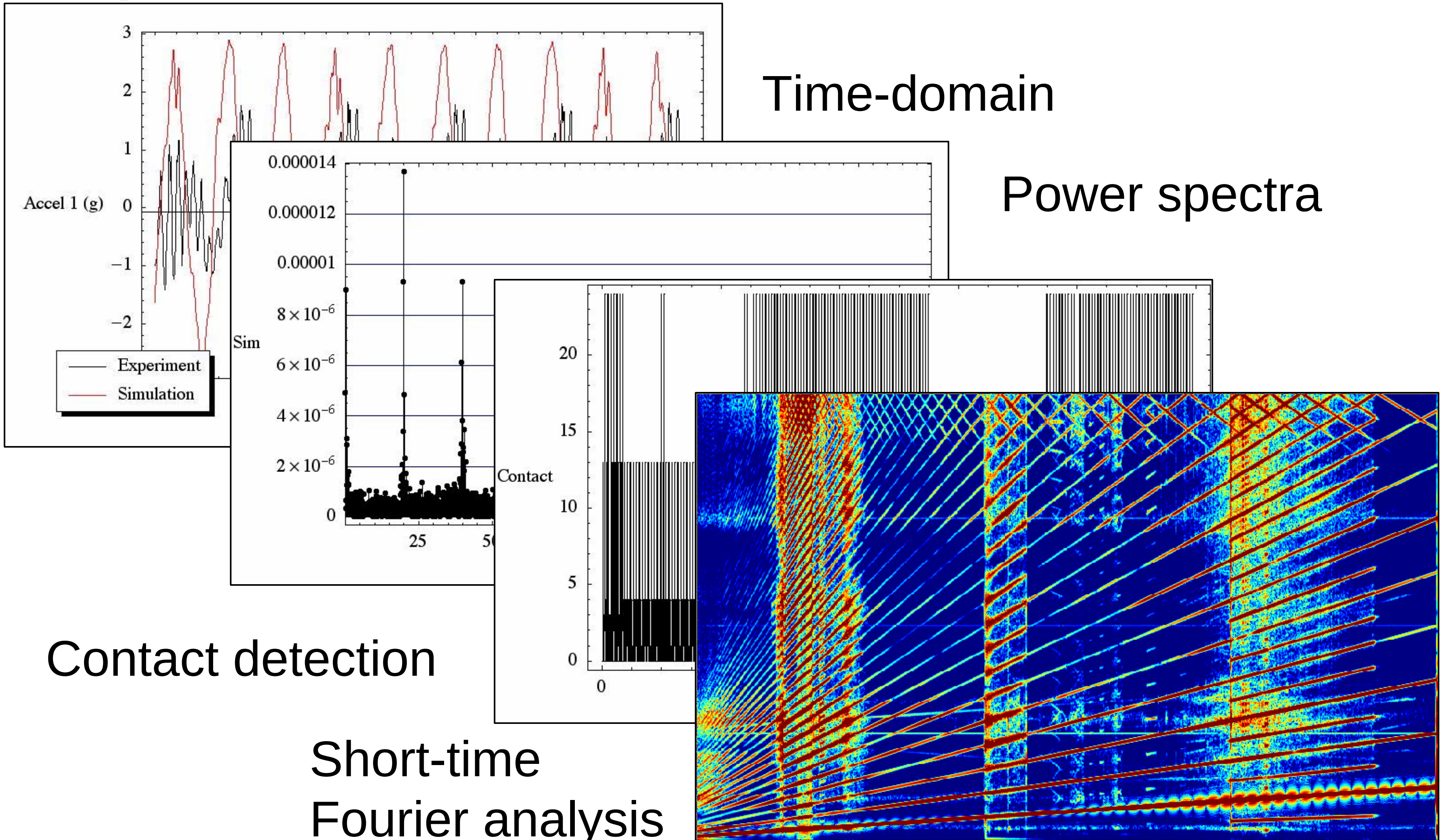
Shaker Test



Deflection



To validate the model, experimental data were compared to simulation data



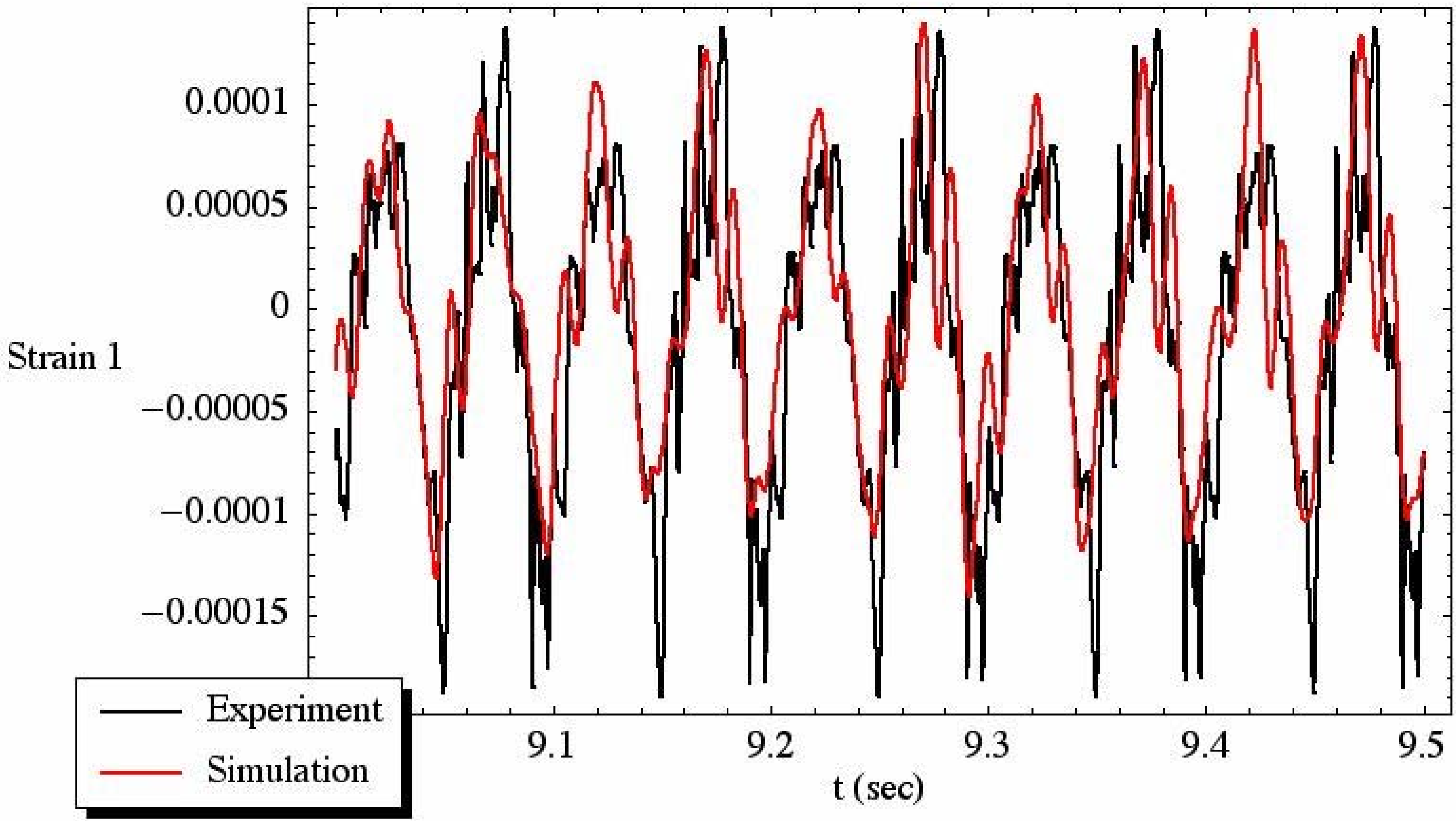
Time-domain

Power spectra

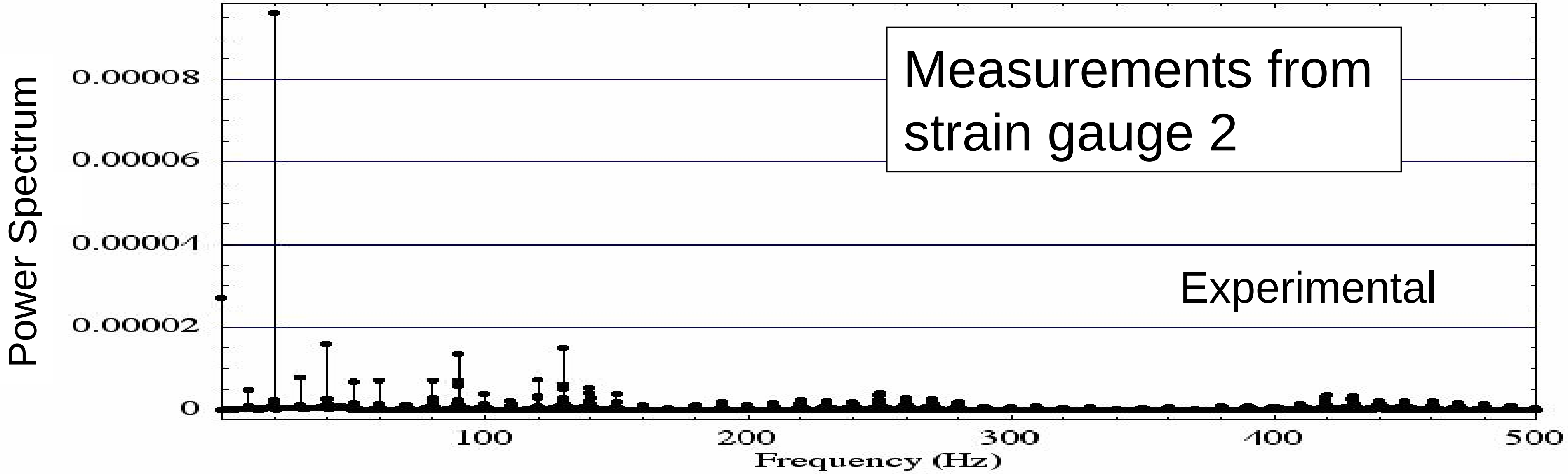
Contact detection

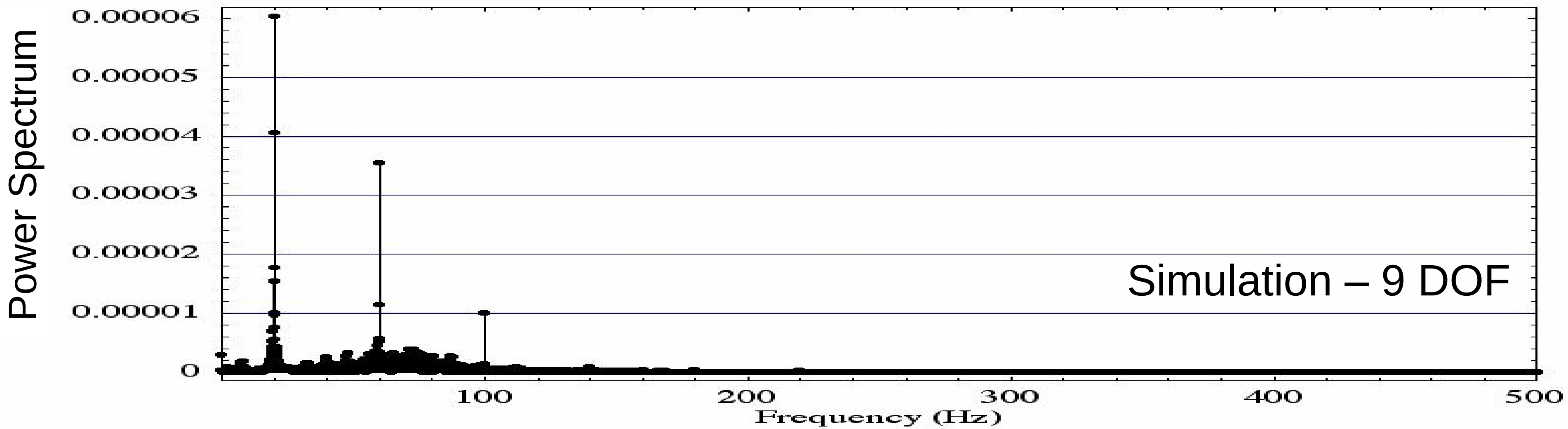
Short-time
Fourier analysis

In the time-domain, the model is under predicting amplitude and frequency content, but overall gives a good approximation for only 9 DOF.

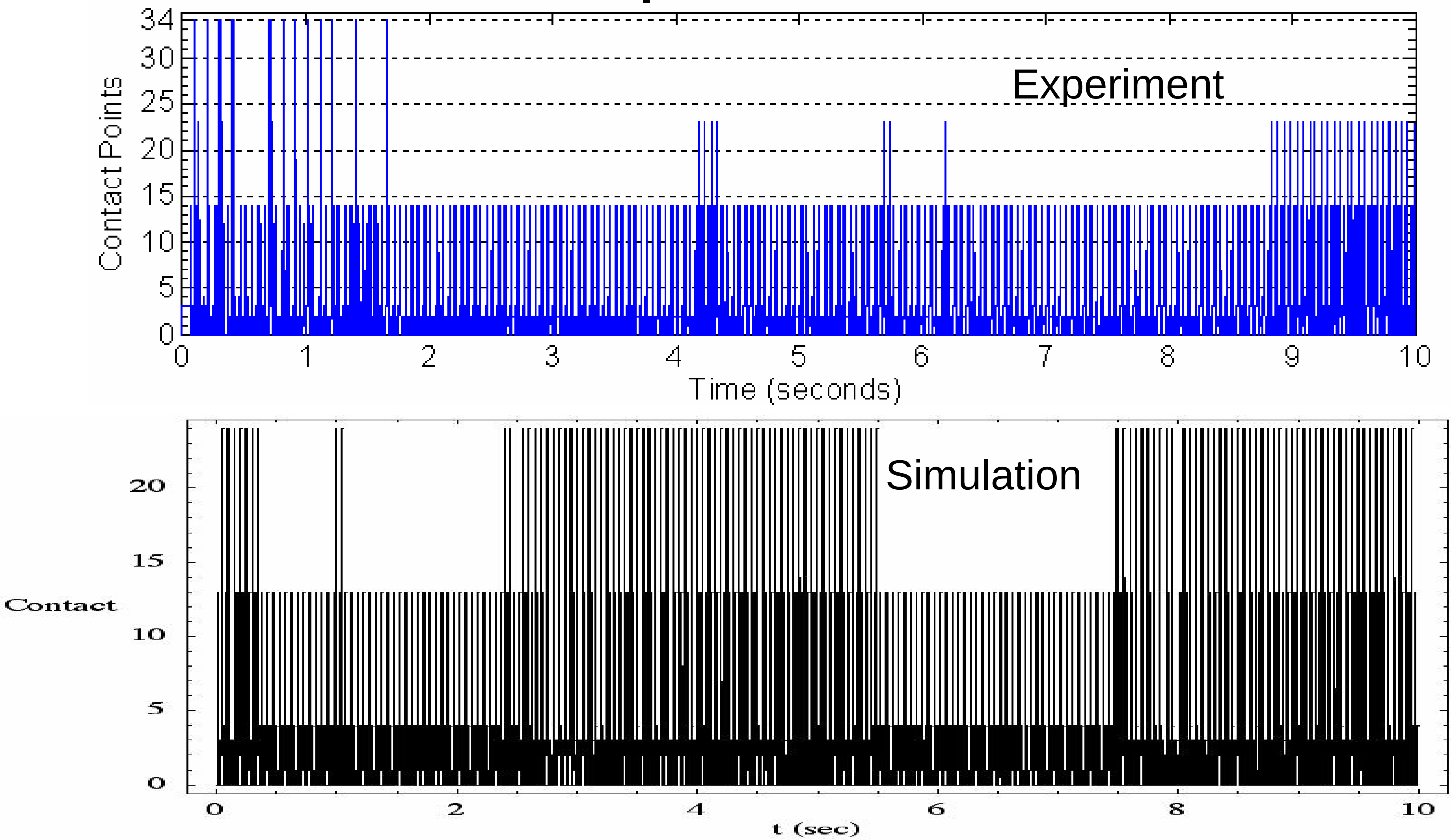


The model is finding integer multiples of the driving frequency, but does not capture details in the experimental data

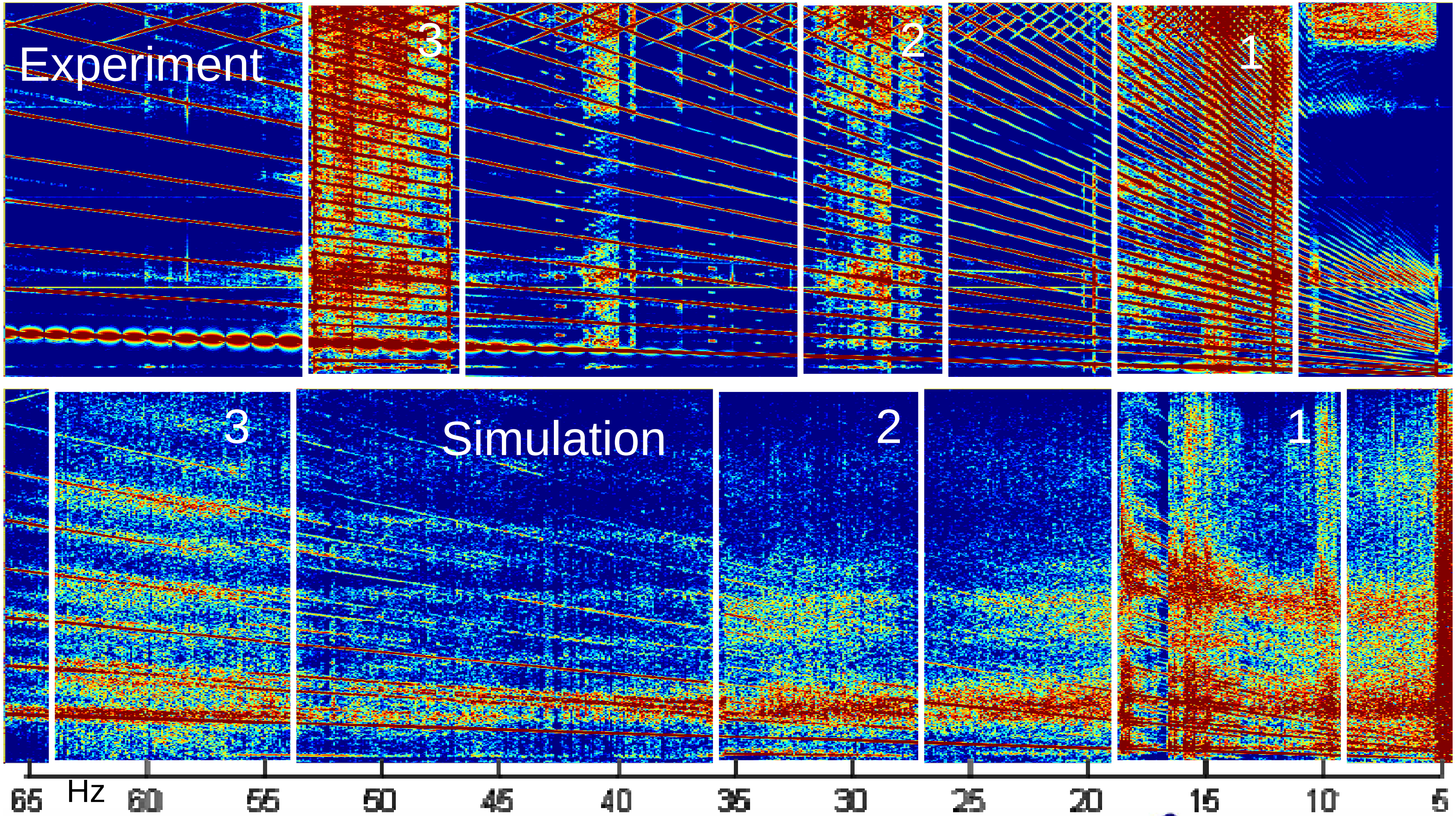




The contact sensors and detection algorithm are not giving results consistent with the predictions of the simulation.



Resonant bands have been shifted up in frequency in the simulated Sine chirps



Some possible future efforts with the model

Create a parameter estimator to improve model accuracy

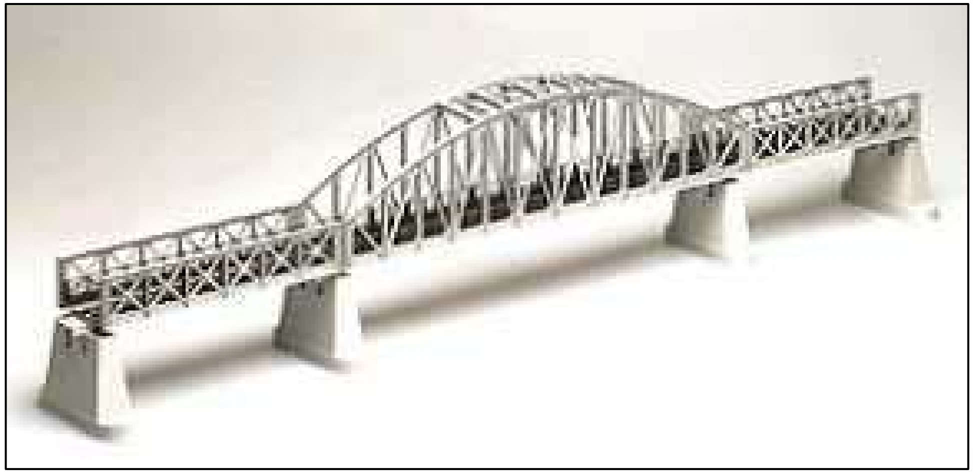
Refine values used for damping

Model the joint as an elastic body

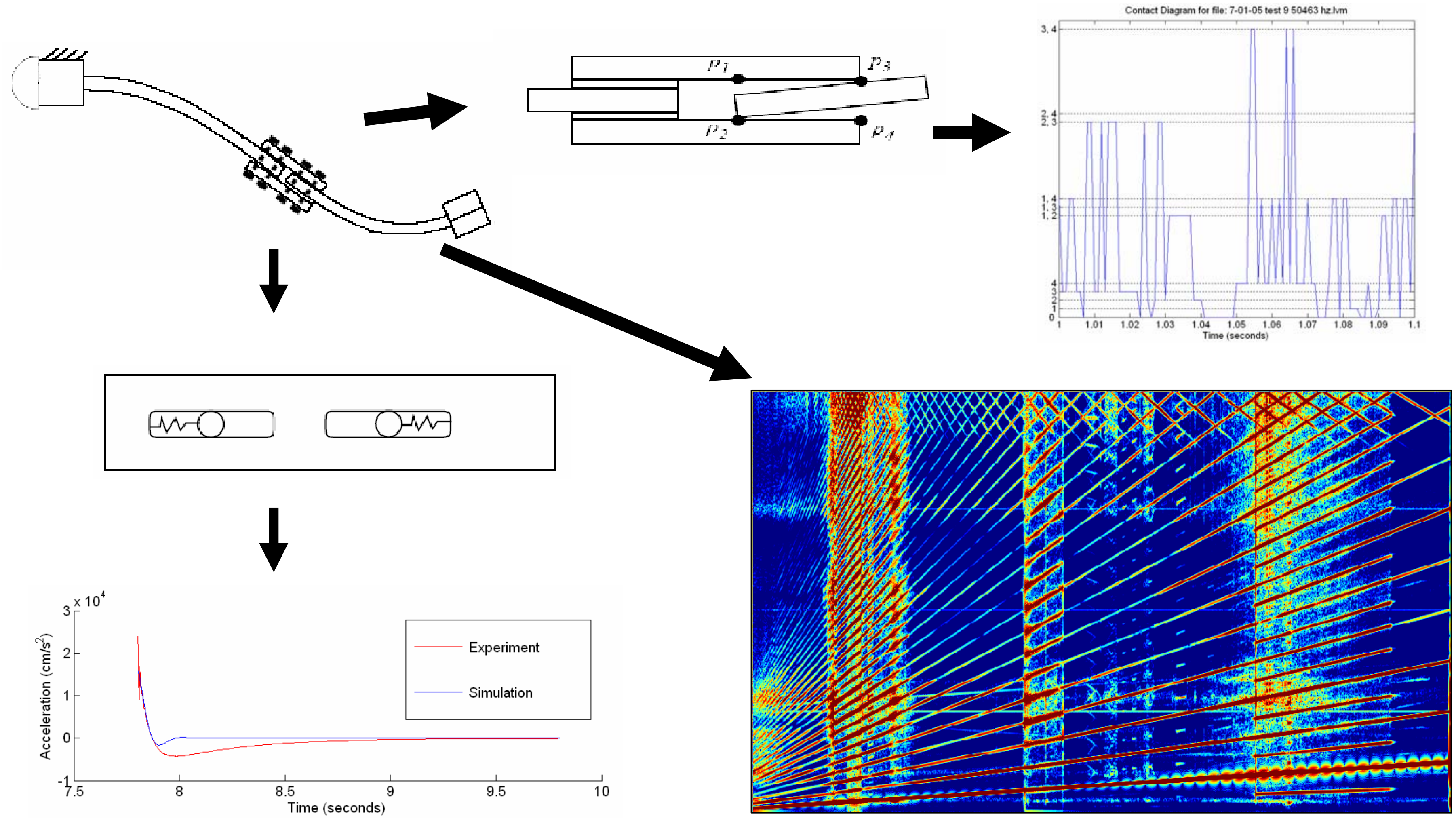
Modularize code for use in FEA programs

Utilize in a controller to mitigate damage

Active damage sensing



In summary, the model has shown some correlation with experimental data and warrants further study



We would like to acknowledge…

•**Engineering Sciences and Applications Division at Los Alamos National Laboratory**

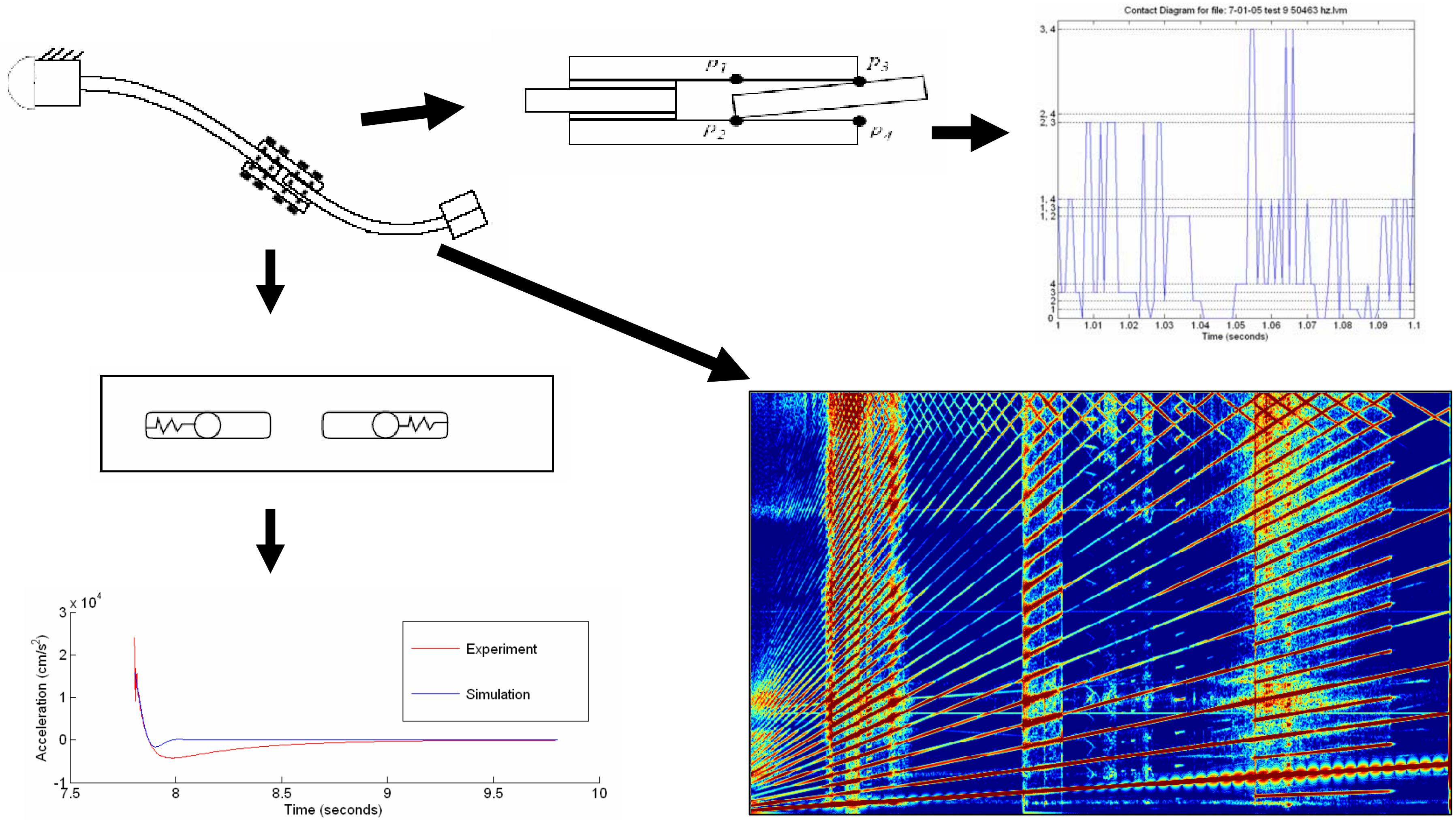
•**The Mathworks, Inc. (MATLAB Software)**

•**ABAQUS, Inc. (ABAQUS Finite Element Software)**

•**Vibrant Technology Inc. (ME'scope Software)**

Thank You

Questions?



p1
p3
p2
p4
Contact Diagram for file: 7-01-05 test 9 50463 hz.lvm
Time (seconds)
x 10^4
Acceleration (cm/s^2)
Experiment
Simulation
Time (seconds)