Experimental Modal Analysis and Damage Detection in a Simulated Three-Story Building

Los Alamos Dynamic Summer School

2001

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Motivation

Damage Detection — **The ability to detect and possibly predict structural damage in a building could be a cost effective tool for verifying safety standards in structures.**

Technology — **Structural health monitoring could be an excellent application of advancements in MEMS, fiber optics, and wireless sensing technology.**

Data Processing and Storage — **The computing power and data storage needed for effective health monitoring are readily available.**

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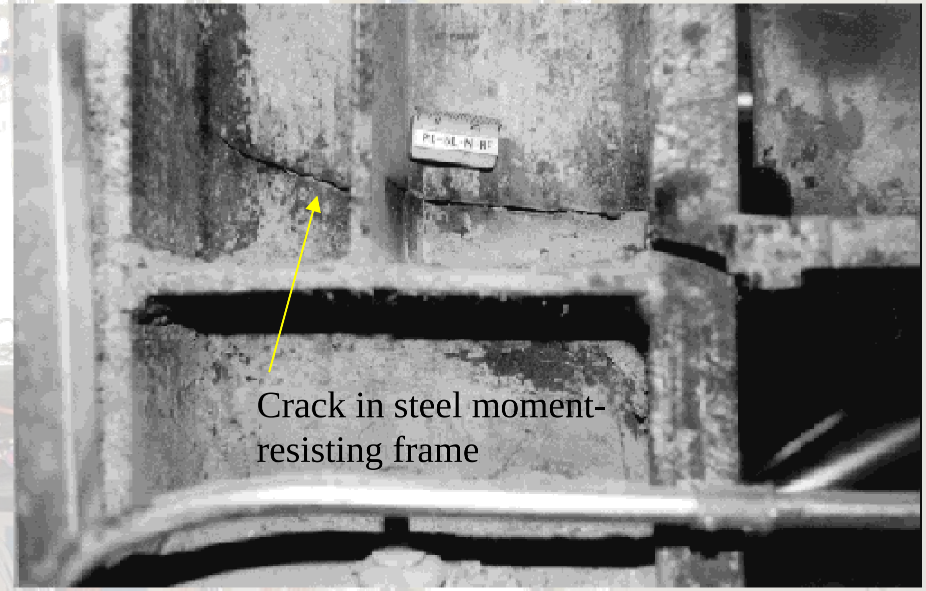
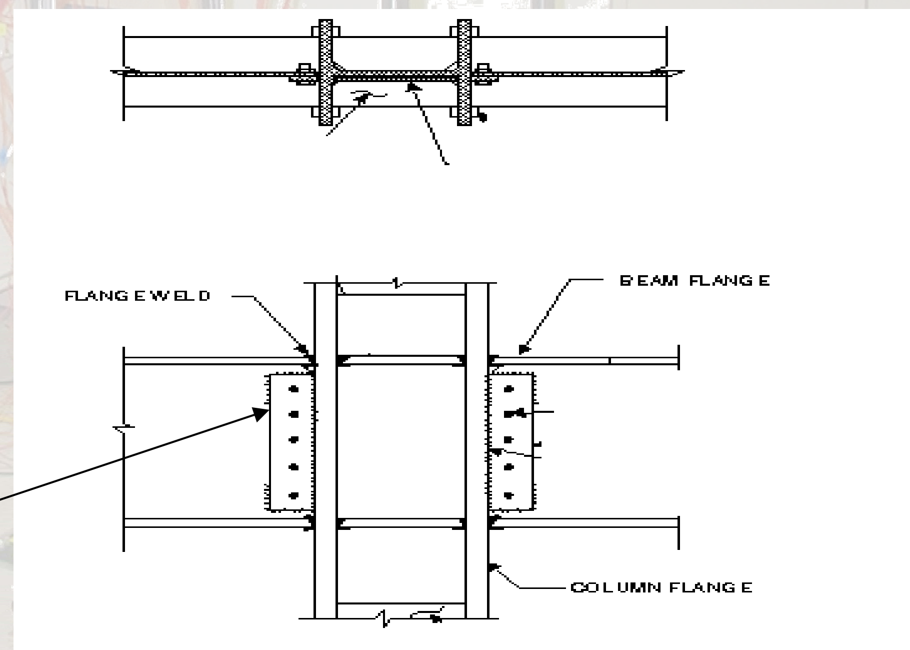
Earthquake Damage

- Specific applications of structural health monitoring include detecting damage in structural connections.
- Moment-resisting connections in steel frame structures are specifically designed to withstand earthquake conditions.
- After the 1994 Northridge earthquake, cracks were found in many of these moment-resisting connections





Welded flanges

Project Goals

- Perform a modal analysis on our structure that can be correlated with a finite element model.
- Determine the feasibility of damage detection in steel frame joints.
- Include operational and test variability in our damage detection process.
- Determine a damage detection process that is repeatable, efficient, and reliable.

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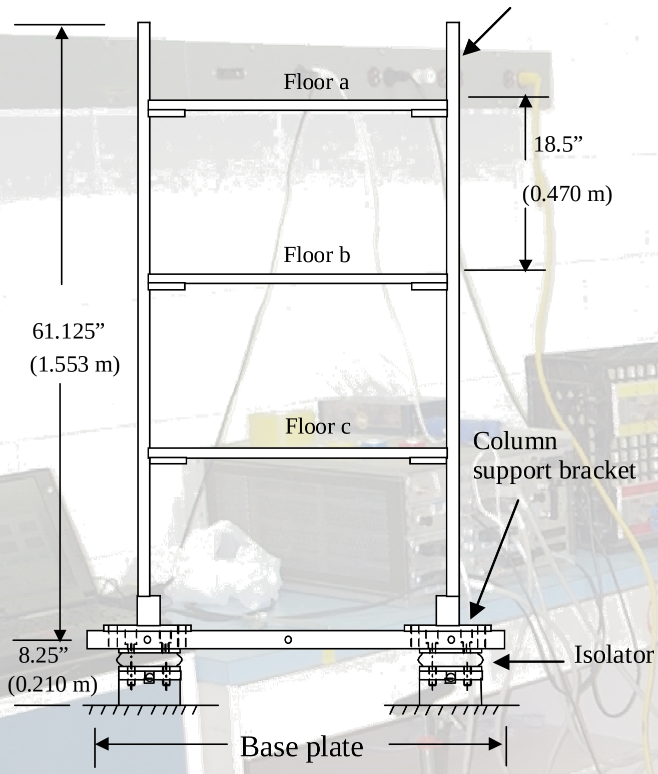
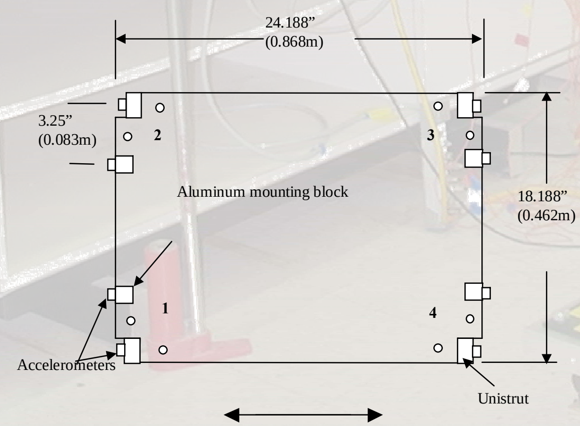
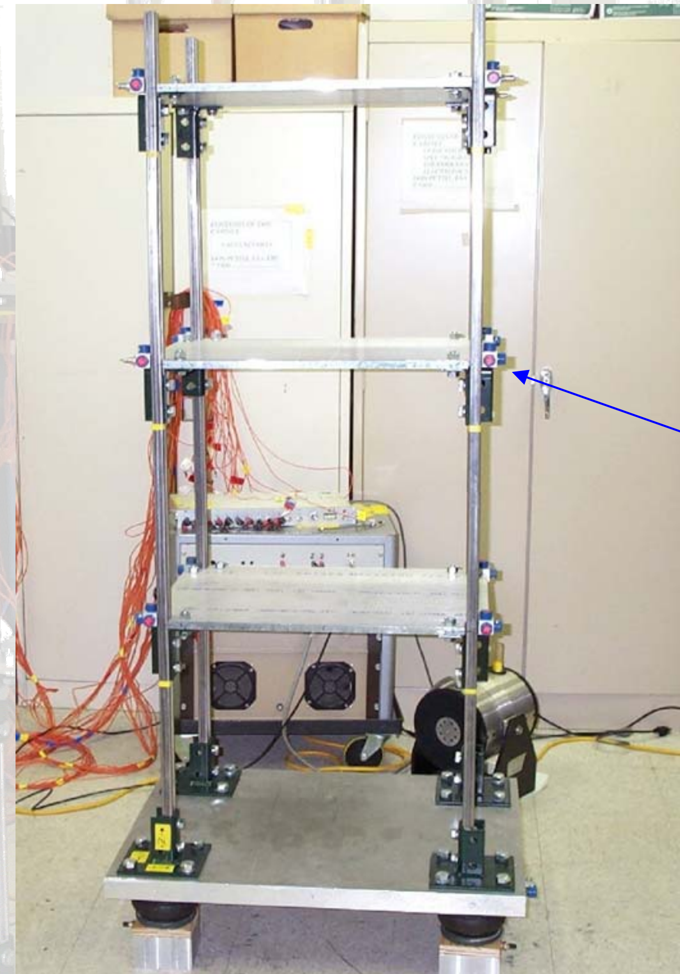
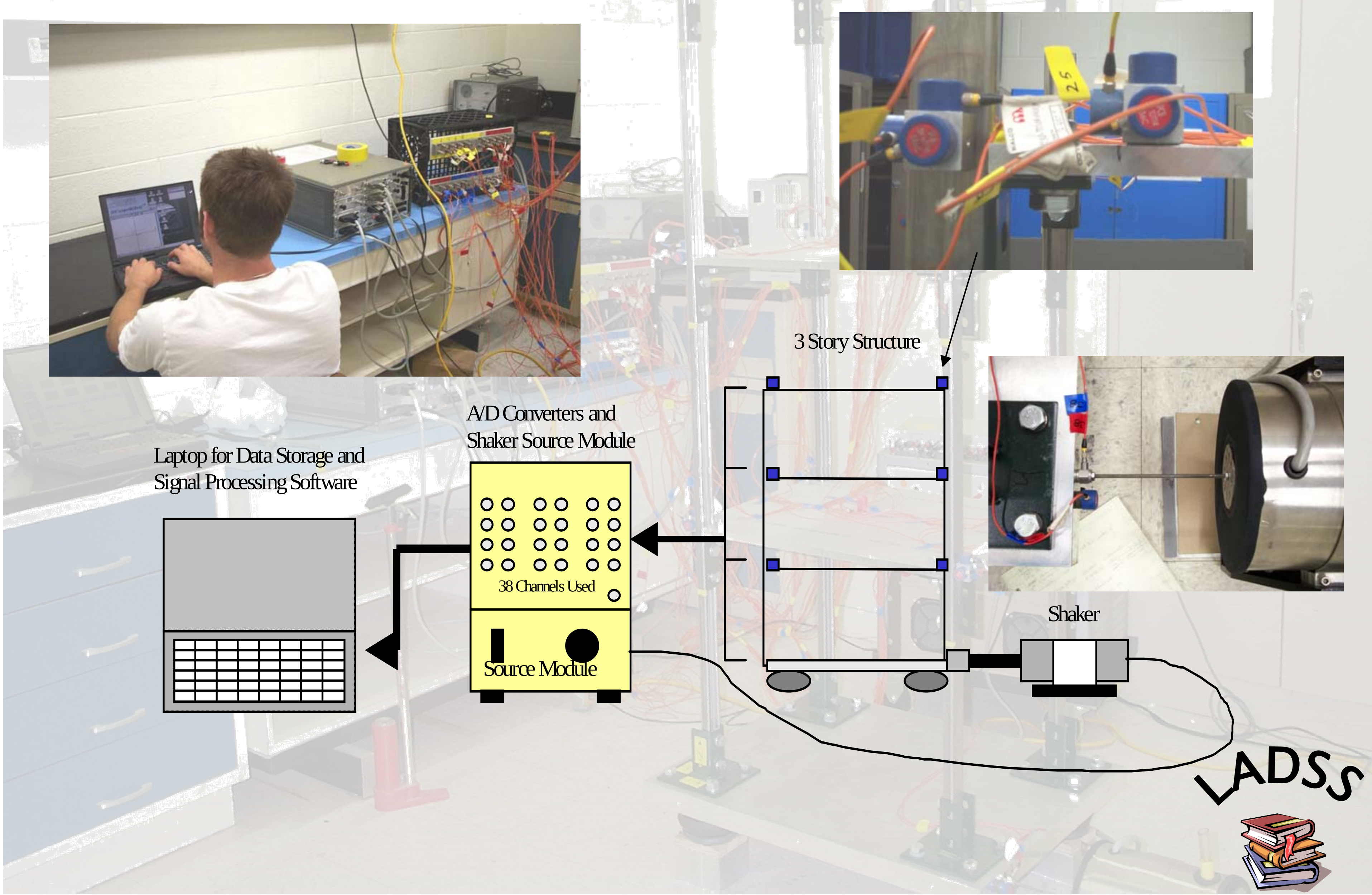
The Structure





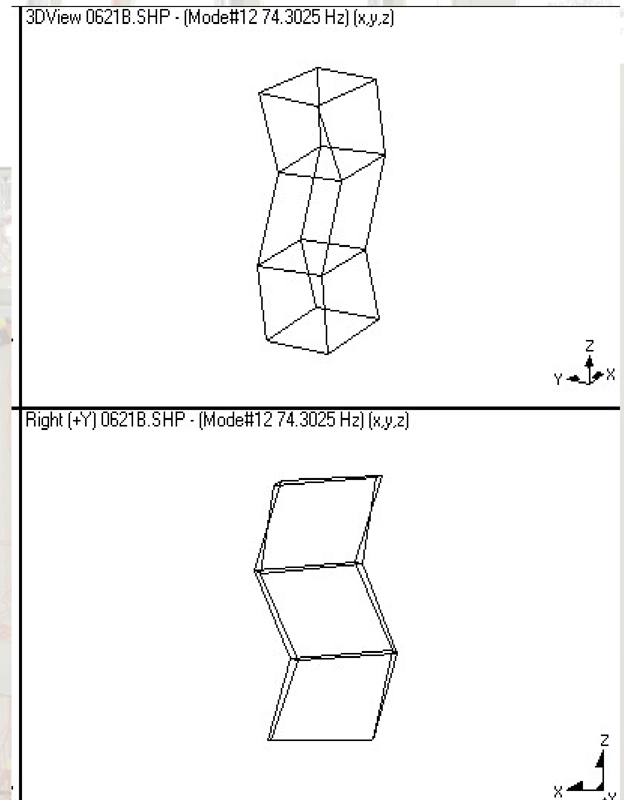


Data Acquisition



Modal Analysis

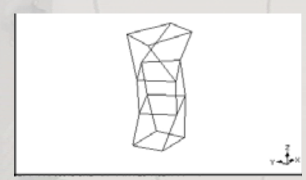
- **Using the HP data acquisition system, the frequency response functions in the range between 0-200 Hz were estimated from the measured time histories.**
- **16 Modes were found using ME' scope experimental modal analysis software.**
- **The third bending mode in the X-direction was found at 74.3 Hz and is pictured to the right.**



Mode Variation

Frequency (Hz)		Mode (X and Y direction)
Test 1	**Test 2**	
2.288	2.309	Rigid body Y
3.037	3.109	Rigid Body X
12.568	12.71	1st Torsion
13.903	14.396	1st Bending X
14.457		1st Bending Y
24.87	24.726	2nd Torsion
32.038	31.749	Possible Unistrut Mode
40.081	39.087	2nd Bending X
49.816	49.297	Possible Unistrut Mode
69.095	66.034	2nd Bending Y
73.424	69.633	3rd Torsion
74.297	71.626	3rd Bending X
120.327	114.651	3rd Bending Y
138.887	134.714	4th Torsion
145.037	144.645	Possible Air Bearing Mode
187.593	184.17	Possible Floor Plate Mode

- **To test for variability in the modal properties, the structure was taken apart and then reassembled and the modal analysis was performed a second time.**
- **This table shows the changes in the modal frequencies between the first and second tests.**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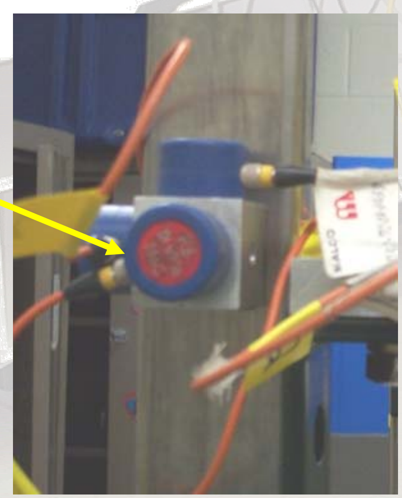
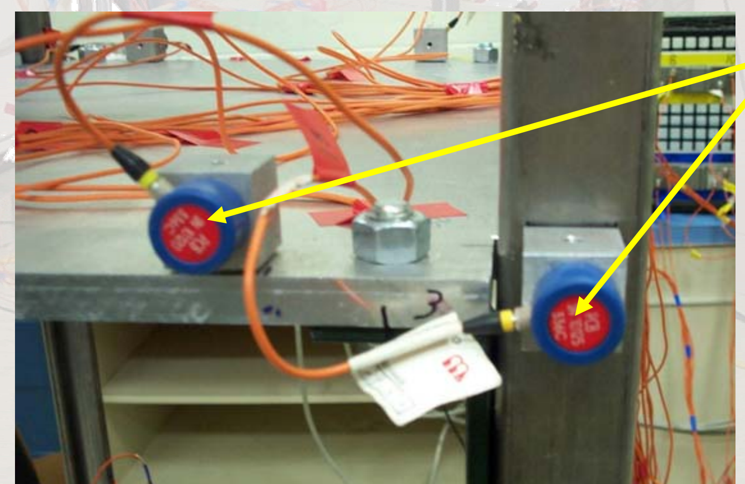
Accelerometer Setup

- For the modal analysis portion of the project, each joint above the ground level was fitted with three sensors.
- One Accelerometer in each direction (X,Y and Z) was screwed in to an aluminum block that had been hot-glued to the structure.
- For the damage detection phase we needed the relative signals between two accelerometers for each corner.
- Another aluminum block was added to the floor plate about 3 ½ inches from the joint.

Modal analysis acc. setup





Damage detection setup

Damage Modeling

- We created damage in our structure joints by loosening the bolts connecting the black bracket to the aluminum floor.
- Our goal was to pick up the signal change between an accelerometer mounted on the floor and an accelerometer mounted on the column.
- The highest torque used for a damage case was 15 inch-pounds. For second damage case we tightened the bolts by hand (approx. 5 inch-pounds), and for the third case we removed the bolts all together.

Top View

Bottom View

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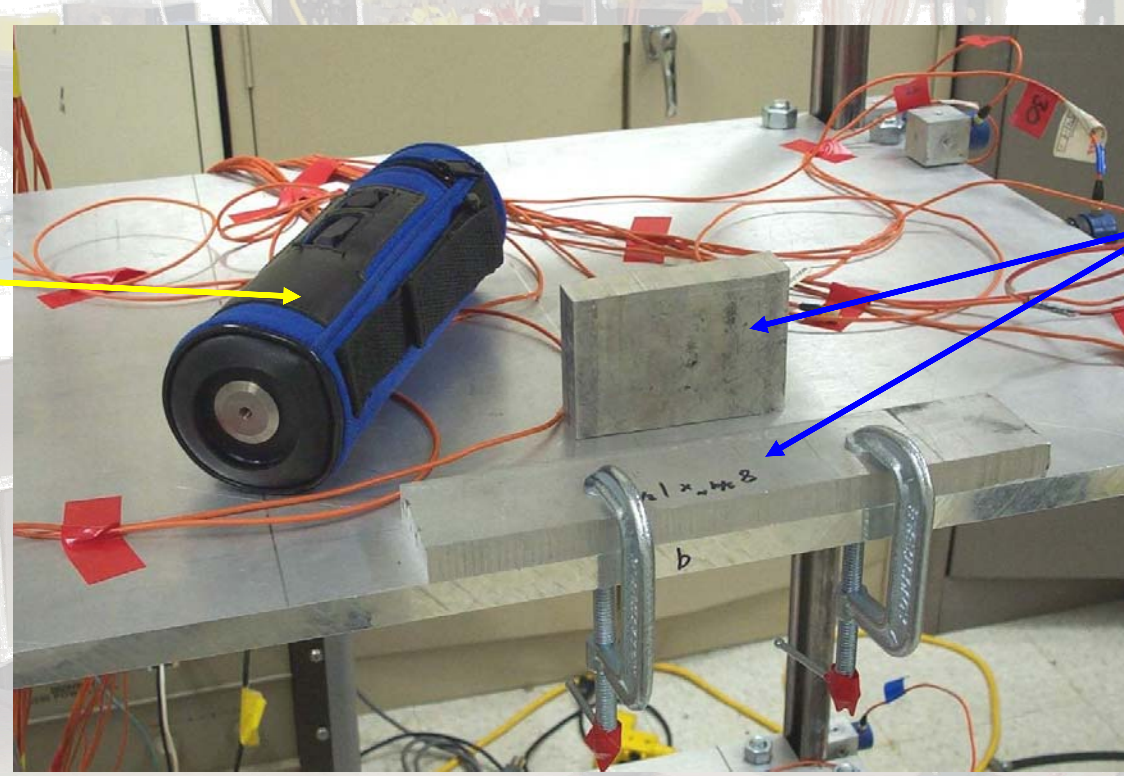
Operational Variability

- **For a damage detection process to be robust, it must be able to sort out joint damage from daily changes in a buildings operational conditions.**
- **A handheld shaker and aluminum blocks were used to create changes that may affect the vibration signature of the structure.**

Handheld shaker that puts out a sign wave



Aluminum blocks used for operational condition testing

The Tests

- Baseline, non-damaged, time histories were recorded with roaming masses.
- Damaged case time histories were recorded according to our test matrix
- Three different excitation levels (1.01 V, .25V, and .128V) were used in an effort to establish a minimum level needed to affectively detect joint damage.
- For most tests the random excitation frequencies were between 0-200 Hz.
- For selected tests the excitation levels were from 0-3000 Hz.

Test Matrix

Damage Case 4**** level c mass	File name
.128 volts, 0-200 Hz, 15 in*lbs torque on bot plate bolts	2c13t4_1,2,3
.128 volts, 0-200 Hz, plate bolts hand tight	2c13h4_1,2,3
.25 volts, 0-200hz, hand tight	2c25h4_1,2,3
1 volt, 0-200 Hz, hand tight	2c1h4_1,2,3
.128 volts, 0-200 Hz, bolts removed	2c13n4_1,2,3
Damage Case 5*** level a & b mass**	
.25 volts, 0-200 Hz, 15 in*lbs torque on both plate bolts	2ab25t51,2,3
.25 volts, 0-3.2 kHz, 15 in*lbs torque	3ab25t51,2,3
.25 volts, 0-200 Hz, both plate bolts hand tight	2ab25h51,2,3
1 volt, 0-200 Hz, bolts hand tight	2ab1h5_1,2,3
.25 volts, 0-200 Hz, bolts removed	2ab25n51,2,3
.25 volts, 0-3.2 kHz, bolts removed	3ab25n51,2,3

*** Joint 2a damage**

**** Joint 4b damage**

***** Joints 4b and 2a damage**

****** Joint 4b with small mass on level a, mid mass on b**

******* Joint 2a and 4b with handheld shaker on level a**

Data Normalization

- To separate our time history data as much as possible from the excitation levels they were recorded at, each channel pairs time history was normalized.

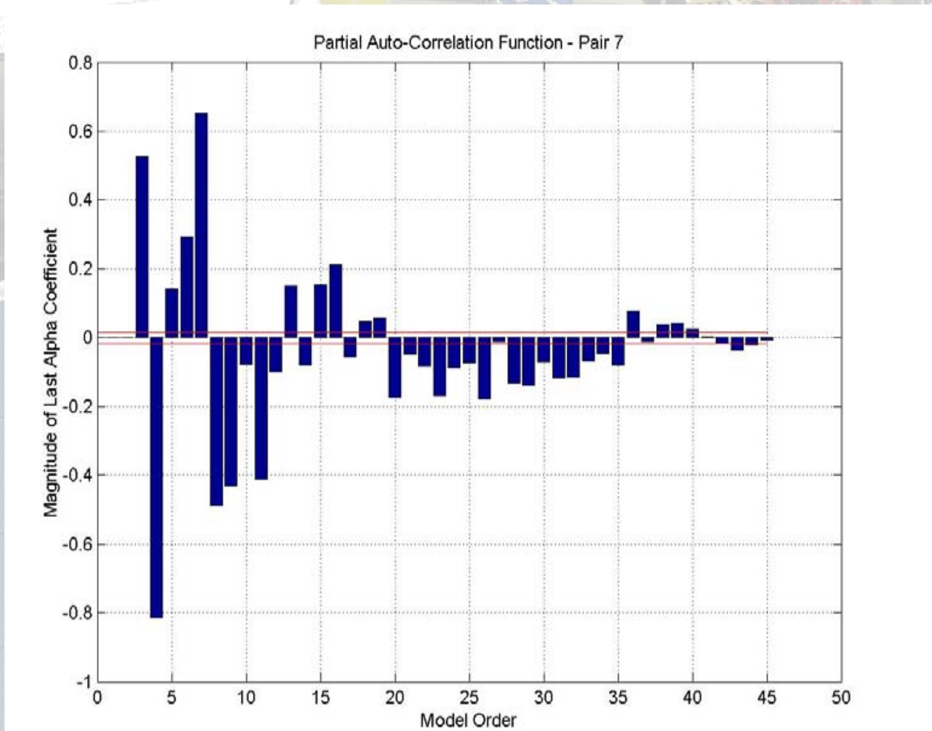
$$\hat{X} = \frac{X - \overline{X}}{S}$$

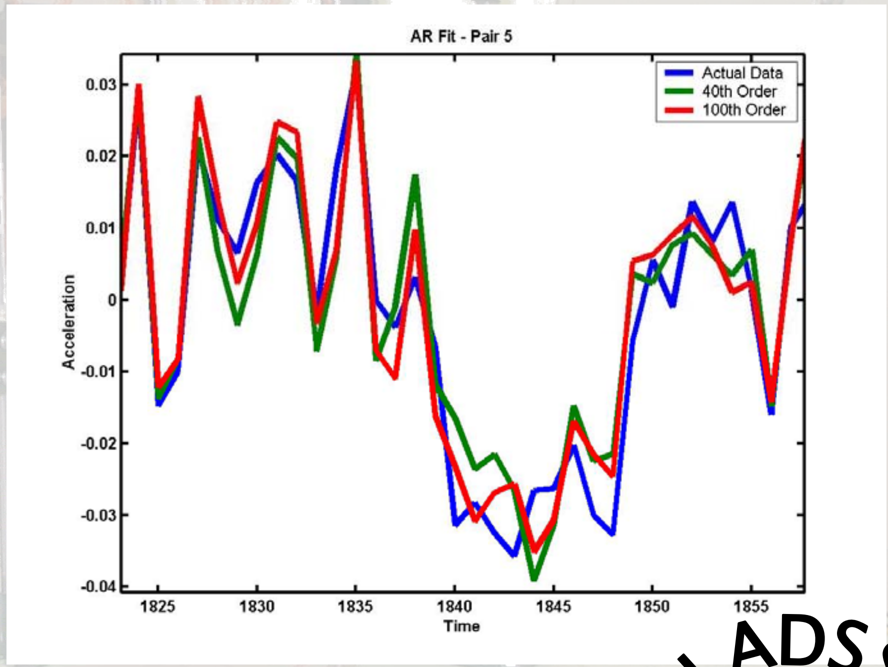
- This was done for baseline data and damage case data

Partial Auto Correlation

• A partial auto correlation was performed to determine the order of our auto regression model.

• A 40th order model was decided on after plotting the 40th order fit compared to a 100th order fit





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AR Model

- **A 40th order AR model of the form**

$$x(t)=\sum_{i=1}^{40}\alpha_i x(t-i)+e(t)$$

was fit to the signal pairs.

- **This was performed for baseline and damaged data**

- **The baseline AR coefficients and residual errors were saved to a matrix for damage case comparisons and for use in the ARX model.**

ARX Model

- An 8th order ARX model of the form

$$x(t) = \sum_{i=1}^{8} \alpha_i x(t-i) + \sum_{j=0}^{7} \beta_j e(t-j) + \varepsilon(t)$$

was fit to the baseline dataset.

- The residual errors of the AR model were used as an approximation of the input to the ARX model

- The damage case data were fit to the selected baseline ARX models. The resulting residual errors were used in the statistical feature analysis.

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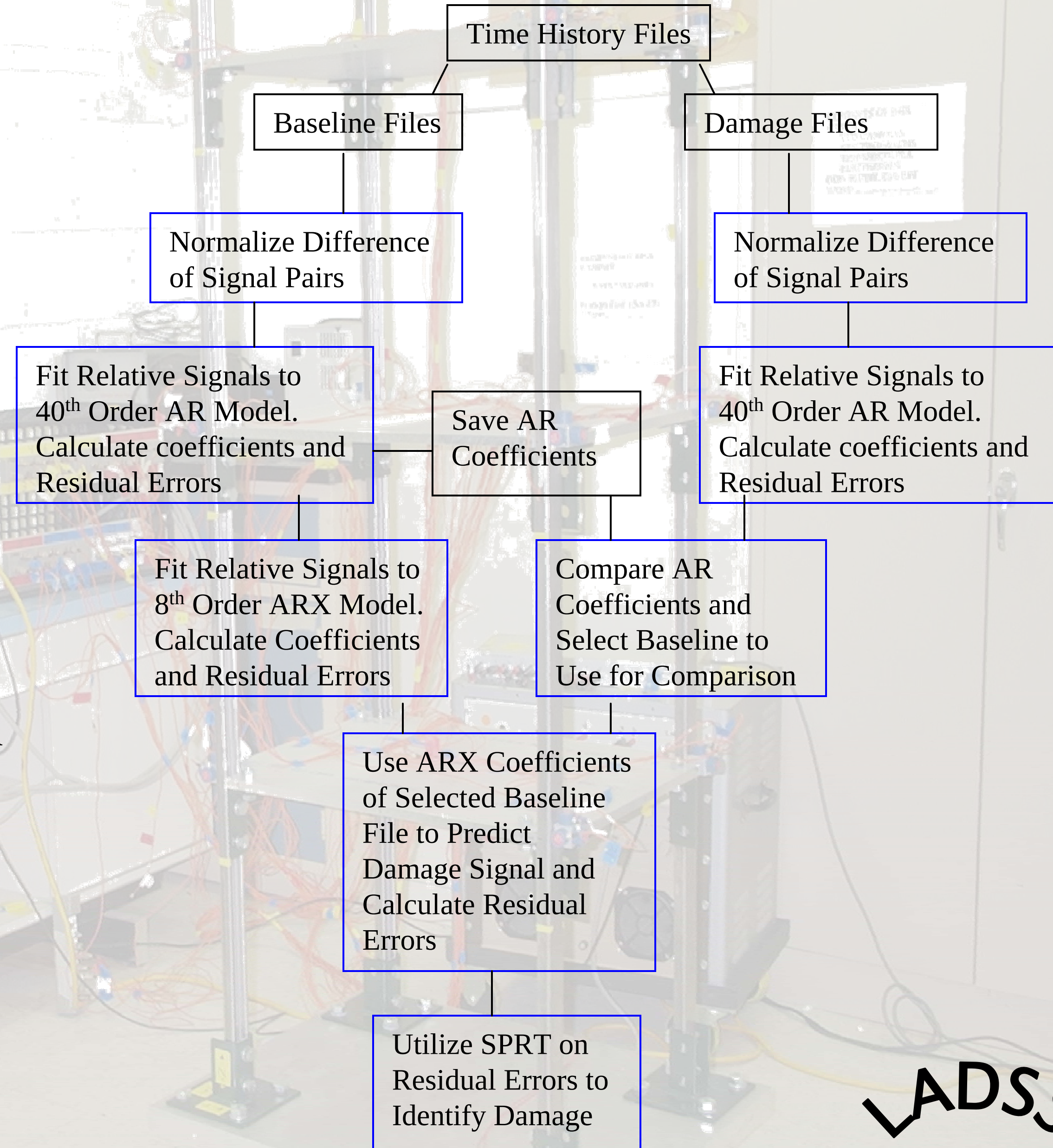
Data Flow

- **Normalization**
- **AR**
- **ARX**
- **Compare AR coef. and select ARX model**
- **SPRT**
- **Decision**



SPRT

- The Sequential Probability Ratio Test (SPRT) is a method of statistical inference meant to minimize the number of samples needed before reaching a decision.

- Given the two simple hypotheses: $H_o : \theta = \theta_o, \quad H_1 : \theta = \theta_1, \quad \theta_o \neq \theta_1$

  where θ is a parameter value

- SPRT will Accept H_o if $Z_n \leq b$

  Reject H_o if $Z_n \geq a$

  Continue observing data if $b \leq Z_n \leq a$

Where: $$Z_n = \ln \frac{f(X_n \mid \theta_1)}{f(X_n \mid \theta_o)}$$ and $$a \cong \ln \frac{1-\beta}{\alpha}$$ $$b \cong \ln \frac{\beta}{1-\alpha}$$

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SPRT

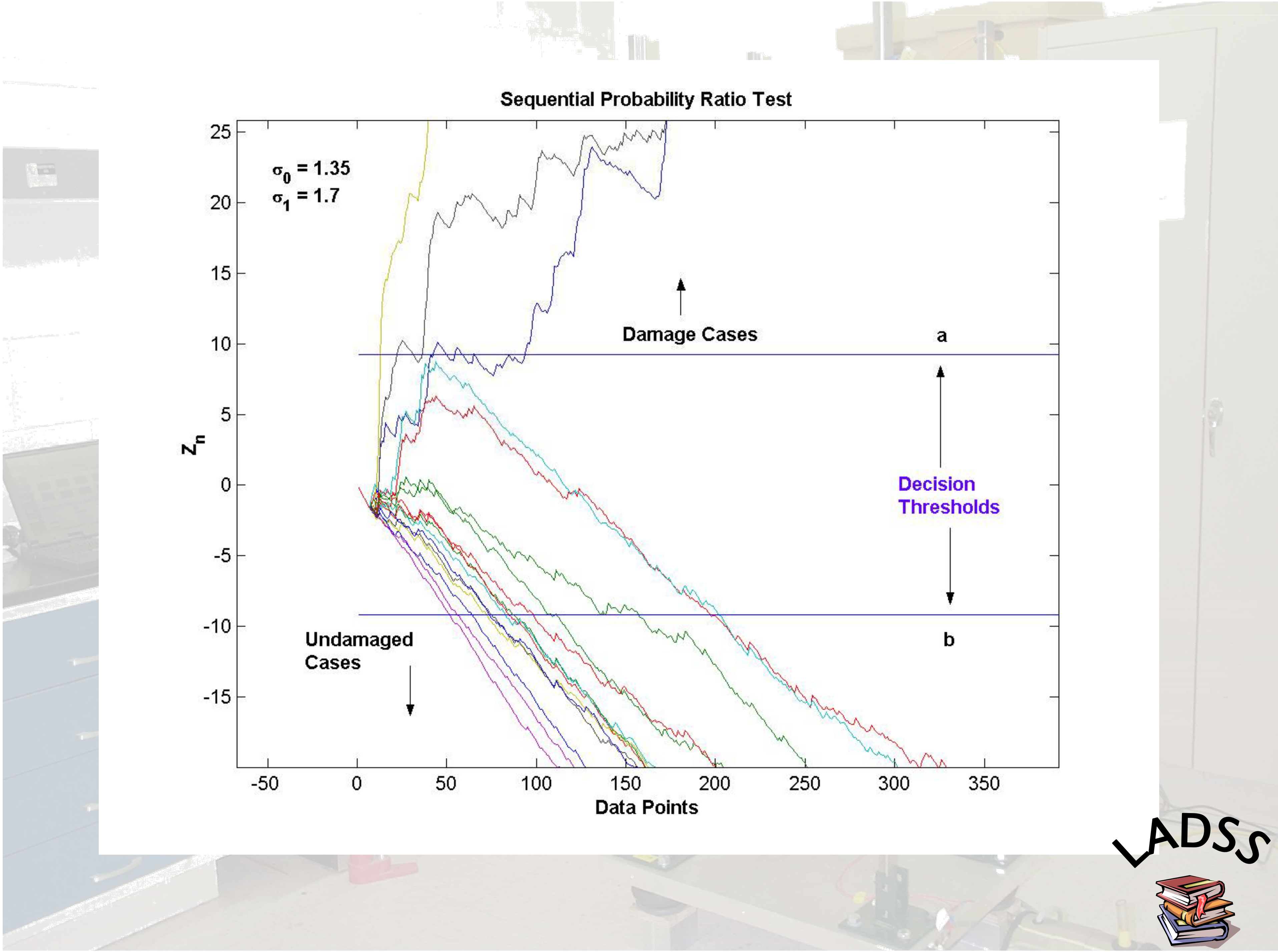
- **In our case, the hypothesis is:**

$$H_o : \sigma \le \sigma_o, \qquad H_1 : \sigma \ge \sigma_1, \qquad 0 < \sigma_o < \sigma_1 < \infty$$

Where the parameter in question is the standard deviation of the residual errors.

- **In this case:** $Z_n = \sum_{i=1}^{n} z_i$ **and** $z_i = \frac{1}{2}\left(\frac{1}{\sigma_o^2} - \frac{1}{\sigma_1^2}\right)(x_i - \mu)^2 - \ln\frac{\sigma_1}{\sigma_o}$

- **The behavior of the z function and therefore the success of the SPRT depends on the values chosen for** σ_o **and** σ_1


Sequential Probability Ratio Test
σ_0 = 1.35
σ_1 = 1.7
Damage Cases
a
Decision Thresholds
b
Undamaged Cases
Z_n
Data Points
25
20
15
10
5
0
-5
-10
-15
-50
0
50
100
150
200
250
300
350
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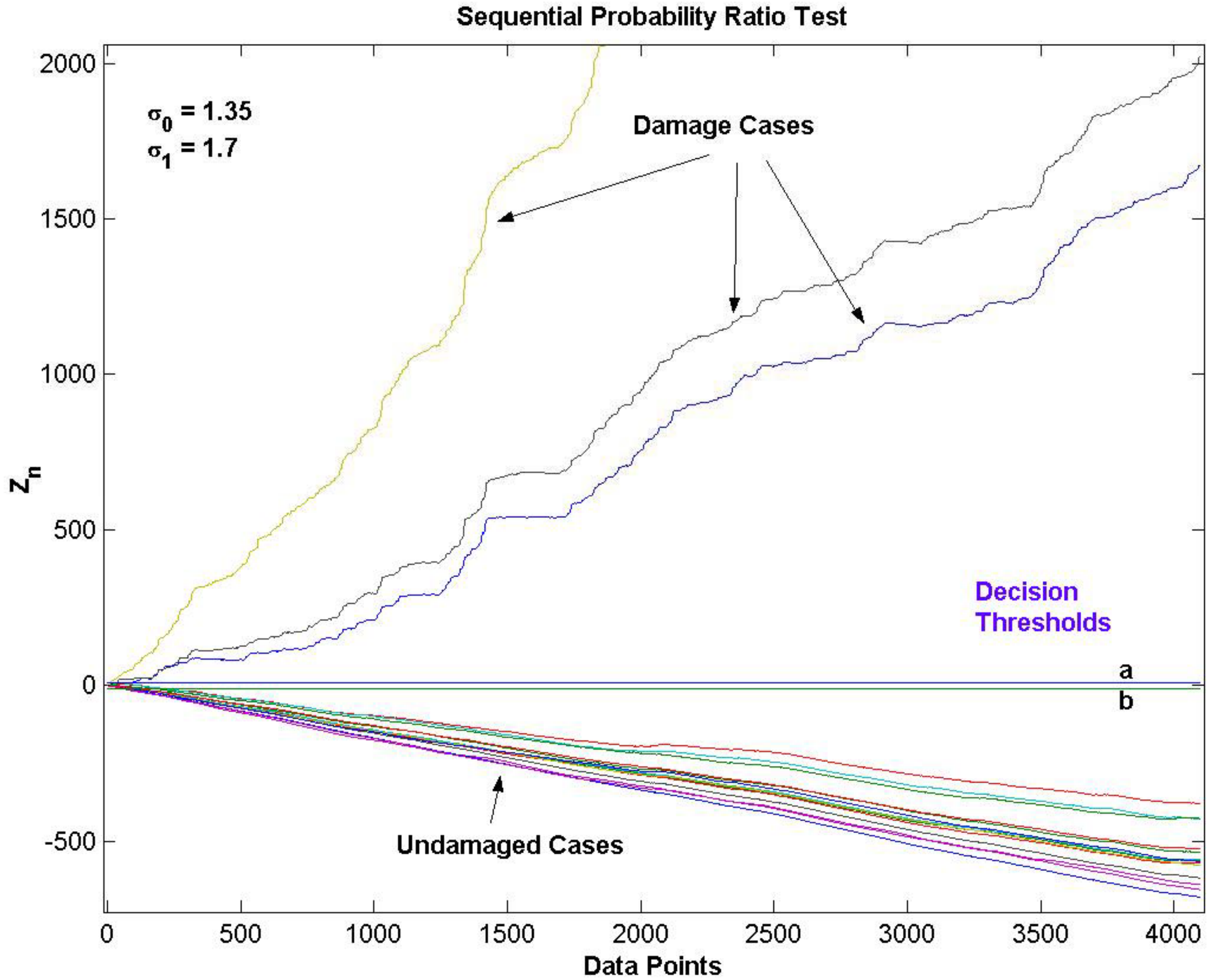
Sequential Probability Ratio Test
σ0 = 1.35
σ1 = 1.7
Damage Cases
Decision
Thresholds
a
b
Undamaged Cases
Zn
Data Points
2000
1500
1000
500
0
-500
0
500
1000
1500
2000
2500
3000
3500
4000

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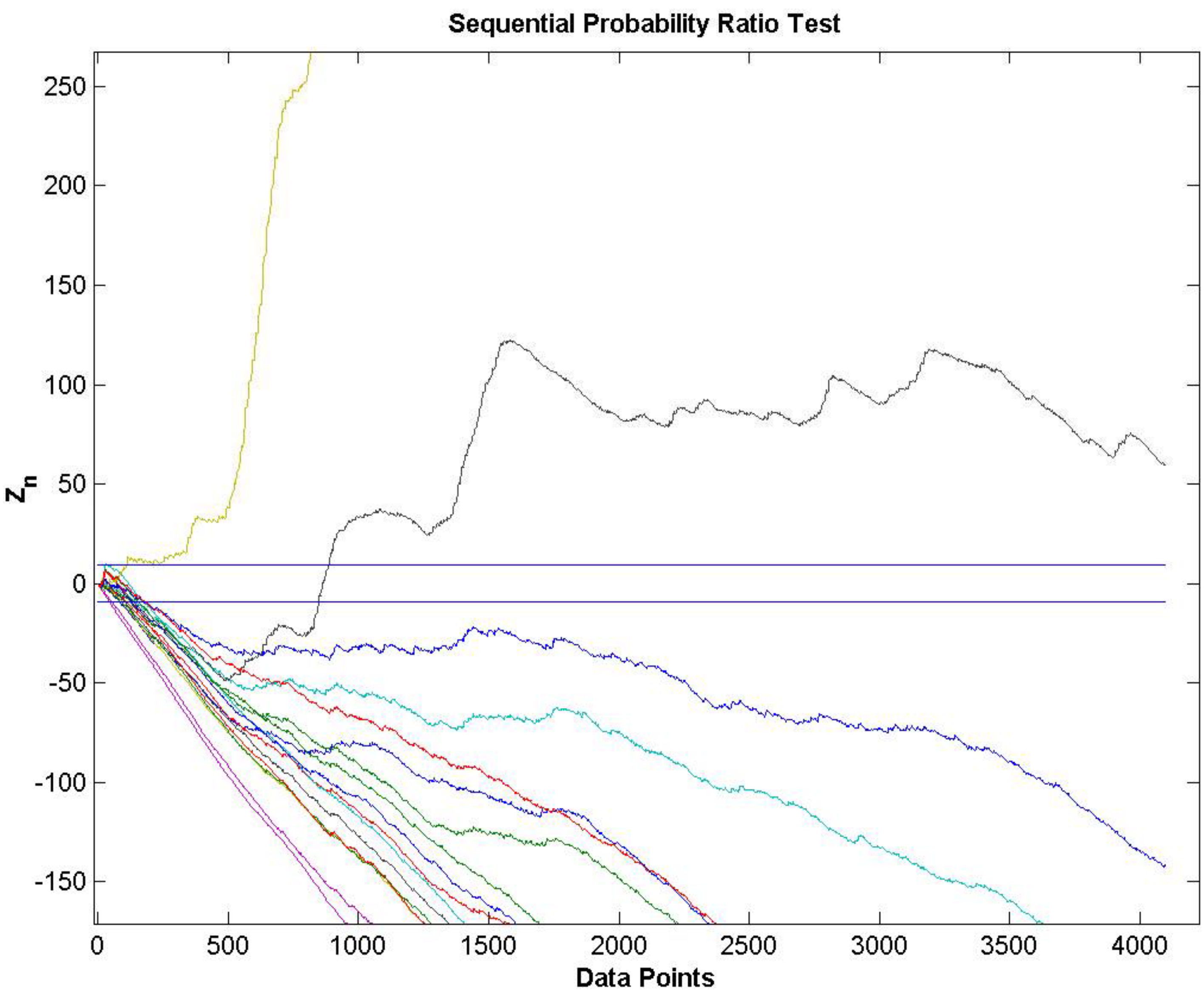

Sequential Probability Ratio Test
250
200
150
100
50
0
-50
-100
-150
Z_n
0
500
1000
1500
2000
2500
3000
3500
4000
Data Points

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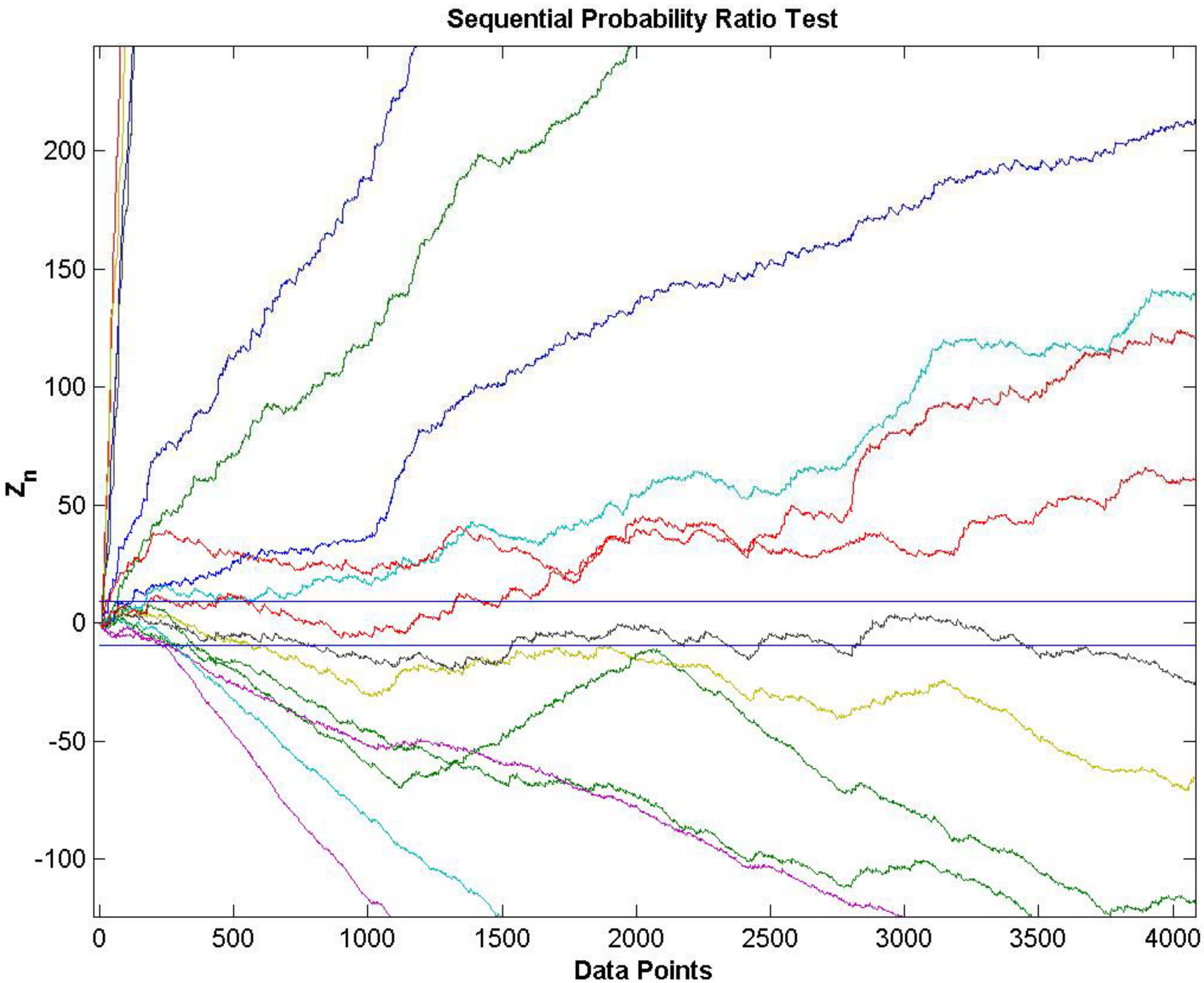
Sequential Probability Ratio Test
200
150
100
50
0
-50
-100
Z_n
0
500
1000
1500
2000
2500
3000
3500
4000
Data Points

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Results

- **Pairs – While +Z direction seemed to be more sensitive to damage it was much more susceptible to false positive indications.**

- **Conclusion – Accelerometers in the direction of excitation (in our case X) are most suited for damage detection**

- **Accelerometers in the off-axis (Y) direction as well as the test case with the accelerometer in the middle of the plate were ineffective at producing correct damage diagnoses.**

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Results- Bolt Tightness

NO BOLTS:

- **Nailed damage cases across the board**
- **Problems with false positives at lower excitation levels and with environmental conditions**

HAND TIGHT:

- **Less problems with false positives… however flase negatives start to appear at low excitation levels and with environmental conditions**
- **Still able to nail high excitation case**

TORQUED:

- **High excitation still gets damage cases**
- **Otherwise a very poor indicator of damage**

➢ **When torqued even at high excitation with multiple damage, it only picked up damage at Joint 2a, NOT at Joint 4b.**

Results – Damage Cases

<u>Case 1 (No mass, Joint 2a Damage) HIGH Excitation:</u>

- **Perfect results for all bolt levels except Y direction is inadequate indicator with tightest bolts**

<u>Case 2 (Level a mass, Joint 4b Damage) MID Excitation:</u>

- **Only able to detect damage with no bolt, however in no bolt case many false positives appear**
- **NO GOOD SOLUTION – probably because of excitation level**

<u>Case 3 (Level b mass, Joints 4b & 2a Damage) HIGH Excitation:</u>

- **Able to detect damage in all bolt cases**

<u>Case 4 (Level c mass, Joint 4b Damage with mass on levels a & b) mainly LOW Excitation:</u>

- **Only able to detect damage with no bolt, however in no bolt case many false positives appear**
- **At higher excitation levels good results for damage detection and very few false positives**

<u>Case 5 (Level a & b mass, Joint 4b & 2a Damage, hand shaker) mainly MID Excitation:</u>

- **Environmental variability proves to be too much to obtain accurate results regardless of the bolt case or excitation level.**

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Results

Excitation Level

1.0 V – High Excitation

- **Overall does very well**
- **Cannot overcome too much background noise**
- **Joint 4b damage with hand tight shows a few false positives**

0.25 V – Mid Excitation

- **Really only effective at locating damage with no bolts present**
- **Smaller sigmas seem to show promise for locating damage when bolt is not gone but then false positives show for extreme damage case (no bolts)**

0.128 V – Low Excitation

- **Only able to locate damage with no bolt case, however many false positives appear in no bolt case**
- **INEFFECTIVE**

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Conclusions

- Data very dependent on excitation and damage levels
- In general it appears that a high excitation value should always be used
- 0-3.2 kHz range could not predict damage very well
- Better method for choosing baseline comparison must be explored
- Even in cases where many false positives are seen, a visual inspection fo the the Z_n plot clearly shows separation of damage cases
- σ_0 values from 1.3-1.4 and σ_1 values from 1.7-1.8 should be further refined
- Normalize signal with input data? (Excitation level, etc.)

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- **Dactron, Inc. (data acquisition hardware)**
- **Vibrant Technologies (experimental modal analysis software)**
- **The Mathworks, Inc. (numerical analysis software)**
- **ANSYS, Inc. (finite element software)**

Thanks !

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