Detection of Small Levels of Incremental Damage Using Likelihood Ratio Approach

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Research Question

How can the efficiency of damage detection techniques be improved for small levels of damage on bridge structures?

Outline

- **Motivation**
  - Structural Health Monitoring (SHM)
  - Problem statement
  - Challenges of the research
  - Objective and hypothesis
- **Methodology and results**
  - Principal Components Analysis (PCA)
  - Statistical tests based on location parameters
  - Likelihood Ratio (LR) test
- **Conclusion**

Introduction to SHM

Local monitoring

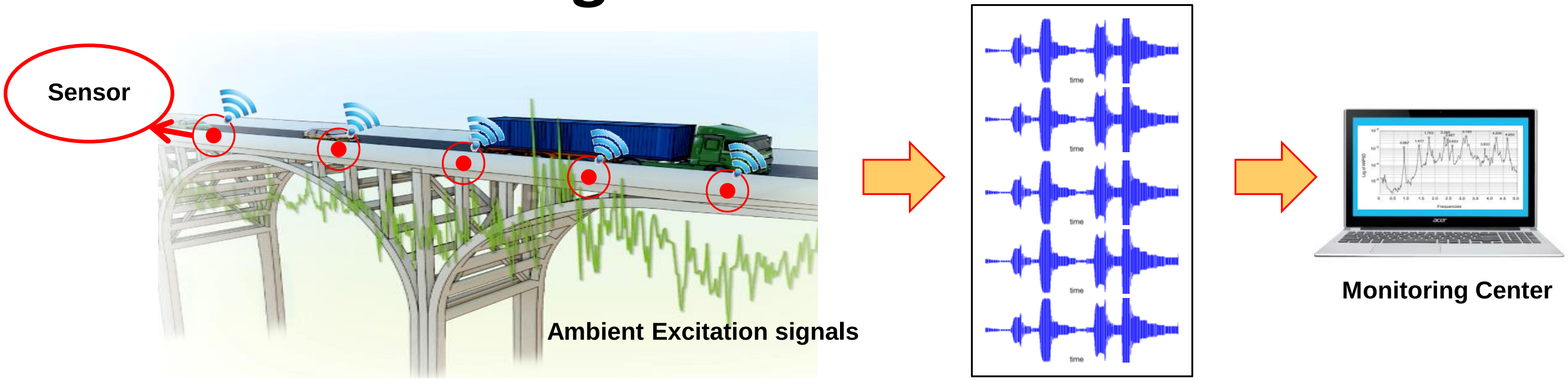
- Depends on the accessible portion of inspection
- Requires large amount of human intervention
- Costly to continuously monitor specific structures
- Needs prior knowledge about approximate location of damage

Inspection of a steel girder by visual inspection study

http://www.fhwa.dot.gov/publications/publicroads/00jan/nde.cfm
http://www.ndt.net/article/v11n01/grosse/grosse.htm

Introduction to SHM

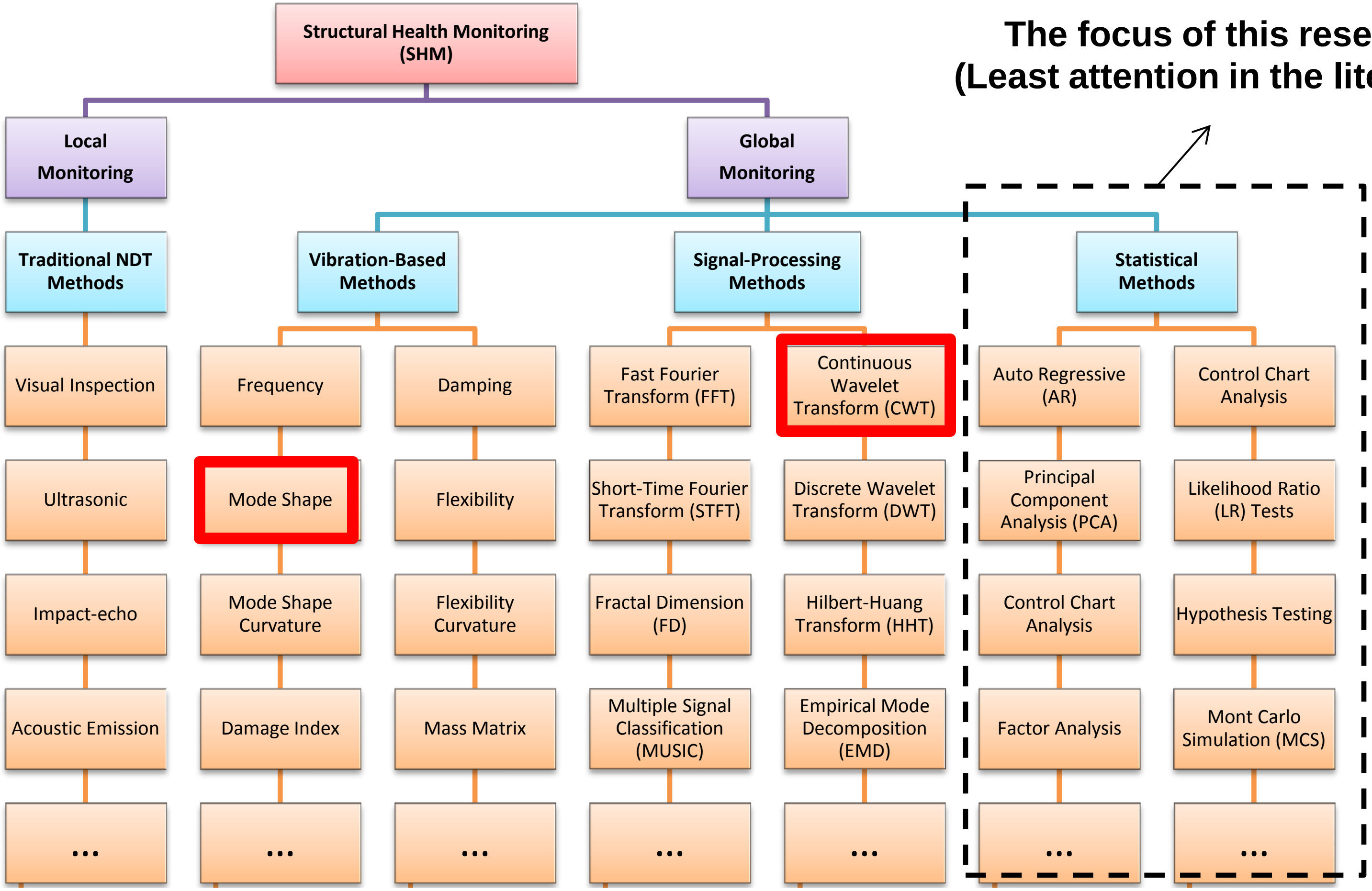
Global monitoring



Remote monitoring of a bridge using ambient excitations

- Measure global parameters of structure at a few easily points.
- Remotely monitor the structure with almost no human intervention (e.g. use of ambient excitations, traffic loads, etc)
- Able to identify actual location of existing damage when one does not have initial information as to the location of damage

Global Classification of SHM



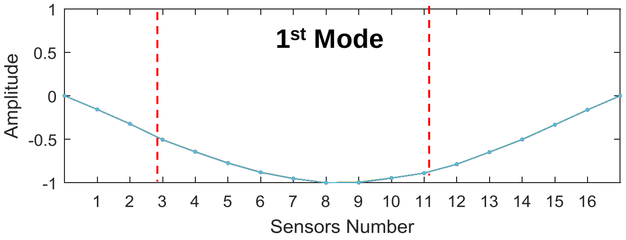
The focus of this research
(Least attention in the literature)

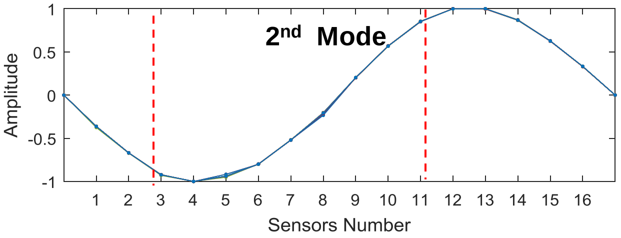
- Structural Health Monitoring (SHM)
  - Local Monitoring
    - Traditional NDT Methods
      - Visual Inspection
      - Ultrasonic
      - Impact-echo
      - Acoustic Emission
      - …
  - Global Monitoring
    - Vibration-Based Methods
      - Frequency
      - Mode Shape
      - Mode Shape Curvature
      - Damage Index
      - …
      - Damping
      - Flexibility
      - Flexibility Curvature
      - Mass Matrix
      - …
    - Signal-Processing Methods
      - Fast Fourier Transform (FFT)
      - Short-Time Fourier Transform (STFT)
      - Fractal Dimension (FD)
      - Multiple Signal Classification (MUSIC)
      - …
      - Continuous Wavelet Transform (CWT)
      - Discrete Wavelet Transform (DWT)
      - Hilbert-Huang Transform (HHT)
      - Empirical Mode Decomposition (EMD)
      - …
    - Statistical Methods
      - Auto Regressive (AR)
      - Principal Component Analysis (PCA)
      - Control Chart Analysis
      - Factor Analysis
      - …
      - Control Chart Analysis
      - Likelihood Ratio (LR) Tests
      - Hypothesis Testing
      - Mont Carlo Simulation (MCS)
      - …

Problem Statement

Modal Analysis

Mode Shape



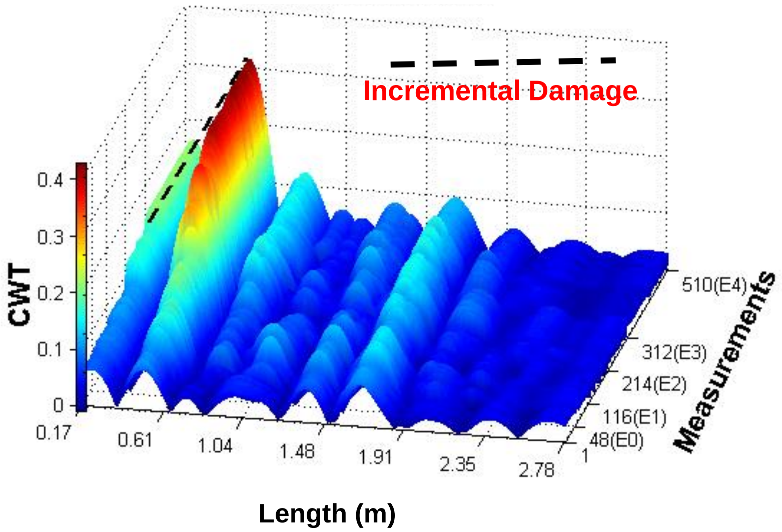


- A common type of global parameters
- Associated with mass and stiffness of a structure
- An indicator of damage location due to induced modifications in mass and stiffness
- Does not exhibit local changes due to small increments of damage

Problem Statement

Signal Processing

Continuous Wavelet Transform (CWT)

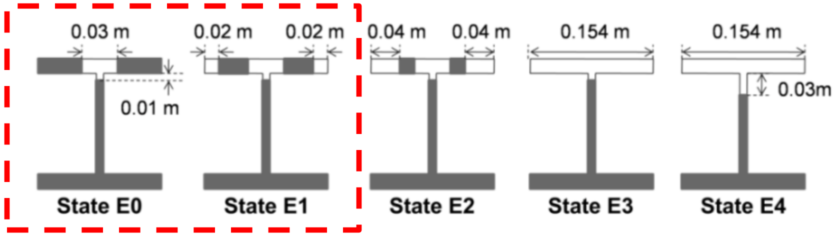


$$CWT_{f(s,u)} = \frac{1}{\sqrt{|s|}} \int_{-\infty}^{+\infty} f(x) \psi^{*}\left(\frac{x-u}{s}\right) dx$$

Scale Position Signal Mother wavelet

- Able to detect abrupt changes, breakdown points and oscillations in signals

- Unable to clearly detect induced defects at small levels of damage



Issues to address?

- Detect incremental damage at small levels of damage which is challenging given a high noise to signal ratio

- Summarize wavelet coefficients with a few new variables that explain most of the variability

- Filter-out noise in the wavelet coefficients

- Identify patterns associated with damage:
  - Damage detection
  - Damage localization

Hypothesis

The development of statistical pattern recognition techniques will exhibit dominant patterns of variations of the wavelet coefficients caused by small increments of damage

Methodology

Principal Component Analysis - PCA → Hypothesis Testing → Likelihood Test

Based on singular value decomposition of a centered sample data (wavelet coefficients in this case)

Applications

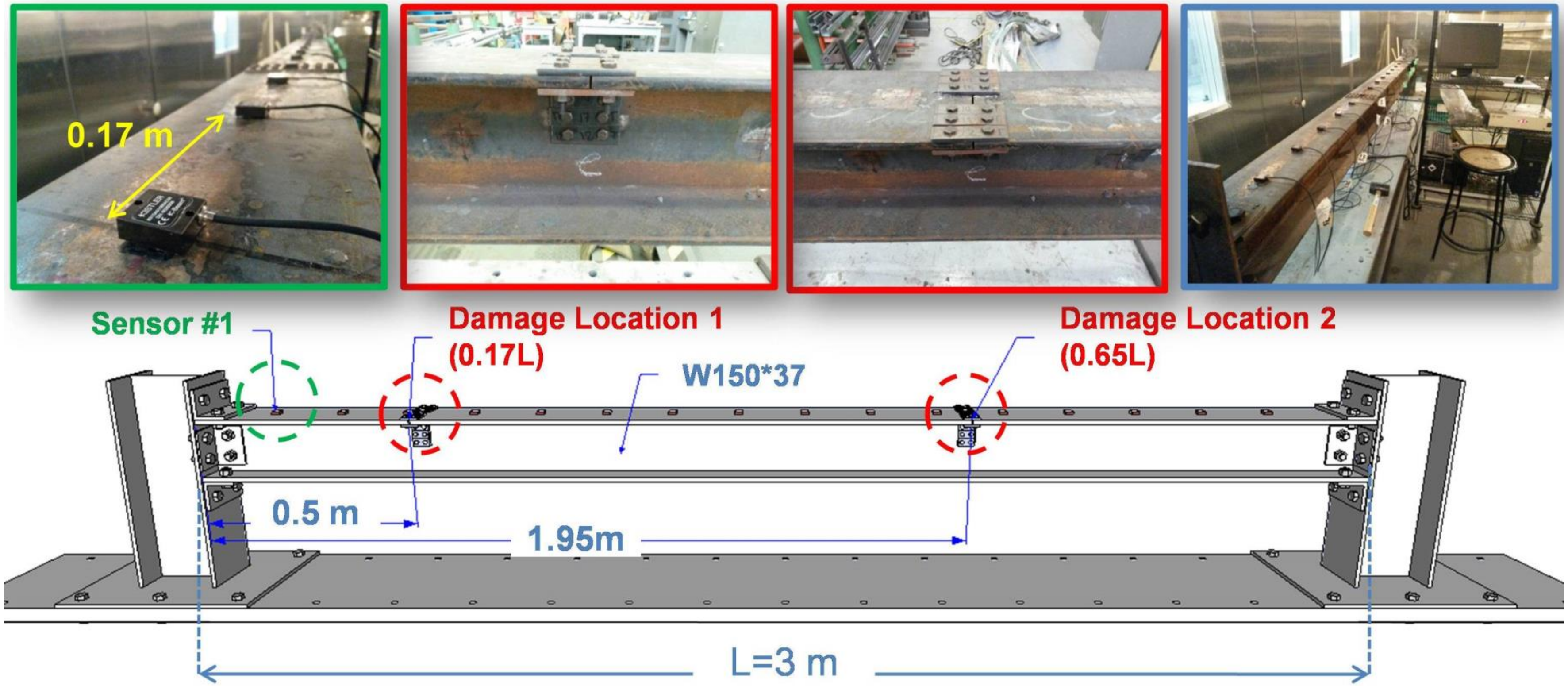
Data reduction and feature extraction

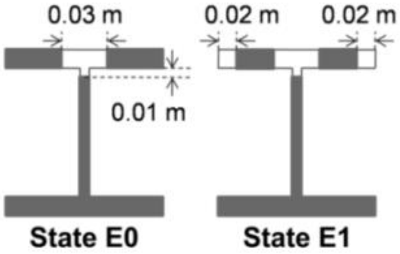
Data normalization

Contribution

- Replace wavelet coefficients with a few new variables highly correlated with damage
- Filter-out noise in the wavelet coefficients

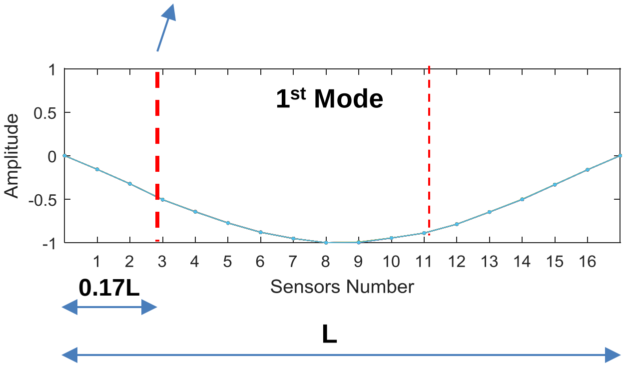
Methodology:
Test Object

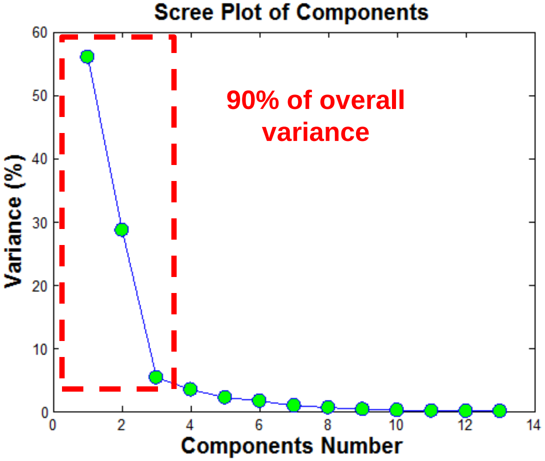




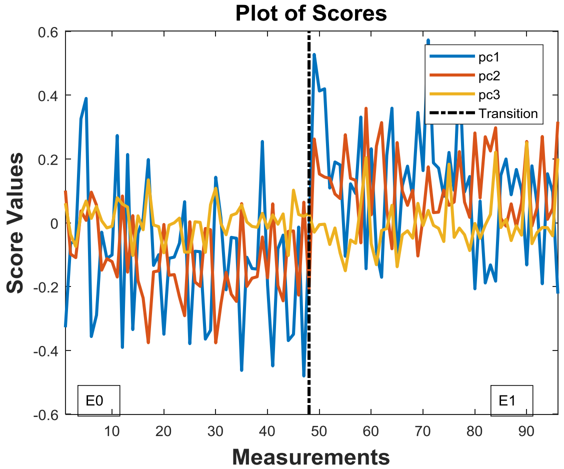
Methodology: PCA

Incremental Damage at 0.17L

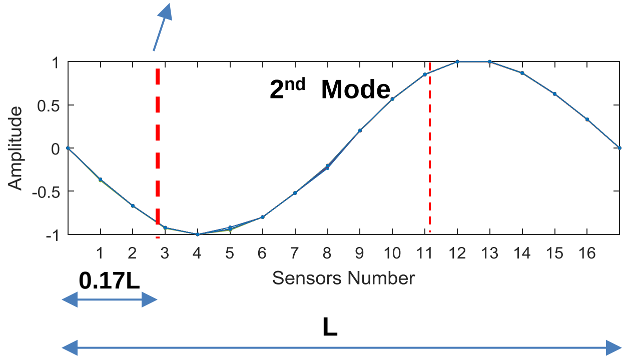


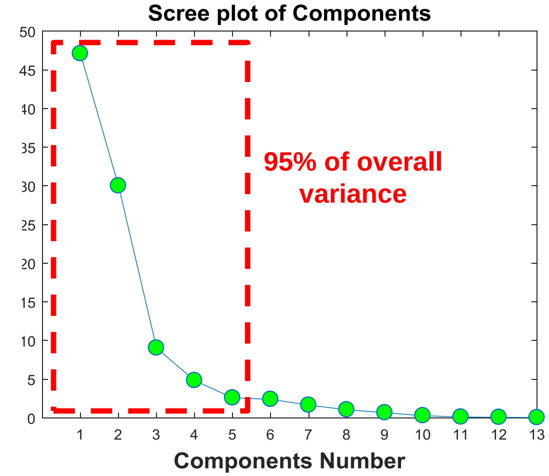


90% of overall variance

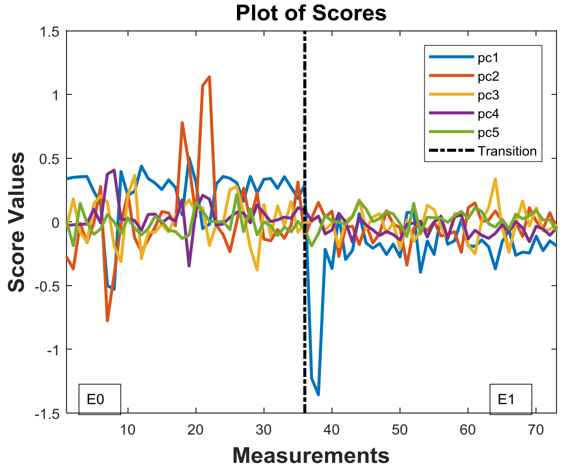


Incremental Damage at 0.17L

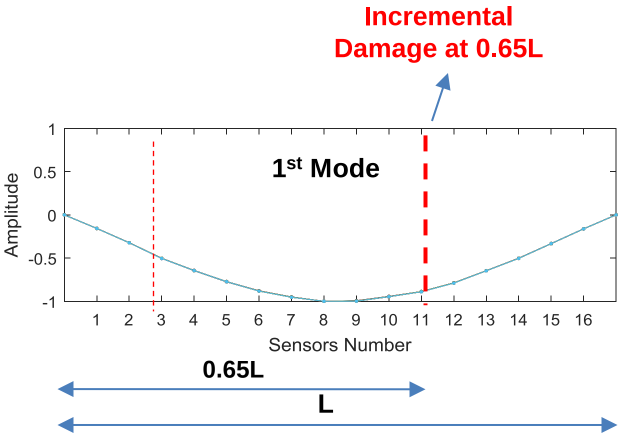


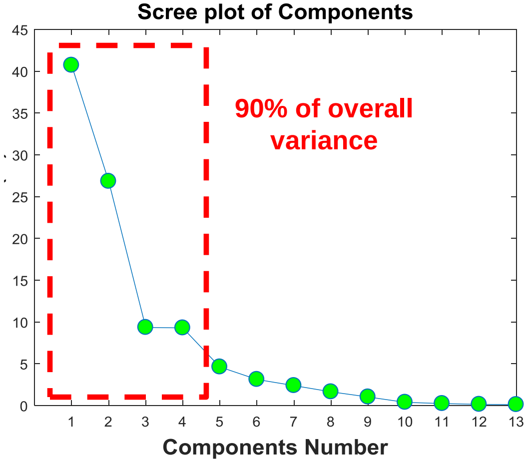


95% of overall variance

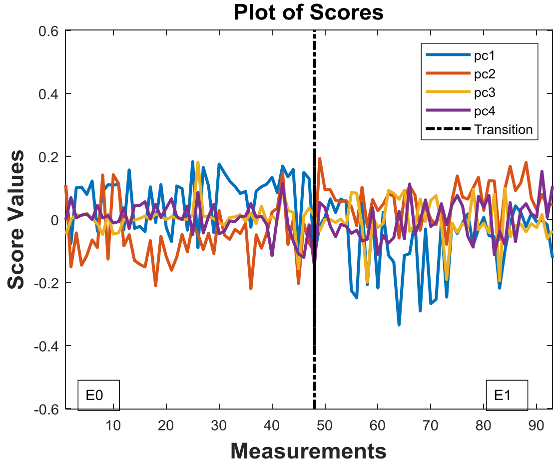


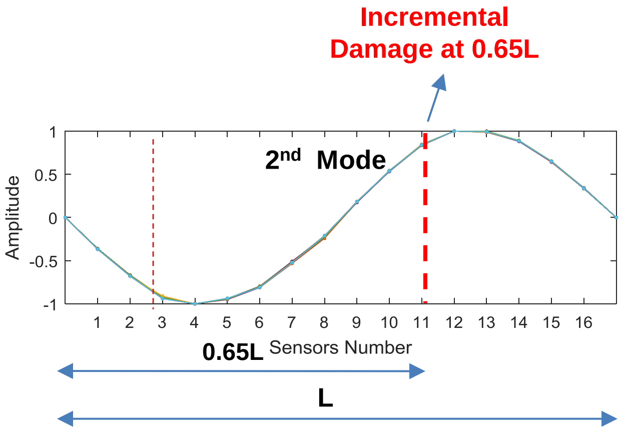
Methodology: PCA

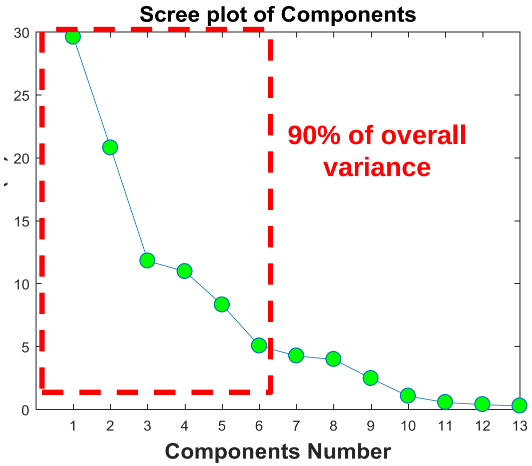

Incremental Damage at 0.65L


Scree plot of Components

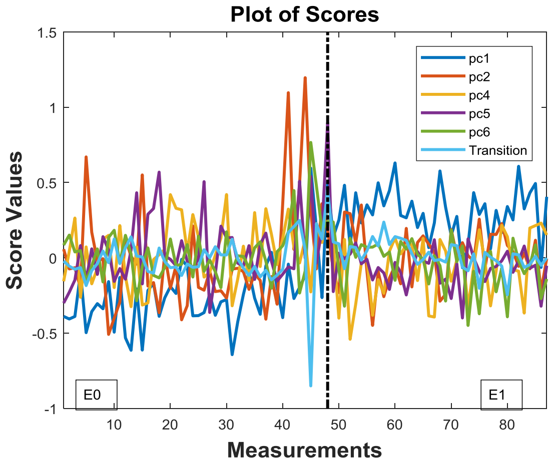
90% of overall variance


Plot of Scores


Incremental Damage at 0.65L


Scree plot of Components

90% of overall variance


Plot of Scores

Methodology:
Statistical Detection of Damage

Principal Component Analysis - PCA → **Hypothesis Testing** → Likelihood Test

Based on the equality of the location parameters (e.g. mean) between two sets of random variables

If H=1 → significant evidence to accept the existence of damage → Damage

If H=0 → significant evidence to reject the existence of damage → No damage

The results of the t-test between two scores at levels E0 and E1.

Mode #	Damage	PC	$\bar{x}_{E0}$	$\bar{x}_{E1}$	σ_{E0}	σ_{E1}	H	P-value	N_{E0}	N_{E1}	DOF	α
1	0.17L	1	-0.11485	0.114849	0.212815	0.198508	1	3.73E-07	48	48	94	1%
		2	-0.11753	0.117534	0.123097	0.117344	1	1.46E-15	48	48	94	1%
		3	0.005847	-0.00585	0.054775	0.087459	0	0.434343	48	48	94	1%
2	0.17L	1	0.234413	-0.22808	0.215917	0.288431	1	3.79E-11	36	37	71	1%
		2	0.038126	-0.0371	0.370449	0.116593	0	0.242584	36	37	71	1%
		3	0.012784	-0.01244	0.174712	0.124488	0	0.47677	36	37	71	1%
		4	0.051724	-0.05033	0.122914	0.065236	1	2.98E-05	36	37	71	1%
		5	-0.01966	0.019133	0.085077	0.070989	1	0.038474	36	37	71	1%
1	0.65L	1	0.066822	-0.07128	0.084352	0.107775	1	9.67E-10	48	45	91	1%
		2	-0.05863	0.062544	0.087387	0.060759	1	1.48E-11	48	45	91	1%
		3	0.004739	-0.00506	0.041973	0.067686	0	4.12E-01	48	45	91	1%
		4	0.001335	-0.00142	0.05205	0.06031	0	0.816891	48	45	91	1%
2	0.65L	1	-0.24268	0.298686	0.240163	0.190874	1	7.79E-20	48	39	85	1%
		2	-0.00565	0.006954	0.351788	0.163776	0	0.839901	48	39	85	1%
		3	0.046675	-0.05745	0.209578	0.19275	1	0.024597	48	39	85	1%
		4	0.057938	-0.07131	0.246667	0.108193	1	0.003441	48	39	85	1%
		5	0.035172	-0.04329	0.187828	0.149667	1	0.04414	48	39	85	1%
		6	-0.01342	0.016522	0.171647	0.082057	0	0.328664	48	39	85	1%

Montgomery, D.C. and G.C. Runger, Applied Statistics and Probability for Engineers. 4th ed. 2012: John Wiley & Sons.

Methodology: Statistical Detection of Damage

Principal Component Analysis - PCA → **Hypothesis Testing** → Likelihood Test

U-test

An alternative method to test the equality of location parameters when the results of the t-test are questionable or data sets are not normally distributed.

The results of the U-test between two scores at levels E0 and E1.

Mode #	Damage	PC	R_{E0}	R_{E1}	σ_{E0}	σ_{E1}	H	P-value	N_{E0}	N_{E1}	α
1	0.17L	1	-4.4955	1714	2942	538	1	6.94E-06	48	48	1%
		2	-6.91362	1384	3272	208	1	4.72E-12	48	48	1%
		3	2.575662	2680	1976	800	1	0.010005	48	48	1%
2	0.17L	1	6.405085	1913	788	85	1	1.50E-10	36	37	1%
		2	0.082753	1340	1361	658	0	0.934048	36	37	1%
		3	0.777878	1403	1298	595	0	0.436641	36	37	1%
		4	4.750024	1763	938	235	1	2.03E-06	36	37	1%
		5	-2.57638	1098	1603	432	1	0.009984	36	37	1%
1	0.65L	1	5.377588	2956	1415	380	1	7.55E-08	48	45	1%
		2	-6.03874	1470	2901	294	1	1.55E-09	48	45	1%
		3	2.048788	2523	1848	813	1	4.05E-02	48	45	1%
		4	0.618865	2337	2034	999	0	0.536006	48	45	1%
2	0.65L	1	-7.19915	1268	2560	92	1	6.06E-13	48	39	1%
		2	-1.48933	1937	1891	761	0	0.1364	48	39	1%
		3	1.839262	2328	1500	720	1	0.065877	48	39	1%
		4	2.334284	2386	1442	662	1	0.019581	48	39	1%
		5	1.301566	2265	1563	783	0	0.193065	48	39	1%
		6	-1.77952	1903	1925	727	1	0.075155	48	39	1%

Montgomery, D.C. and G.C. Runger, Applied Statistics and Probability for Engineers. 4th ed. 2012: John Wiley & Sons.

Methodology: Localization of Damage

Principal Component Analysis - PCA → Hypothesis Testing → **Likelihood Test**

Likelihood test is developed based on an adaptation of the Likelihood Ratio (LR) test

$$LR(i)=\frac{L\left(S_R \mid \mu_R,\sigma_R\right)}{L\left(S_i \mid \mu_i,\sigma_i\right)}$$

Reference model

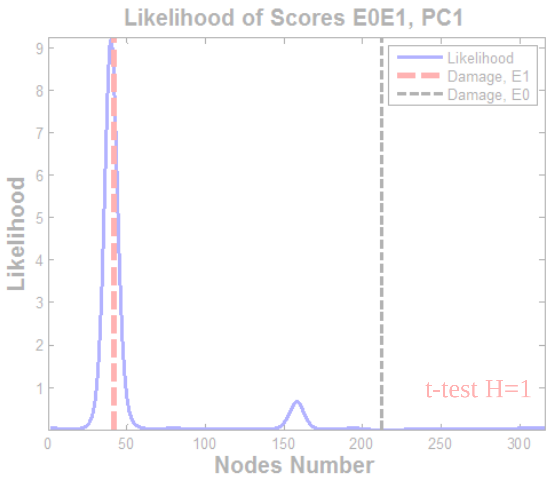
Alternative model

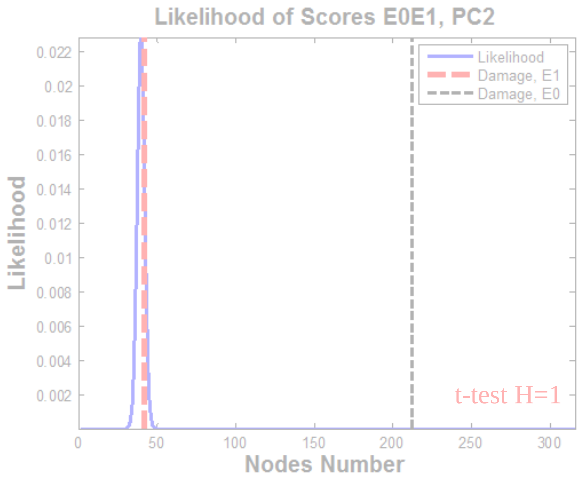
Sampling node

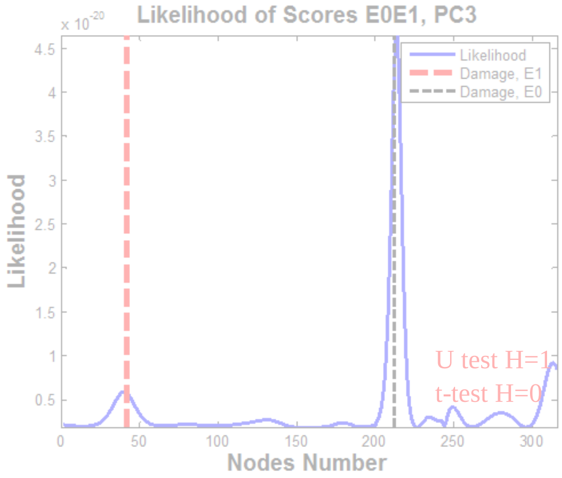
Since the model with the removed node (alternative model) that is closest to the damage is expected to be least informative (or likely) in comparison to the full model, the LR achieves its maximum value which is identified as the likely location of damage.

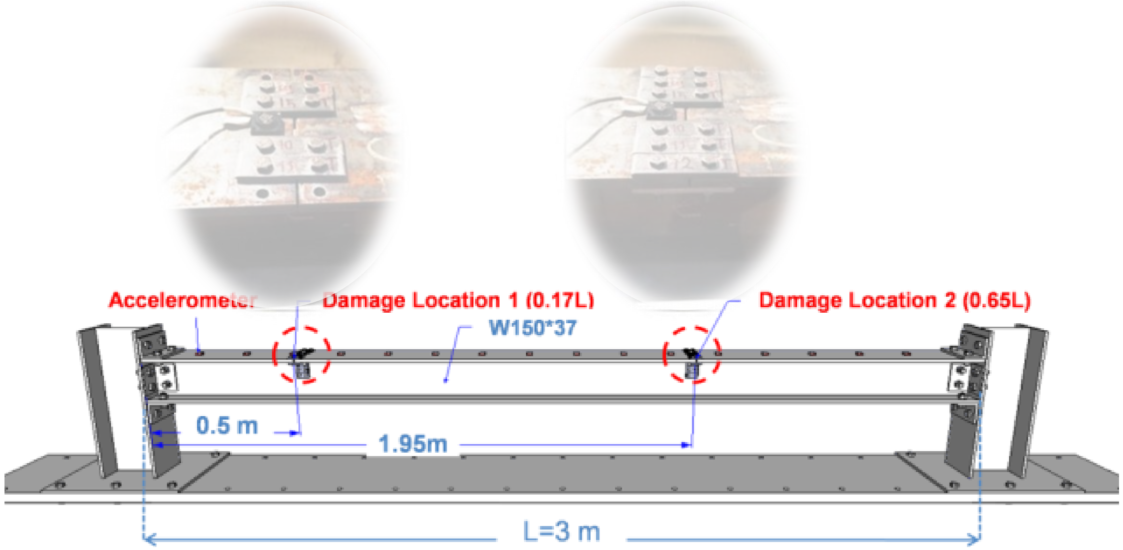
Kendall M, Stuart A (1979) The Advanced Theory of Statistics, vol 2. 4th edn. Charles Griffin, London

Results Mode 1:
Incremental Damage at 0.17L

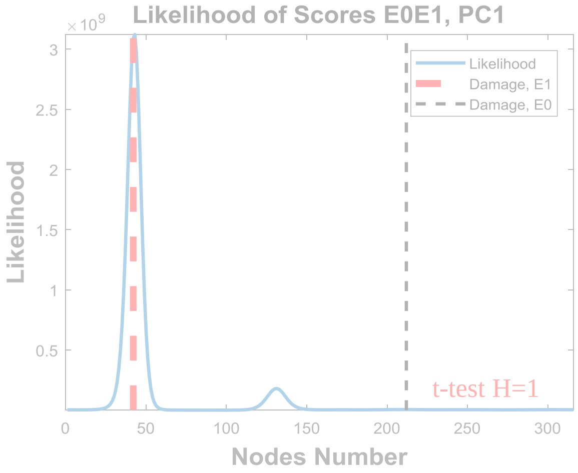


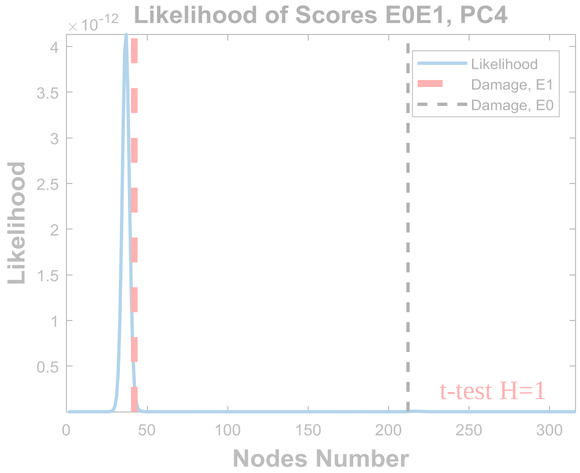


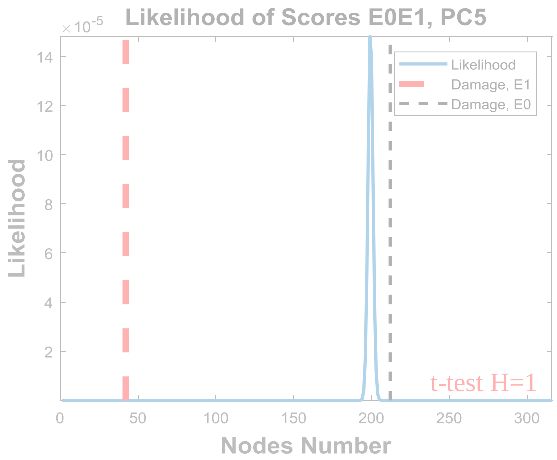


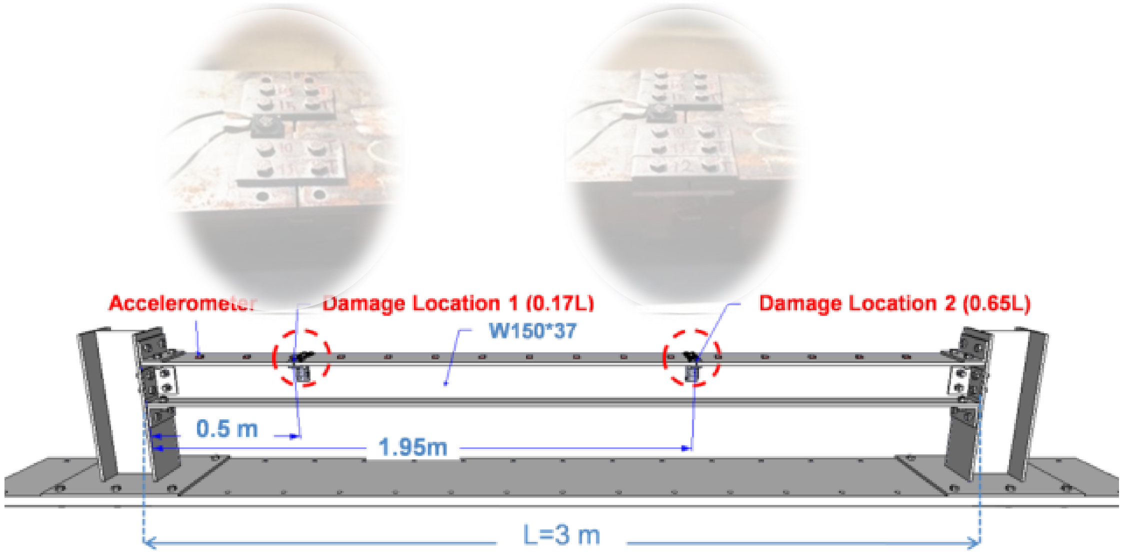


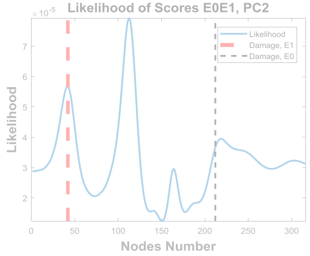
Results Mode 2: Incremental Damage at 0.17L



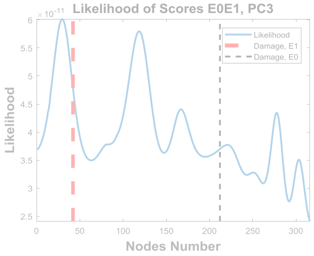






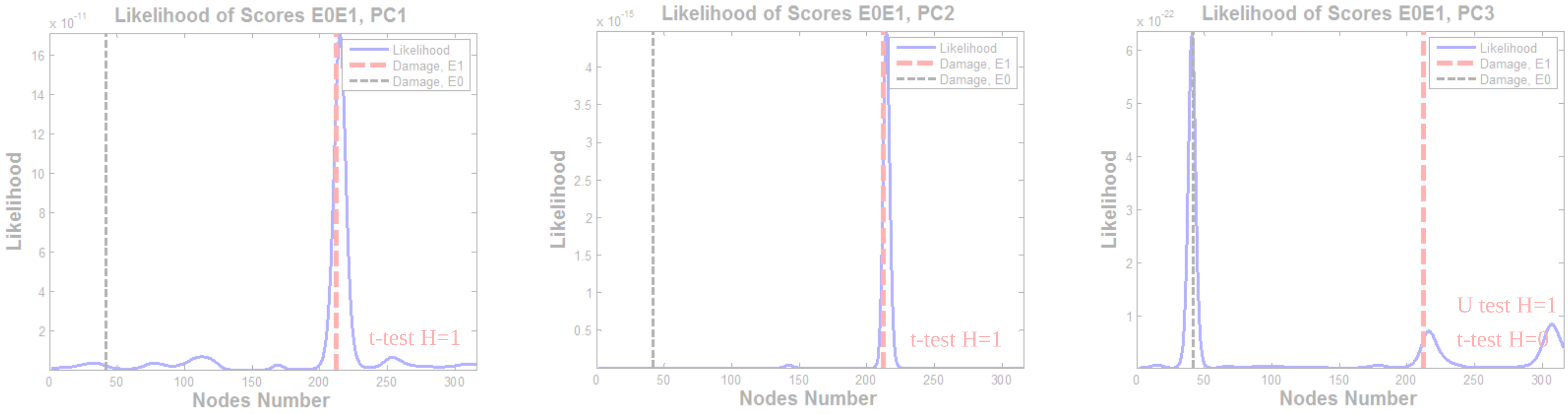


t-test H=0
U-test H=0



t-test H=0
U-test H=0

Results Mode 1: Incremental Damage at 0.65L



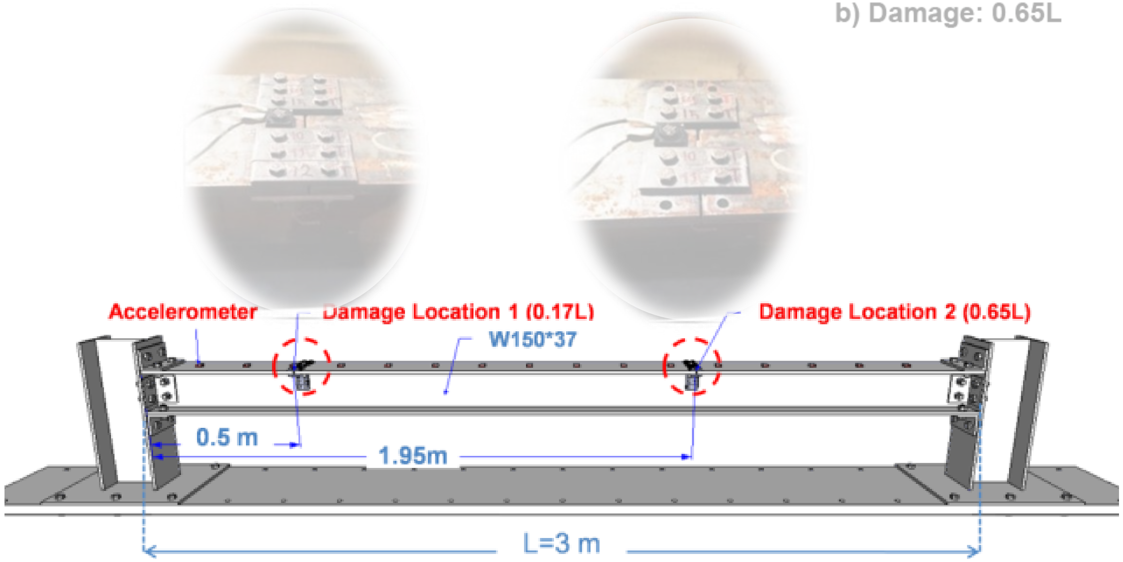
t-test H=1

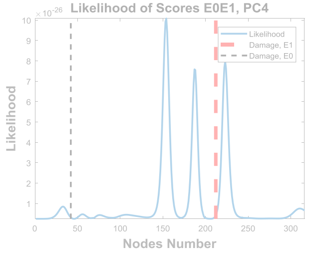
t-test H=1

U test H=1

t-test H=0

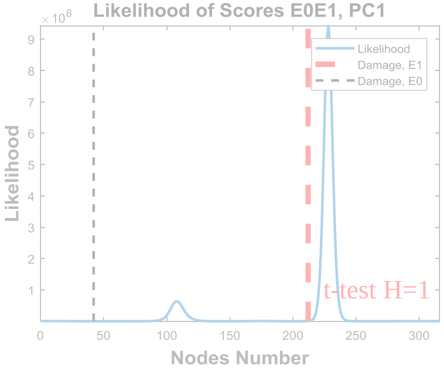
b) Damage: 0.65L

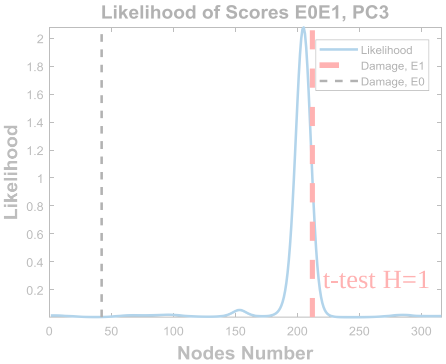


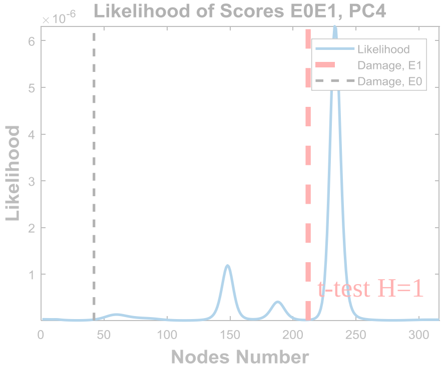


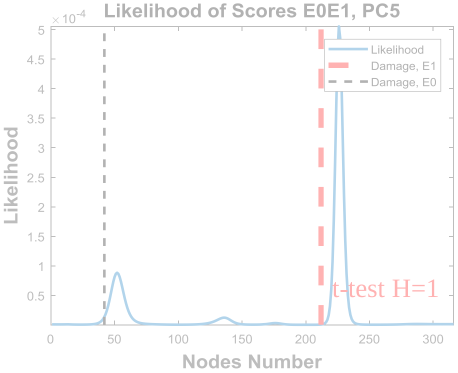
t-test H=0
U-test H=0

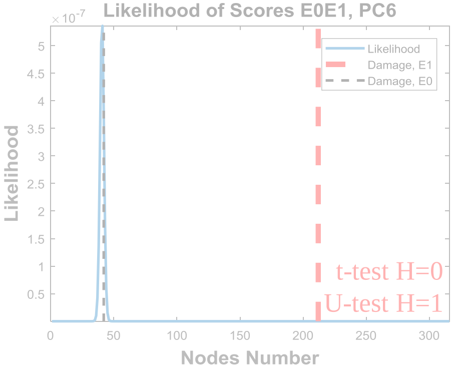
Results Mode 2: Incremental Damage at 0.65L

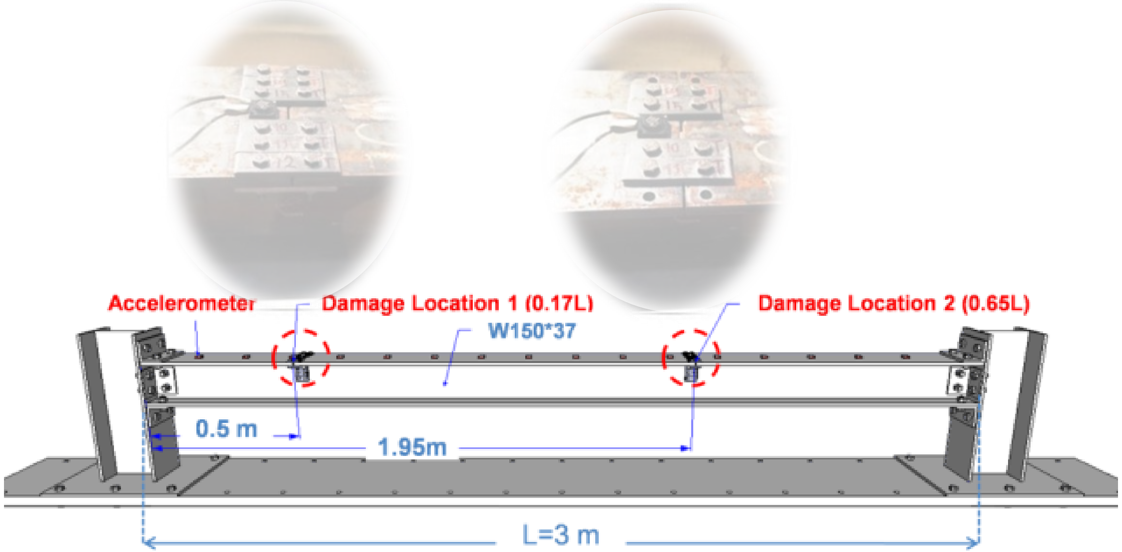




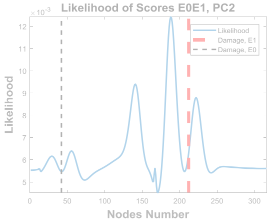








t-test H=0
U-test H=0



Conclusions

- The potential of the CWT method for low levels of damage is not quite satisfactory on its own.
- The combined application of the PCA and the CWT method can improve the efficiency of damage detection and minimize false indications of damage.
- Likelihood test results corresponding to the first fundamental mode shape was found to be more consistent and accurate compared to the second mode.
- For the second mode shape the contribution of principal components (PC) at higher orders was shown to be important for damage detection.
- Statistical detection of damage was demonstrated for low levels of damage.
- Further validations are necessary for other types of structures and real field tests.

Acknowledgements

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