UML
Civil Engineering

Masters Thesis Defense
(11-21-2011)

UMASS
LOWELL

Model Test and Numerical Simulation for the Structural Health Monitoring of a Truss Bridge

by

Jeremiah K. Otchere-Nyarko

Advisor: Tzu-Yang Yu

Department of Civil and Environmental Engineering
University of Massachusetts Lowell
Lowell, Massachusetts

SERG

Outline

- Introduction
  - Motivation of research study
  - Structural health monitoring (SHM)
- Literature Review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research Findings
- Reference
- Acknowledgement

Motivation

- In the 2009 Report Card by the U.S. DOT, Bridges in the U.S had a grade C.
  - Over 27% of bridges in the U.S are either "structurally deficient" (12.1%) or "functionally obsolete" (14.8%). (There were 600,905 bridges in the U.S. in 2008).
  - According to the 2009 Report Card, $17 million U.S. dollars are needed to rectify the problem.[5]

Motivation (cont.)

- Images of structurally deficient bridges and functionally obsolete bridges in the U.S

Structurally deficient bridge

Functionally obsolete bridge

SHM

- ☐ Definition: SHM is a damage detection and characterization procedure for engineering structures. It is the acquisition, validation and analysis of technical data to facilitate life–cycle decision in monitoring the health of structures.
- ☐ Damage is defined as the change in the material properties and or geometry of a structure.
- ☐ Damage can also be defined from vibration testing as the change in dynamic parameters of a structure, i.e. mass, stiffness and damping of the structure.
- ☐ Changes in the dynamic parameters lead to the changes in dynamic characteristics of a structure such as the natural frequency, mode shapes, impulse response, frequency response functions, modal damping and the damping loss factors.

SHM

- Conventional approach – NDT/E/I such as visual inspection, radar technology, acoustic approach, x-rays and gamma rays (visual imaging).
- Why SHM?
  - Less labor intensive [1]
  - Inexpensive [2]
  - Less time consuming [3]

SHM

- SHM is a statistical pattern recognition model, that is categorized in four main steps; namely;
  - ☐ Operational Evaluation
  - ☐ Data acquisition, Fusion and Cleansing
  - ☐ Feature extraction and information condensation
  - ☐ Statistical Model development for Feature Discrimination. [4]

SHM

- Four questions are generally asked when considering SHM:
  - ☐ Is there a damage on the structure?
  - ☐ What is the location of damage?
  - ☐ What is the degree of damage?
  - ☐ What caused the damage?

Outline

- Introduction
  - Motivation of research study
  - Research approach
  - Structural health monitoring (SHM)
- Literature review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research findings
- Reference
- Acknowledgement

Literature review

- Wang *et al.* (2010) discussed recent developments in damage detection and condition assessment techniques based on vibration-based damage detection and statistical method.
- Yan *et al.* (2007) reviewed current developments of vibration based structural damage detection techniques.
- Huynh *et al.* (2005) presented a damage detection method known as Damage Location Vector (DLV) using FRF data to detect structural damage.
- Lui *et al.* (2003) proposed a scheme using FRF shape-based identification method as a tool for structural damage localization.
- Majumder *et al.* (2002) illustrated the use of induced vibration by a moving vehicle to detect the change in stiffness in the bridge structure.
- Xuea *et al.* (2011) used model test and FEA to understand the mechanical behavior of composite joint.

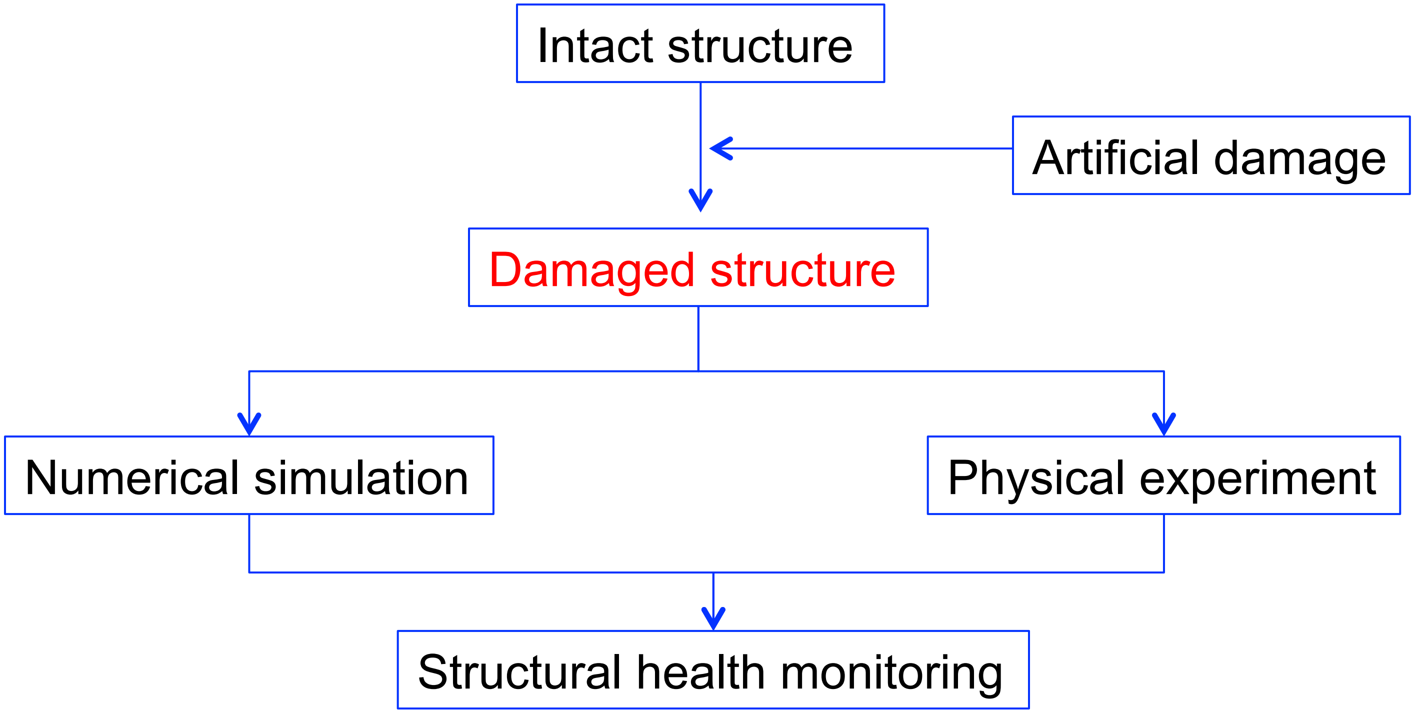
Literature review (cont.)

- Zong *et al.* (2003) calibrated an FE model based on results obtained from experimental model analysis of a concrete-filled tube arch bridge.
- Teughels *et al.* (2002) presented a FE model updating method using experimental modal data.
- Kim *et al.* (2002) evaluated both frequency-based damage detection (FBDD) method and mode-shape-based damage detection (MSDD) method for detecting damage location and estimating the size of cracks in a beam.
- He *et al.* (2001) discussed the use of natural frequency to detect damage in structure.
- Wang *et al.* (2009) validated studies of the mechanical behavior of special joint in a rigid suspension stiffened steel truss bridge using model test and numerical finite element analysis (FEA).

Outline

- Introduction
  - Motivation of research study
  - Research approach
  - Structural health monitoring (SHM)
- Literature review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research findings
- Reference
- Acknowledgement

Research Approach



Intact structure

Artificial damage

Damaged structure

Numerical simulation

Physical experiment

Structural health monitoring

Outline

- Introduction
  - Motivation of research study
  - Research approach
  - Structural health monitoring (SHM)
- Literature review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research Findings
- Reference
- Acknowledgement

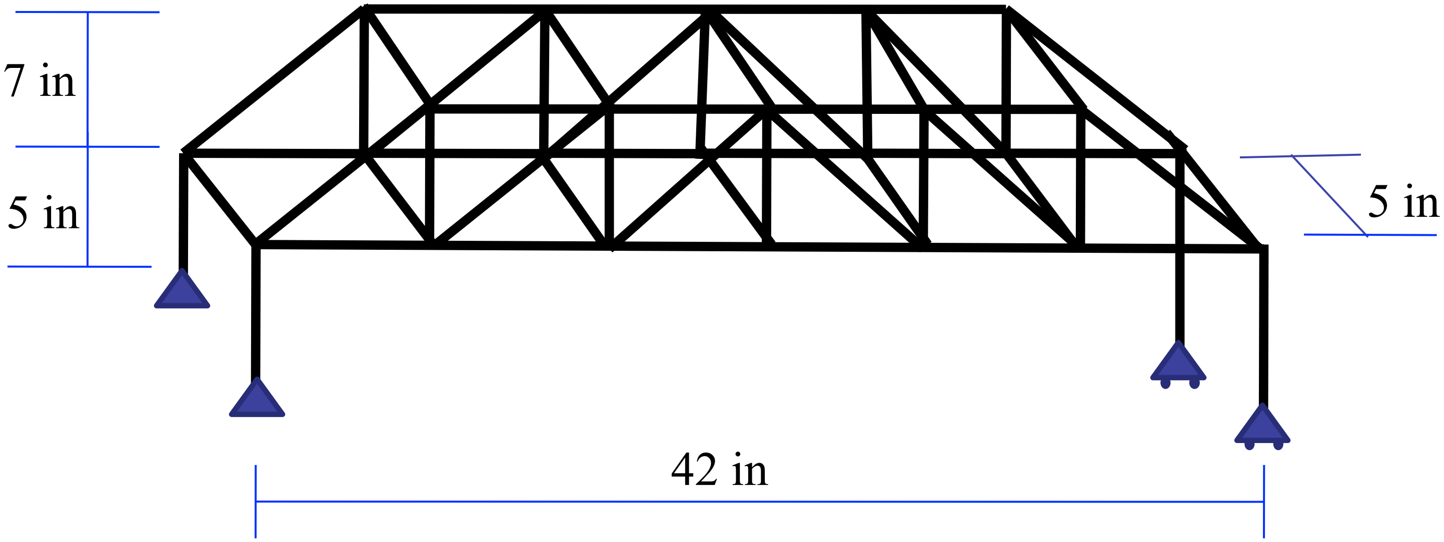
Numerical Simulation

- SAP2000 (Version 9.01): is a general purpose Finite element (FE) analysis computer program, which has very sophisticated and versatile user interface powered by an unmatched analysis engine and design tools for engineers (bridge engineers, transportation engineers, public works, etc.)
- This user interface can rapidly and intuitively create structural models.
- Bridge Designers can use SAP2000 Bridge Templates for generating Bridge Models, Automated Bridge Live Load Analysis and Design, Bridge Base Isolation, Bridge Construction Sequence Analysis, Large Deformation Cable Supported Bridge Analysis and Pushover Analysis.

Numerical Simulation

Application

- A SAP2000® three dimensional (3-D) truss bridge model was created and used in the numerical simulation.
- Dimensions: Span = 42 inches / width = 5 inches / height =12 inches
- Numerical models were created based on the geometry and material properties of the physical truss bridge model used in the experiment.
- 3kg mass was applied to the numerical models.
- Artificial damage was introduced to the truss bridge by reducing the area of a truss member at 20% intervals.



Numerical Simulation

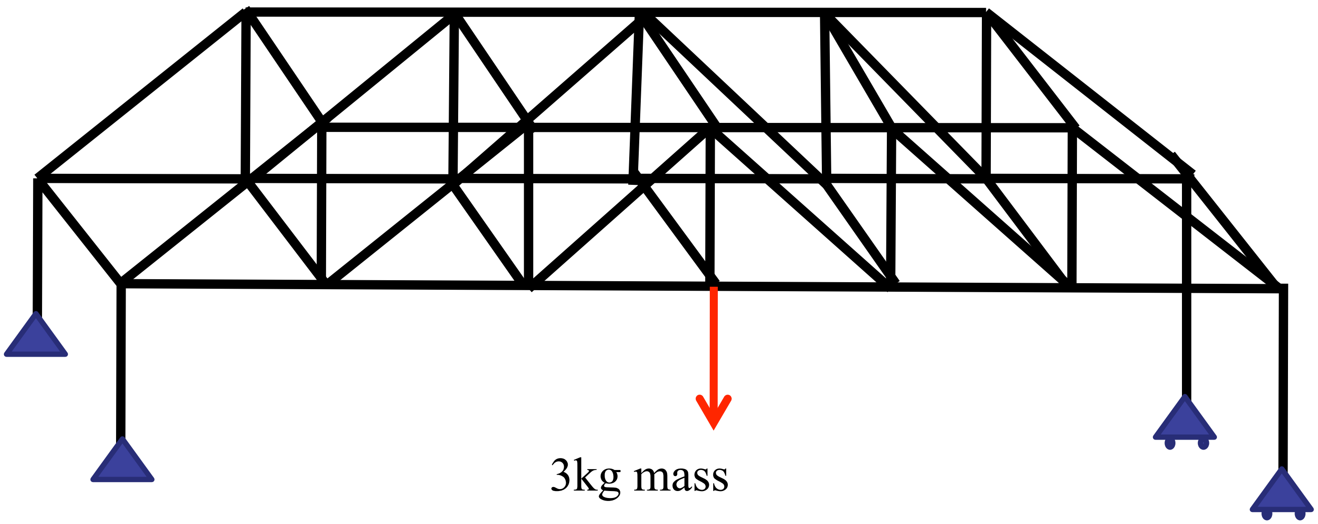
Application(cont.)

- Three numerical truss bridge models are simulated.
  - ☐ Unloaded intact
  - ☐ Loaded intact
    - baseline for the numerical simulation
  - ☐ Loaded damaged
    - Damage identification

SERG
Microwave Material
Characterization Lab

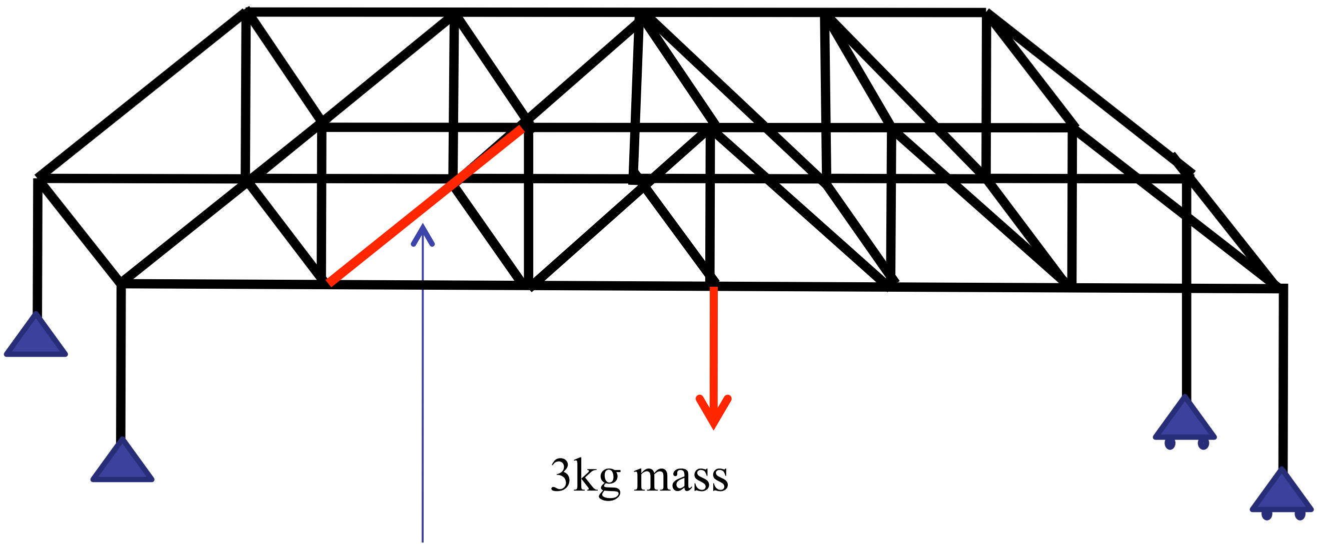
Numerical Simulation

Schematic of intact loaded



Numerical Simulation

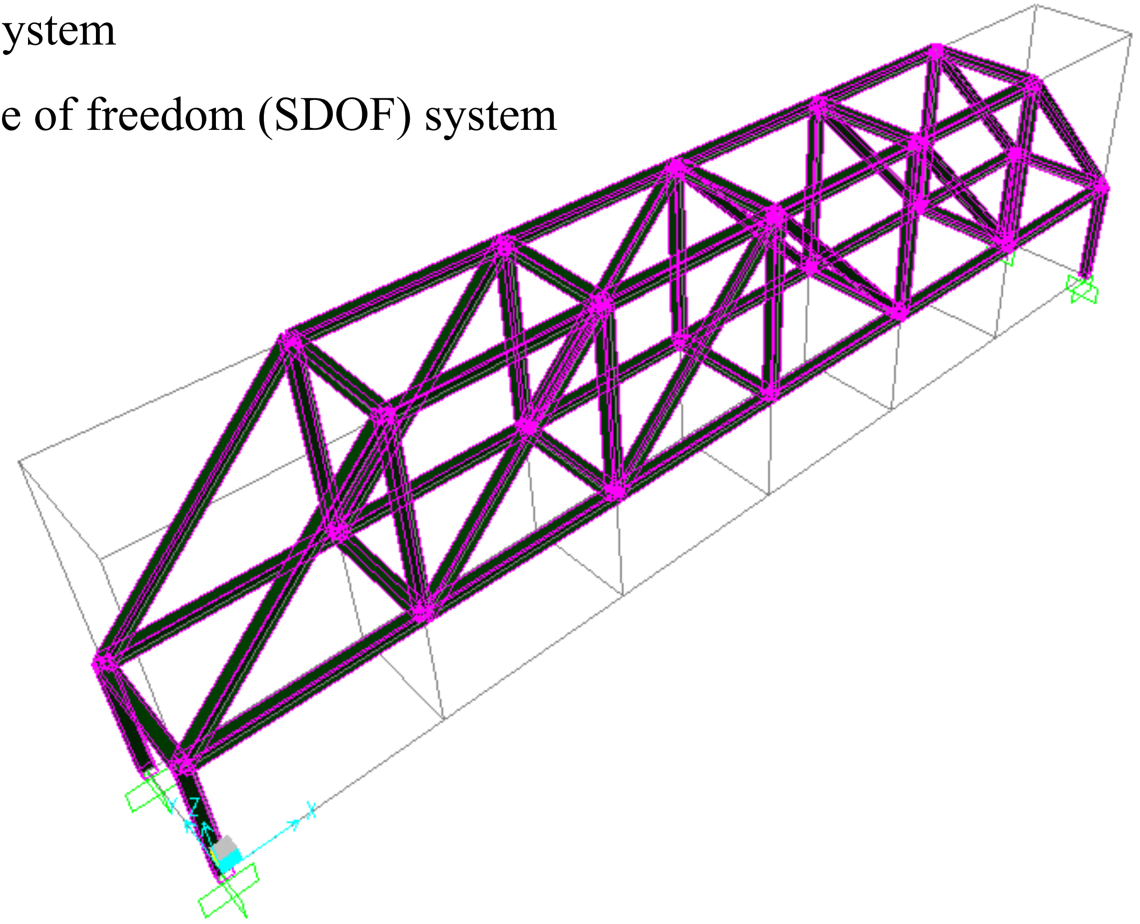
Schematic of damaged loaded



Numerical Simulation

Numerical truss bridge model

- Undamped system
- Single degree of freedom (SDOF) system



Numerical Simulation

Frequency analysis

$$f = \frac{1}{T}$$

where f = frequency (Hz), and T = period.

$$\omega_n = \sqrt{\frac{K}{M}}$$

where ω_n = natural frequency (rad/sec), K = stiffness, and M = mass.

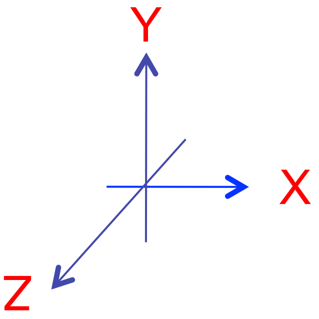
Numerical Simulation

Stiffness analysis

$$K = \frac{P}{\Delta L} \qquad P = mg$$

where K represents the stiffness, ΔL is the elongation of the truss member. P is the applied force on the structure, and g is the force of gravity acting on the truss bridge.

$$\Delta L = \sqrt{(\Delta x_1 - \Delta x_2)^2 + (\Delta y_2 - \Delta y_1)^2 + (\Delta z_2 - \Delta z_1)^2}$$



Δx, Δy, and Δz are the displacements in x, y, and z directions.

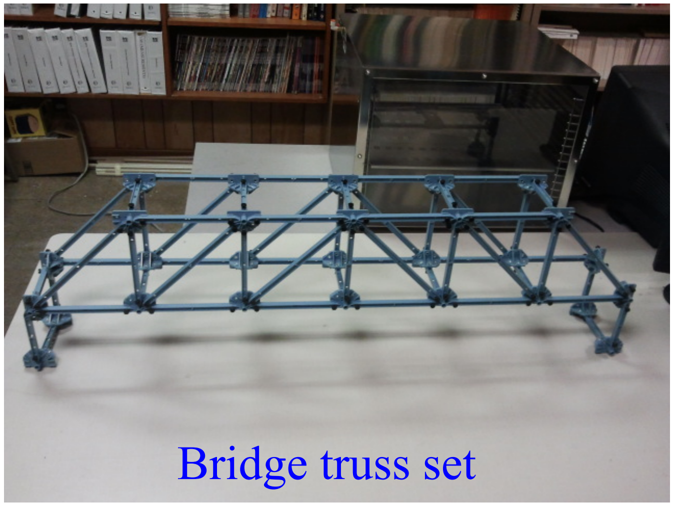
Outline

- Introduction
  - Motivation of research study
  - Research approach
  - Structural health monitoring (SHM)
- Literature Review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research Findings
- Reference
- Acknowledgement

Physical Experiment

Components of experimental setup

- Bridge truss set (PS-6991): the bridge set is used with force sensor to demonstrate the compression and tension members of truss members.


Bridge truss set

- Force sensor (PS-2201) :measures the force acting in the truss members. The measures ranges from -5N to +5N. The force sensor (load cell) is designed to be integrated into the structure without changing the length of the members.


Force sensor

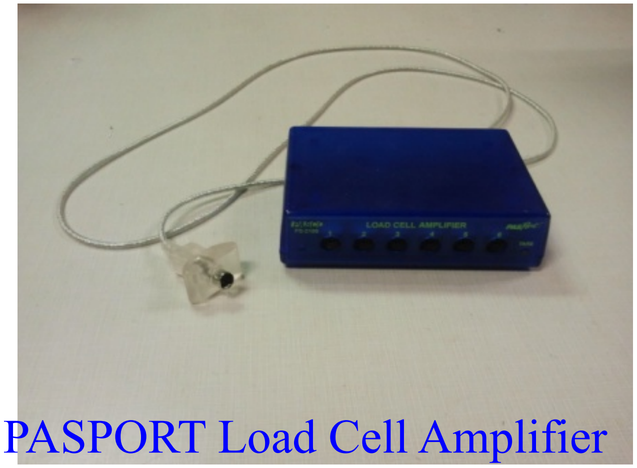
Physical Experiment

Components of experimental setup (cont.)

- PowerLink (PS-2198): has three-sensor port USB Link with a built-in general purpose USB hub and PDA connectivity. It uses power from an adapter. Each sensor has a status LED to indicate an active connection. DataStudio software, version 1.8 or higher (version: 1.9.8r7) are required.

PowerLink

- PASPORT Load Cell Amplifier (PS-2198): works with a maximum of six load cells which collect streams of tension or compression force data. Load cells are connected individually to any of the six load cell amplifier input ports.



PASPORT Load Cell Amplifier

Physical Experiment

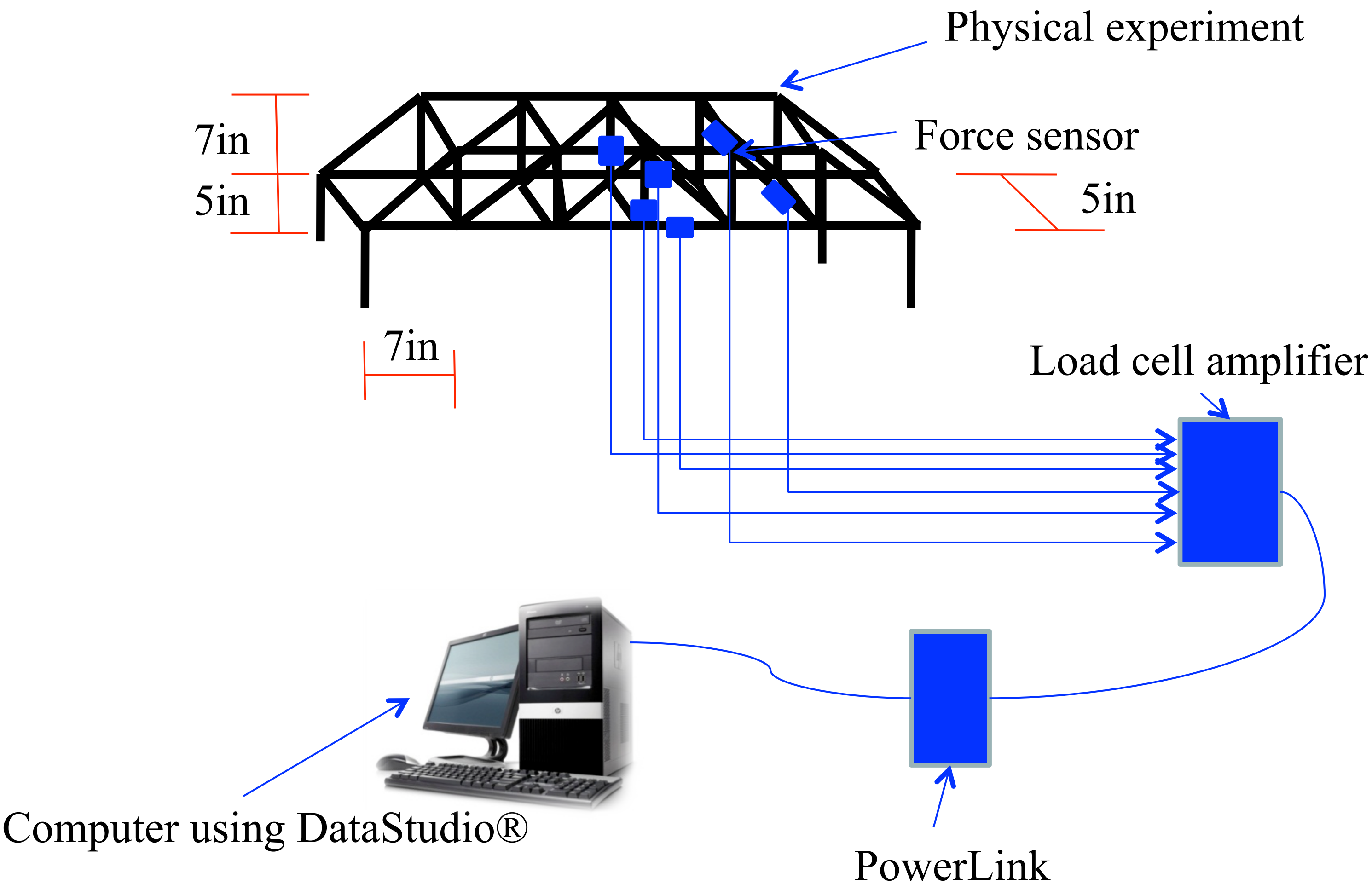
Components of experimental setup (cont.)

- Large Slotted Mass Set (ME-7566): is made up of nine iron disks of 0.5 kg each and a hanger, which is also 0.5 kg. Both the iron disk and the hanger are cast and machined to 1 gram accuracy to operate PowerLink.

Large Slotted Mass Set

Physical Experiment

Schematic of experimental setup



Physical experiment

7in

5in

Force sensor

5in

7in

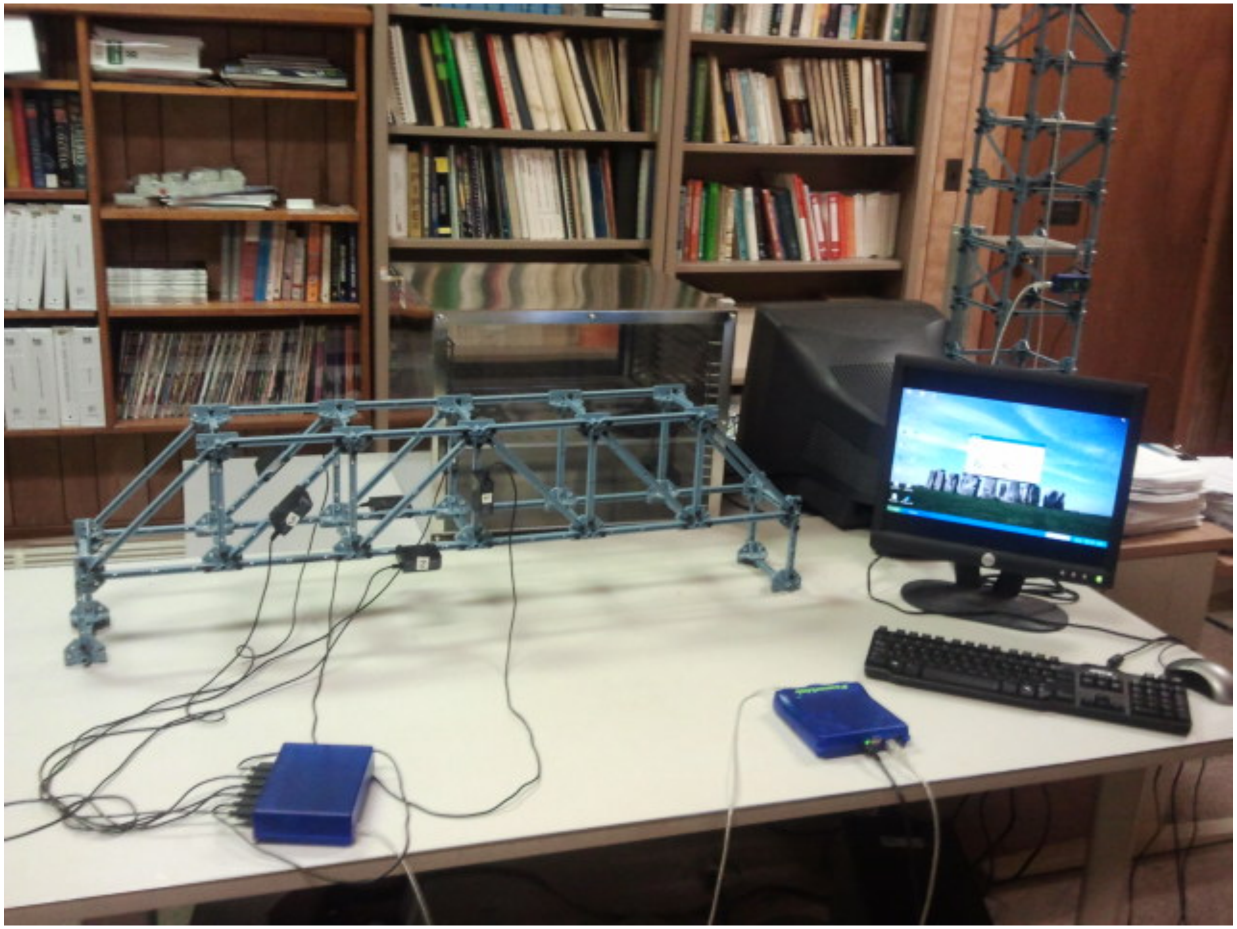
Load cell amplifier

Computer using DataStudio®

PowerLink

Physical Experiment

Experimental setup



Physical Experiment

Experimental procedure

- Check all joints and connections to make sure they are firmly fixed.
- Run the DataStudio® on the computer for 20 seconds before loading the intact truss bridge to obtain static response.
- Apply 3kg live load after 20 seconds on the intact truss bridge to obtain transient and oscillation response.
- Collect and record data from six force sensors.
- Introduce artificial defect by removing one diagonal member from one side of the truss bridge model to create a damaged structure.
- Repeat the experiment five times. Record the result.
- Illustrate collected data in force vs. time and Relative amplitude vs. frequency for frequency analysis using Matlab®.

Physical Experiment

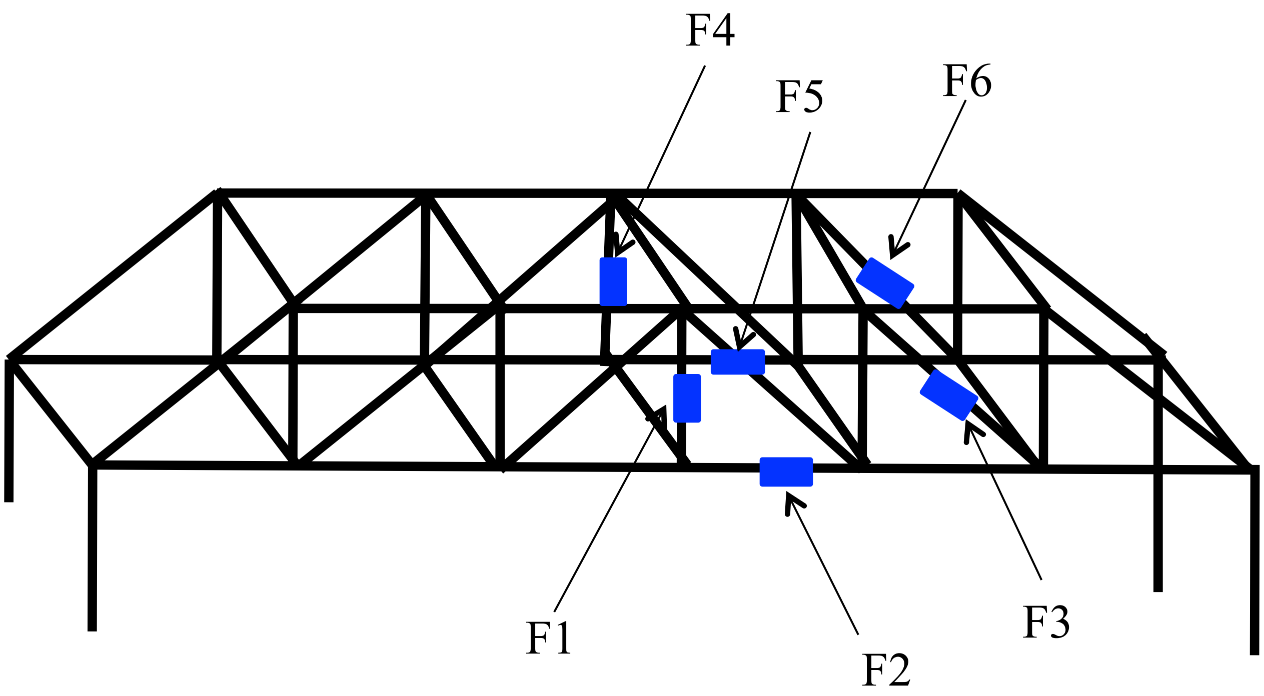
Simulation cases

- Simulation cases
  - ☐ Unloaded intact
    - Data consistency
  - ☐ Loaded intact
    - Baseline for physical experiment
  - ☐ Loaded damaged
    - Damage identification

SERG
Microwave Material Characterization Lab

Physical Experiment

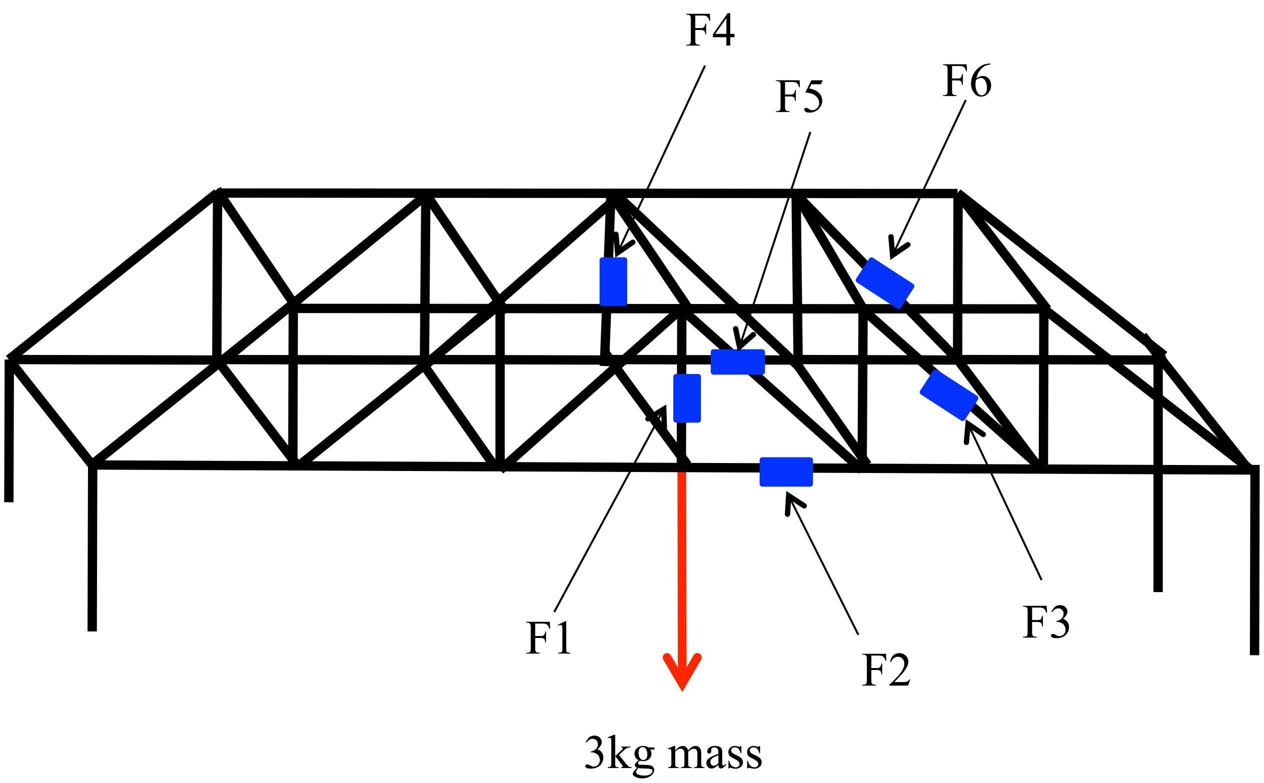
Schematic unloaded intact truss bridge



F=Force sensor

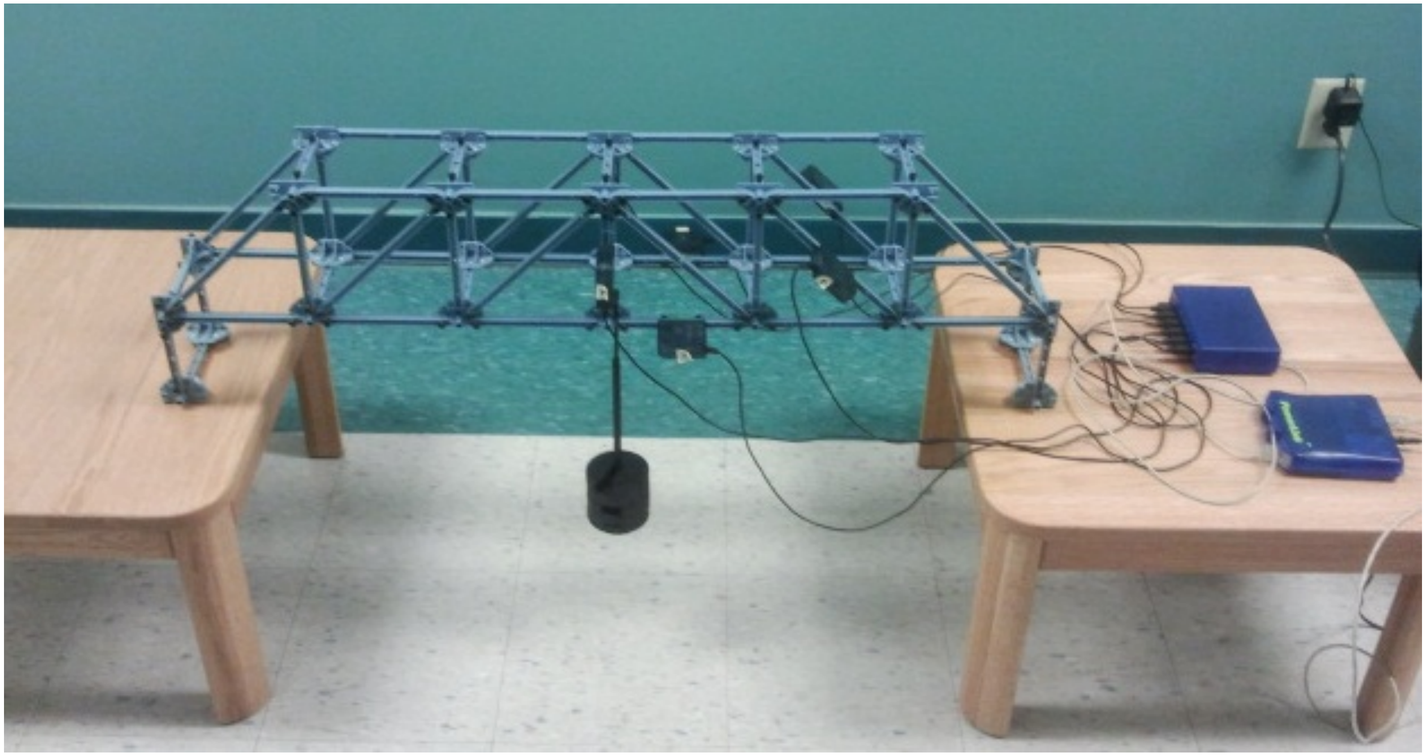
Physical Experiment

Schematic loaded intact truss bridge



Physical Experiment

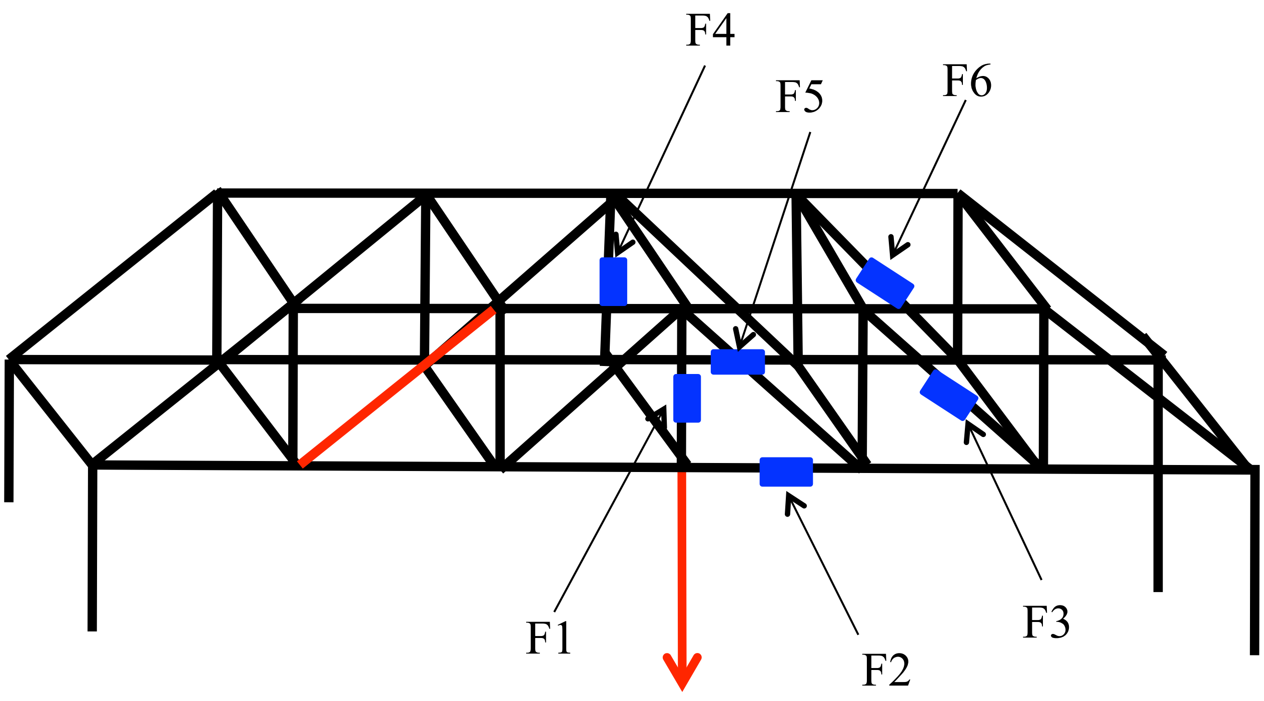
Experimental loaded intact truss bridge



SERG
Microwave Material
Characterization Lab

Physical Experiment

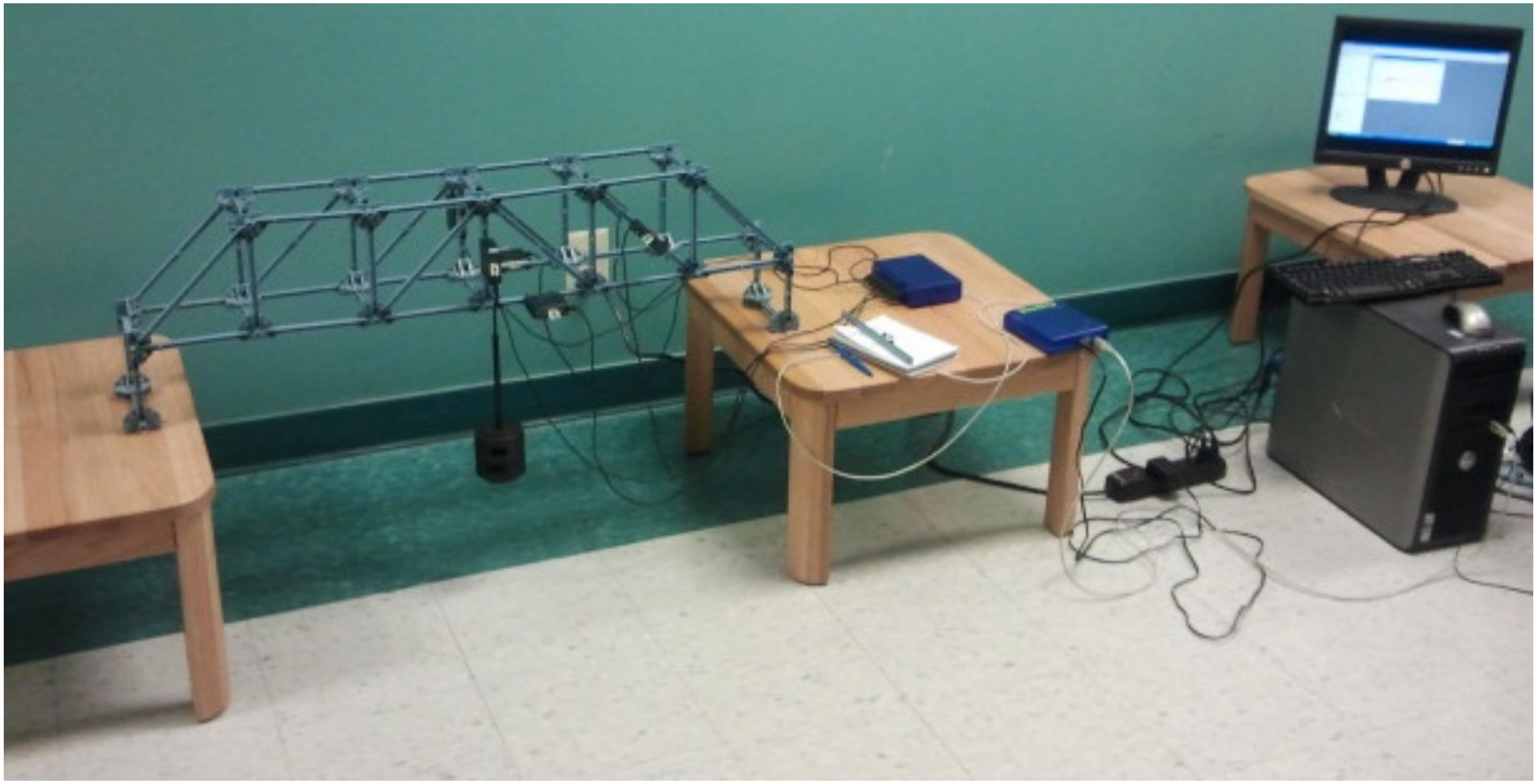
Schematic loaded damaged truss bridge



3kg mass

Physical Experiment

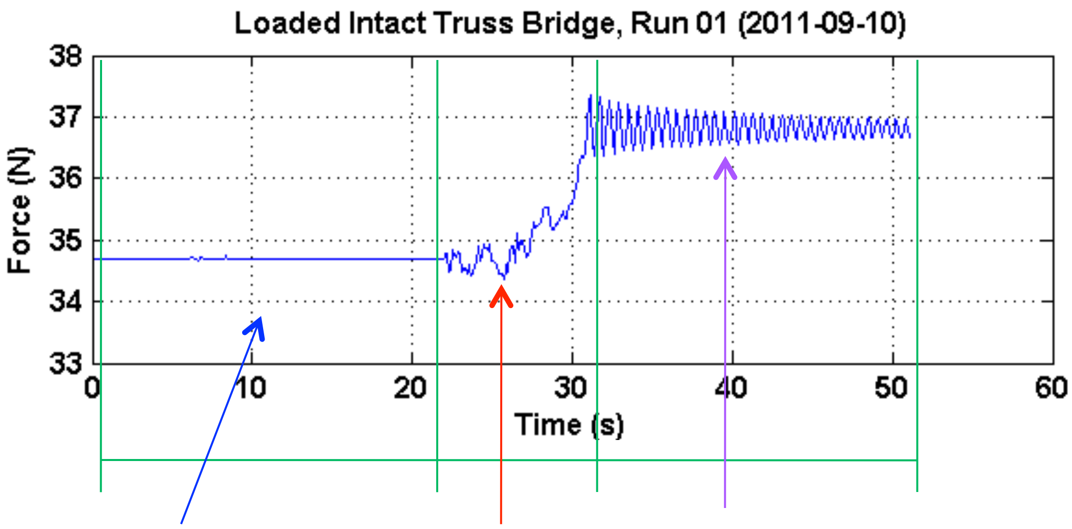
Experimental loaded <u>damaged</u> truss bridge



Physical Experiment

Force & frequency analysis

- The plot of force against time represents dynamic response of the structure after the truss bridge is loaded.
- The dynamic response of the structure is forced vibration.
- The force-time graph is divided into three zones, namely;
  - Static zone
  - Transient zone
  - Oscillation/harmonic zone



Static zone Transient zone Oscillation zone

Outline

- Introduction
  - Motivation of research study
  - Structural health monitoring (SHM)
- Literature Review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research Finding
- Reference
- Acknowledgement

Simulation & Experimental Results

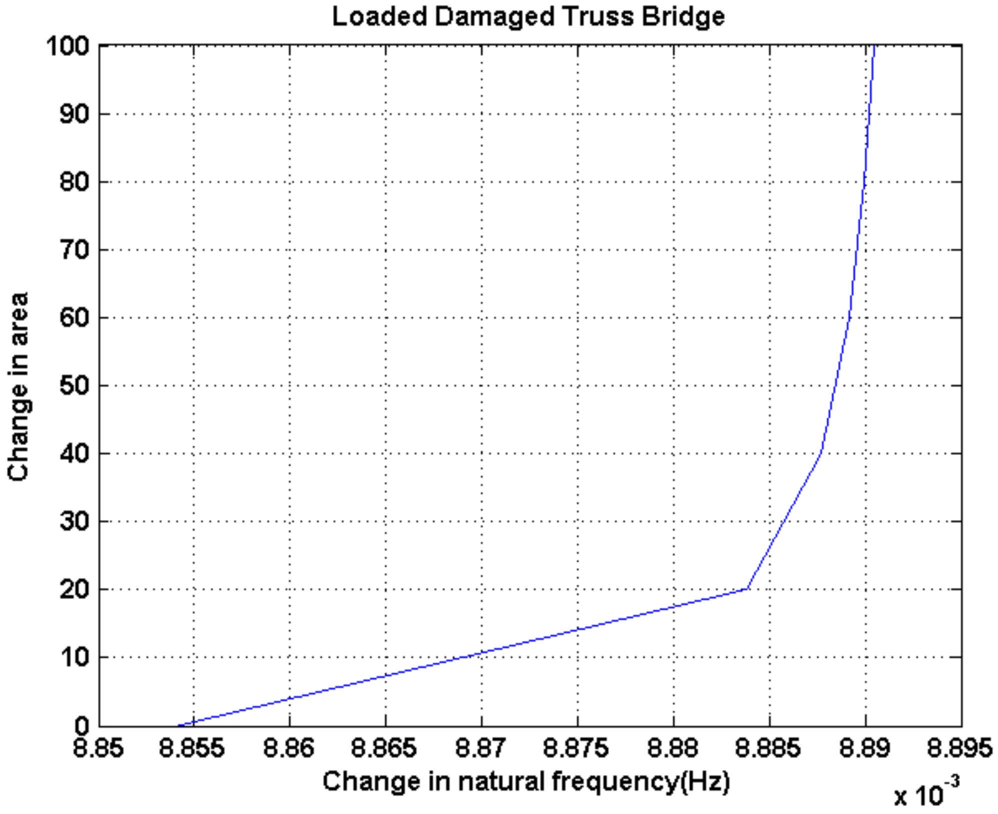
- Simulation results – Intact and damaged truss bridges

Table 1B: Change in area and change in natural frequency

Change in area by %	Change in natural frequency (rad/sec)
100	8.89048E-03
80	8.88997E-03
60	8.88917E-03
40	8.88766E-03
20	8.88383E-03
0	8.85393E-03

Simulation & Experimental Results

- A graph of change in area against change in natural frequency



Simulation & Experimental Results

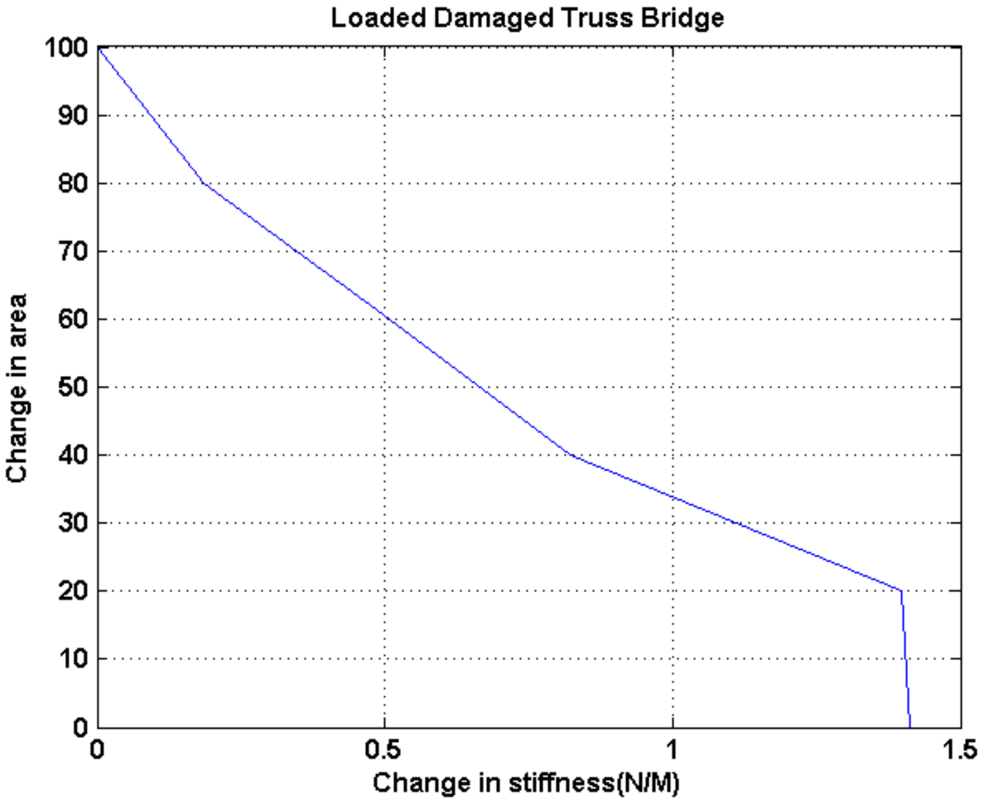
- Simulation results – Intact and damaged truss bridges

Table 1A: Change in area and change in natural frequency

Change in area by %	**Change in stiffness (N/M)**
100	0
80	0.186
60	0.507
40	0.823
20	1.396
0	1.413

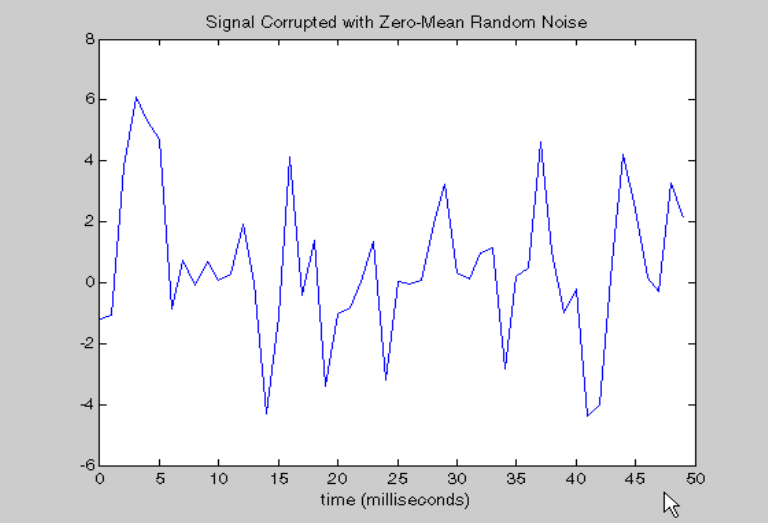
Simulation & Experimental Results

- A graph of change in area against change in stiffness



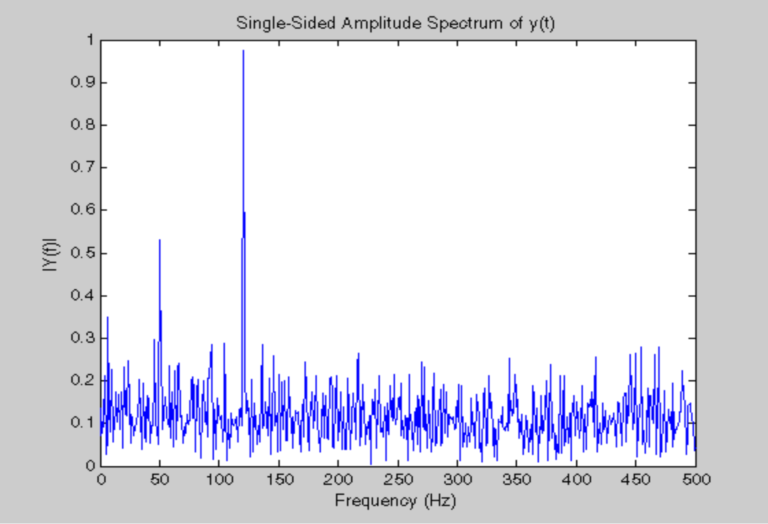
Simulation & Experimental Results

- Fast Fourier Transform (FFT)



Time-domain

FFT



Frequency-domain

Simulation & Experimental Results

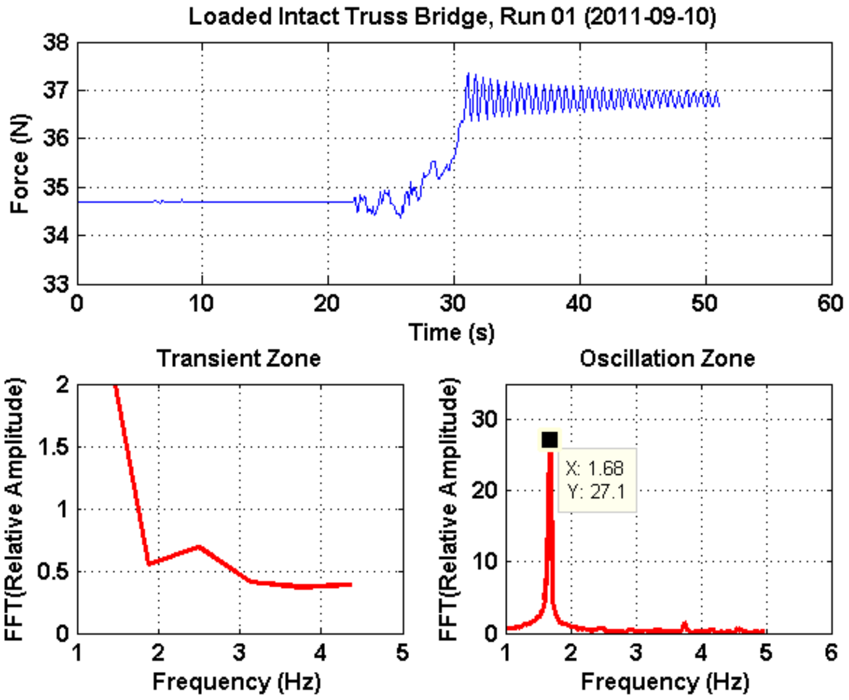


Figure B-1. Physical Experiment: Loaded intact truss bridge-Force sensor 1 (F1)

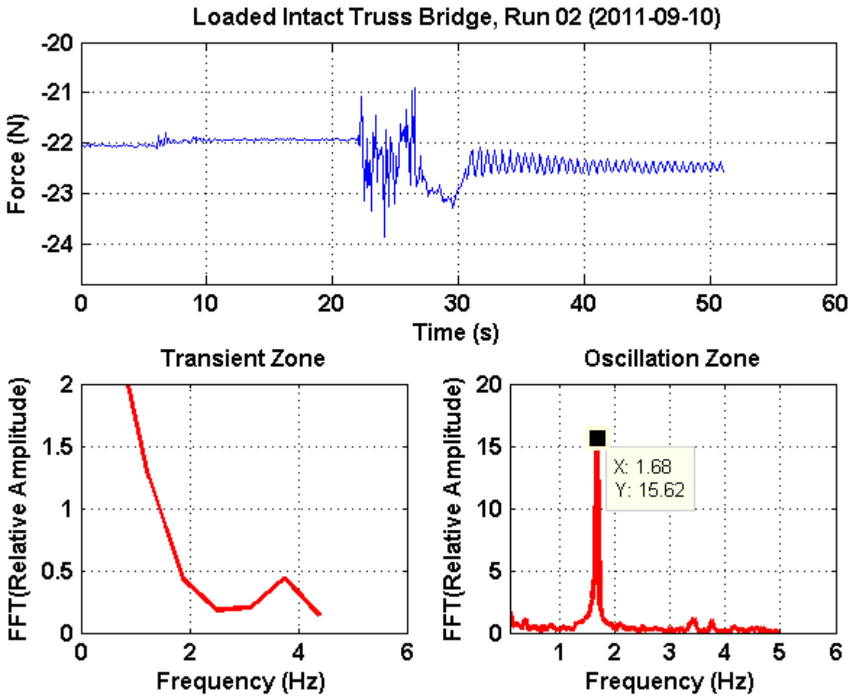
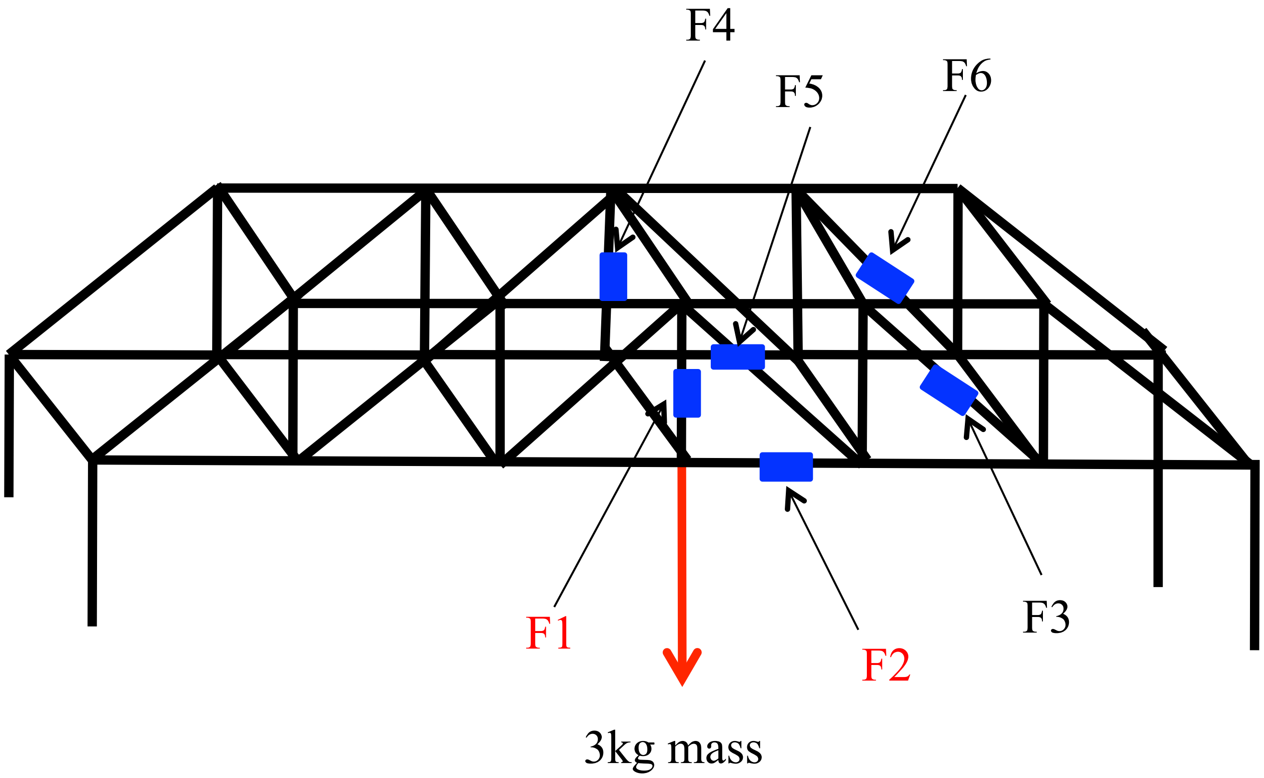


Figure B-2. Physical Experiment: Loaded intact truss bridge-Force sensor 2 (F2)

Simulation & Experimental Results

- Schematic of loaded intact truss bridge:



SERG

Microwave Material
Characterization Lab

Simulation & Experimental Results

UMASS LOWELL

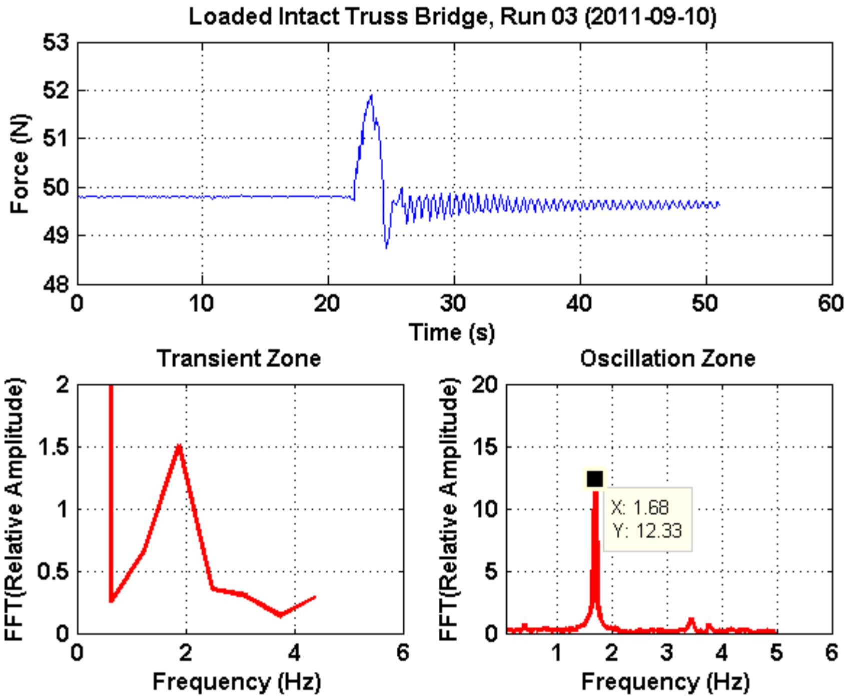


Figure B-3: Physical Experiment: Loaded intact truss bridge-Force sensor 3 (F3)

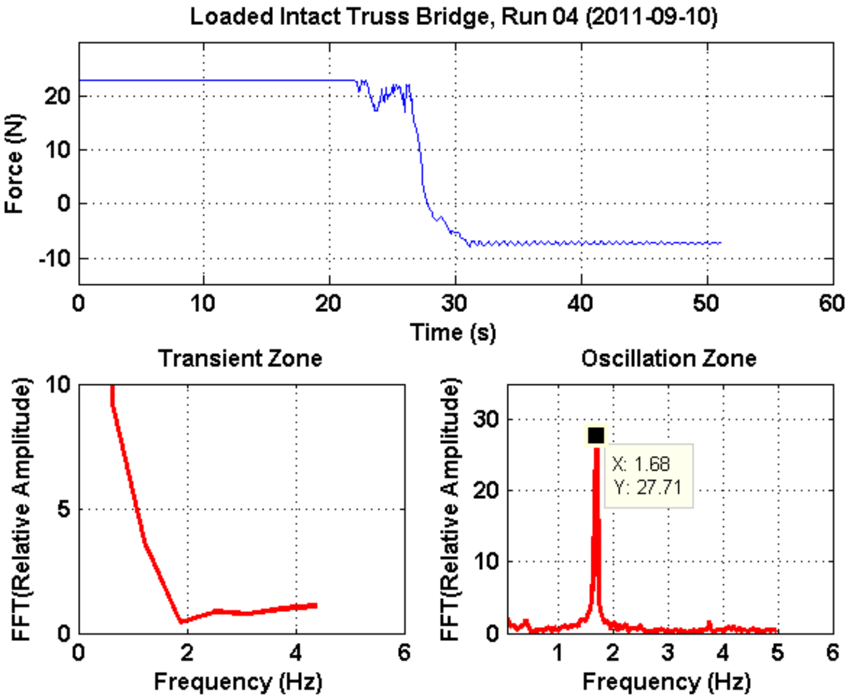


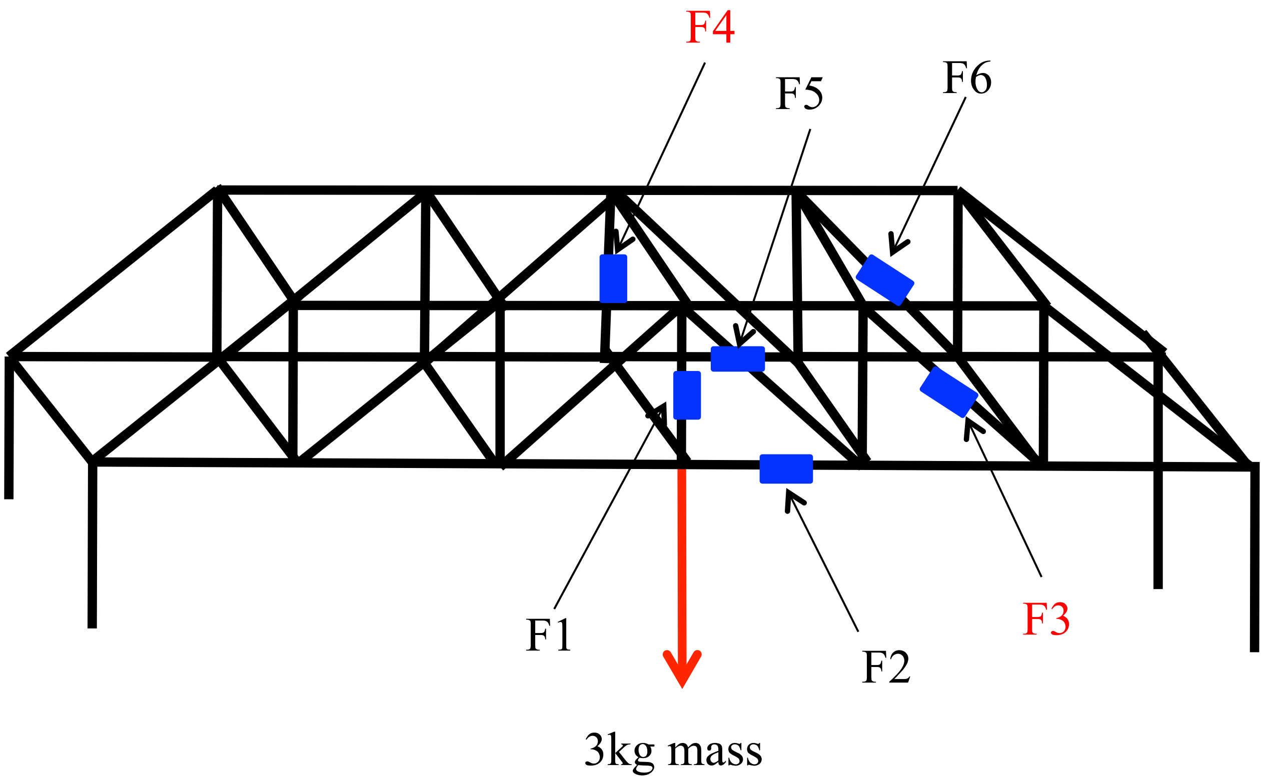
Figure B-4: Physical Experiment: Loaded intact truss bridge-Force sensor 4 (F4)

SERG

Microwave Material Characterization Lab

Simulation & Experimental Results

- Schematic of loaded intact truss bridge:



Microwave Material Characterization Lab

Simulation & Experimental Results

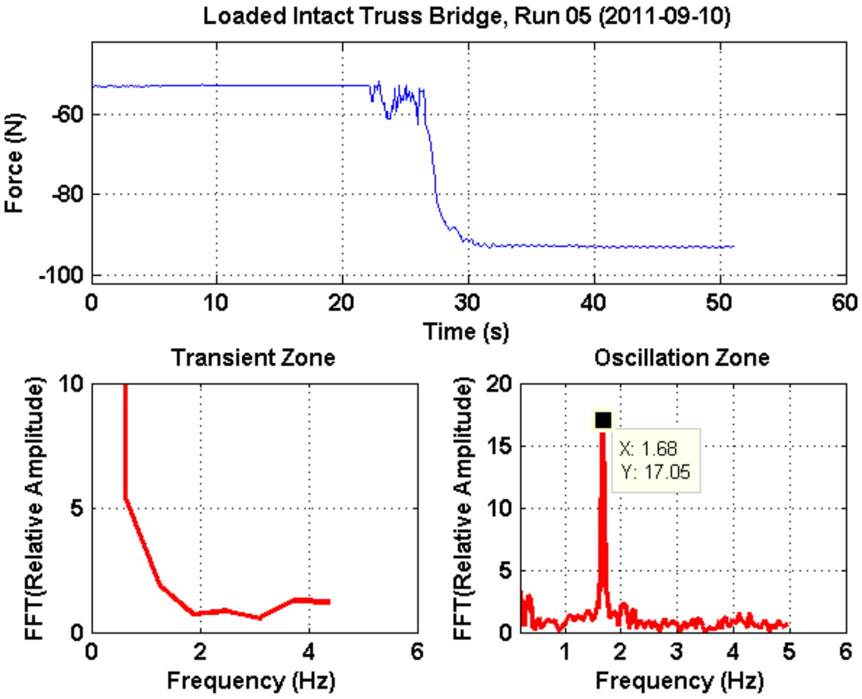


Figure B-5: Physical Experiment: Loaded intact truss bridge-Force sensor 5 (F5)

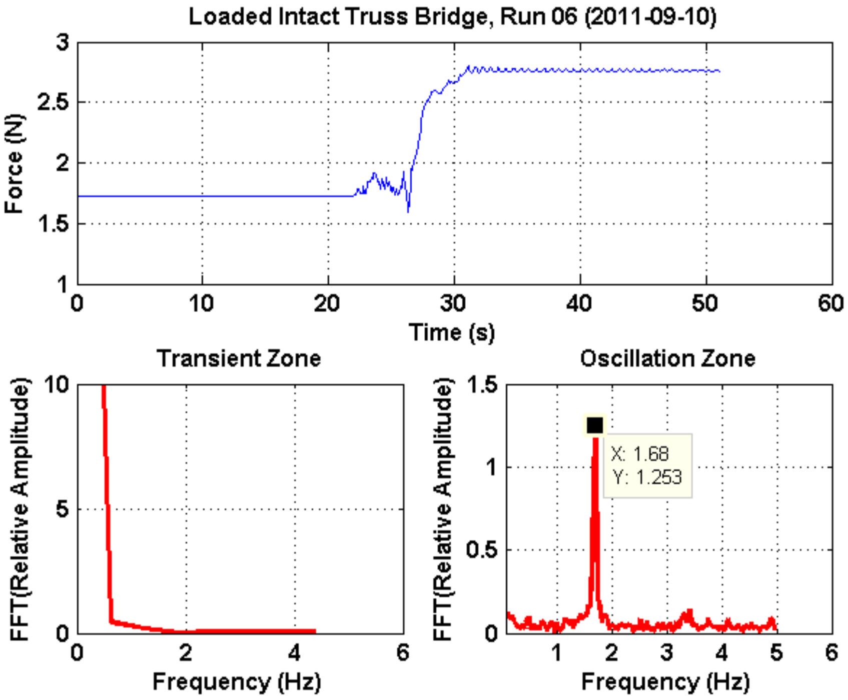
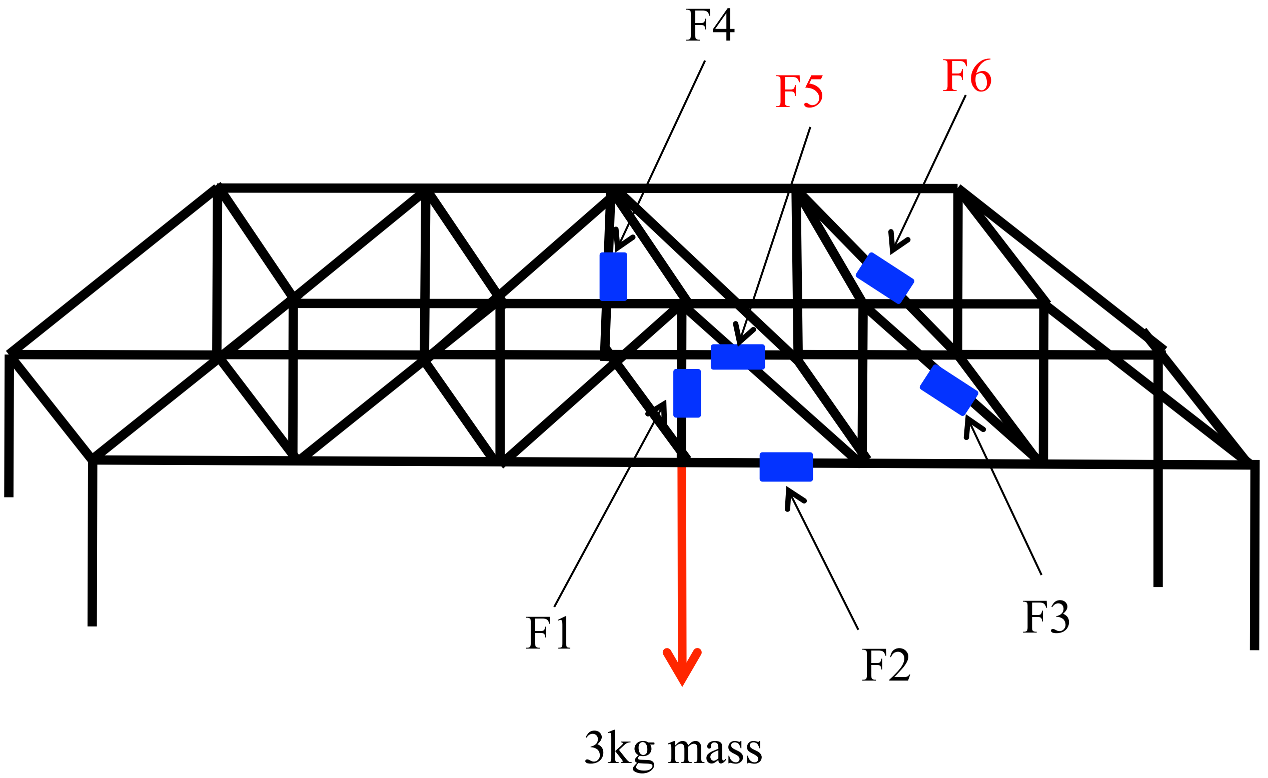


Figure B-6: Physical Experiment: Loaded intact truss bridge-Force sensor 6 (F6)

Simulation & Experimental Results

- Schematic of loaded intact truss bridge:



Simulation & Experimental Results

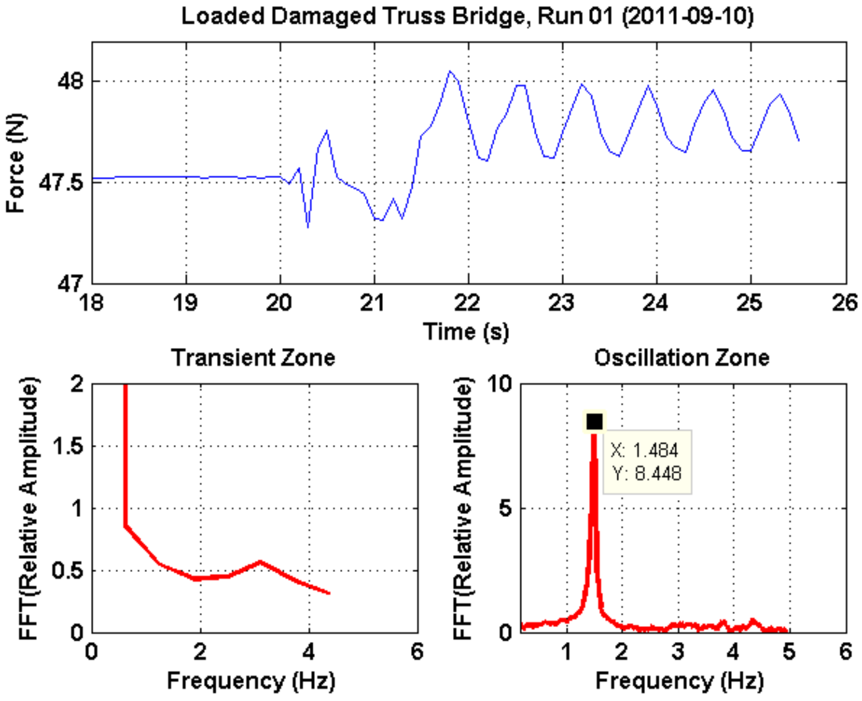


Figure B-1: Physical Experiment: Loaded damaged truss bridge-Force sensor 1 (F1)

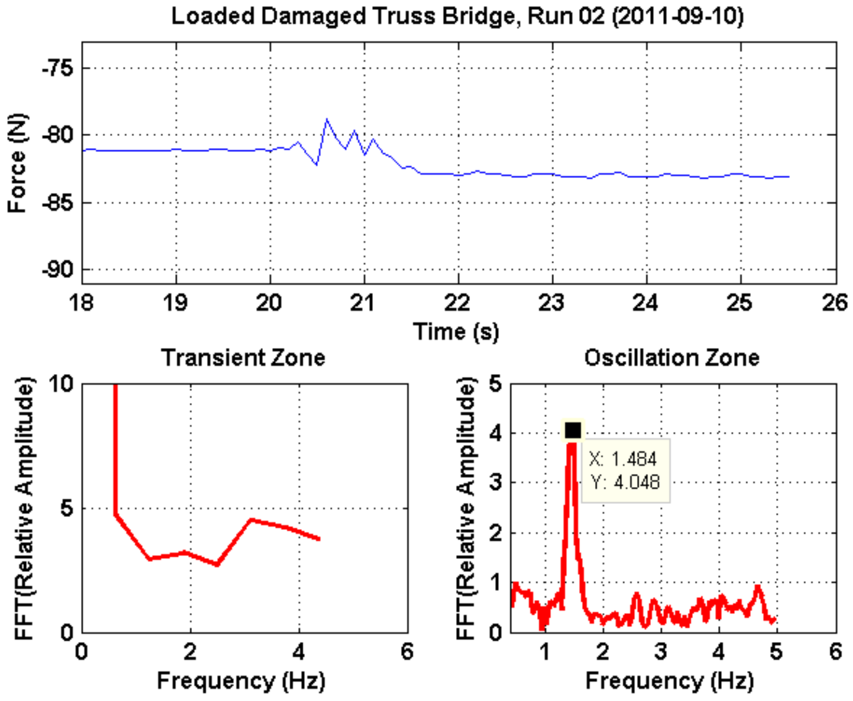
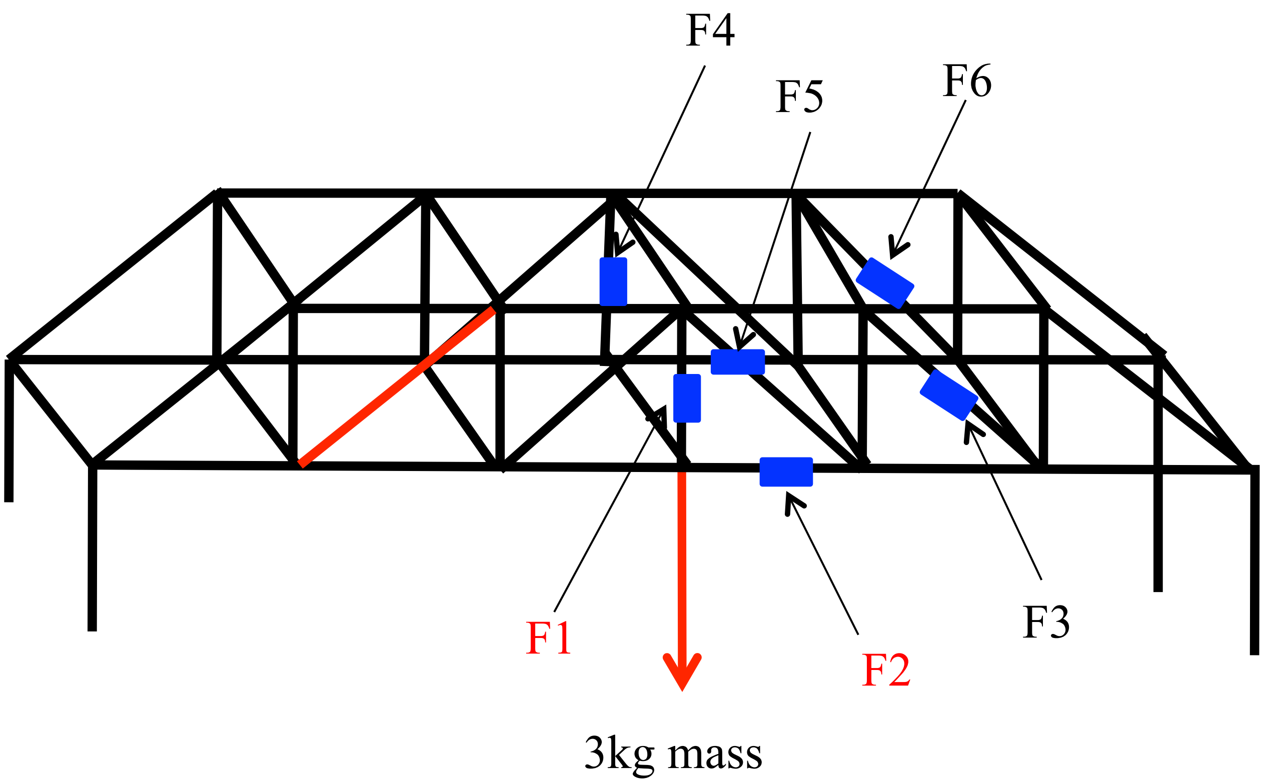


Figure B-2. Physical Experiment: Loaded damaged truss bridge-Force sensor 2 (F2)

Simulation & Experimental Results

- Schematic of loaded damaged truss bridge:



Simulation & Experimental Results

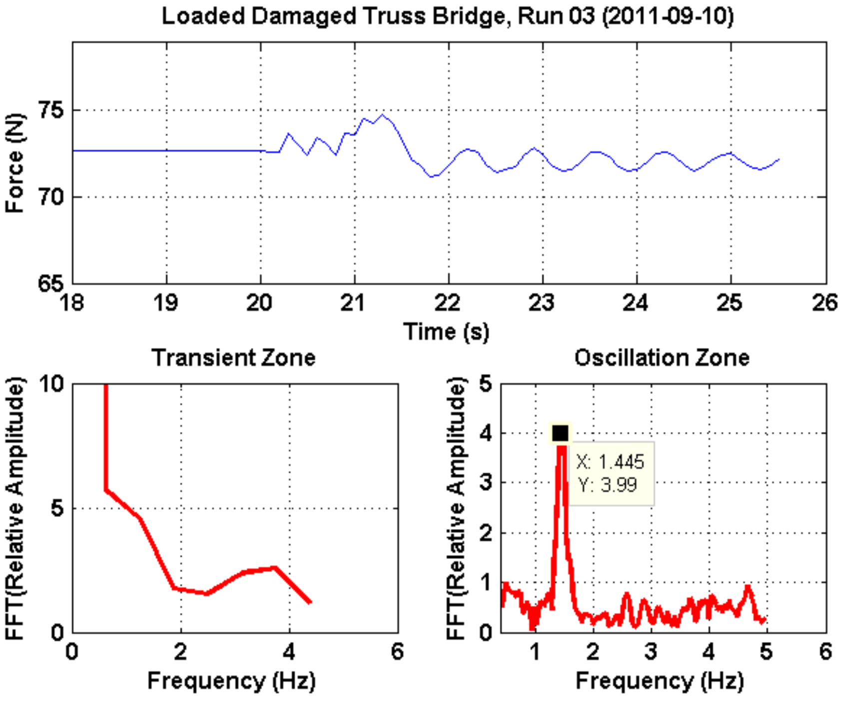


Figure B-3: Physical Experiment: Loaded damaged truss bridge-Force sensor 3 (F3)

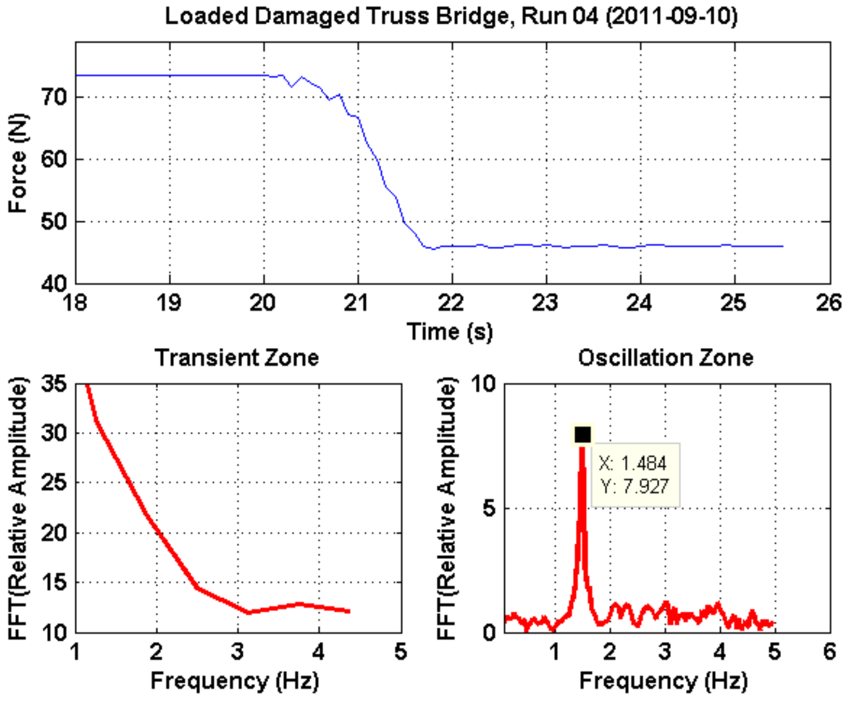
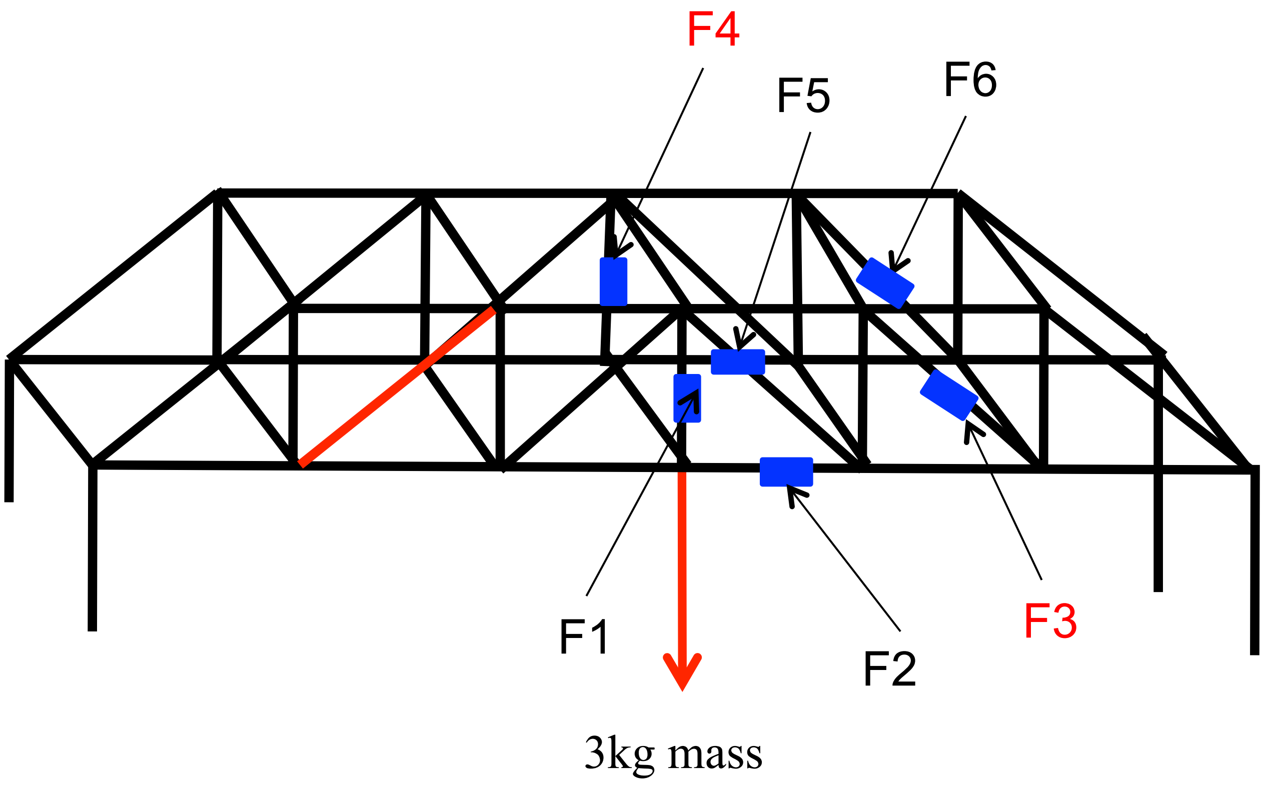


Figure B-4: Physical Experiment: Loaded damaged truss bridge-Force sensor 4 (F4)

Simulation & Experimental Results

- Schematic of loaded damaged truss bridge:



Simulation & Experimental Results

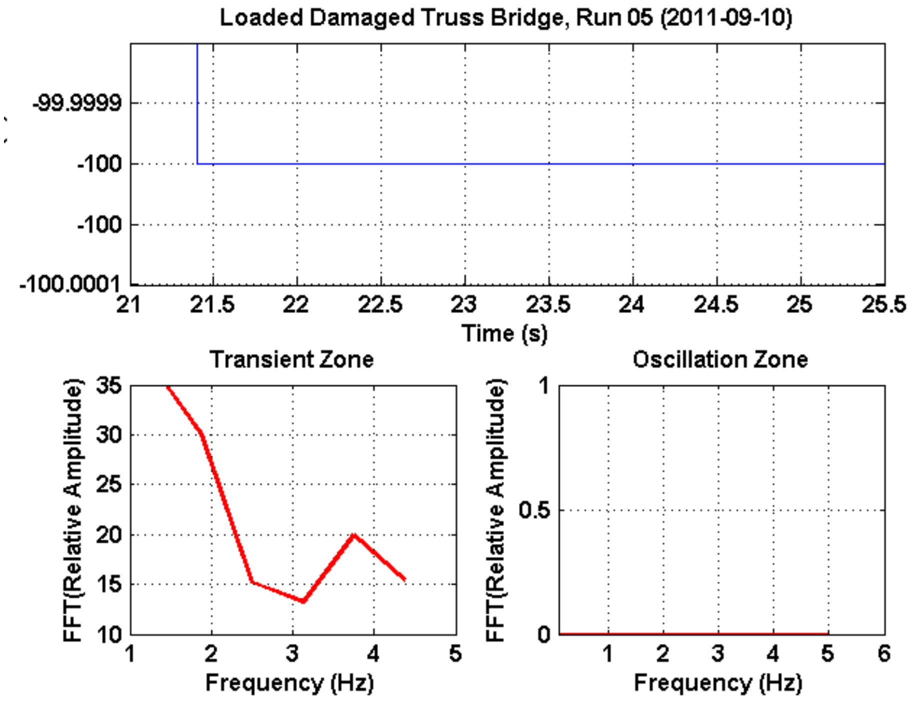


Figure B-5: Physical Experiment: Loaded damaged truss bridge-Force sensor 5 (F5)

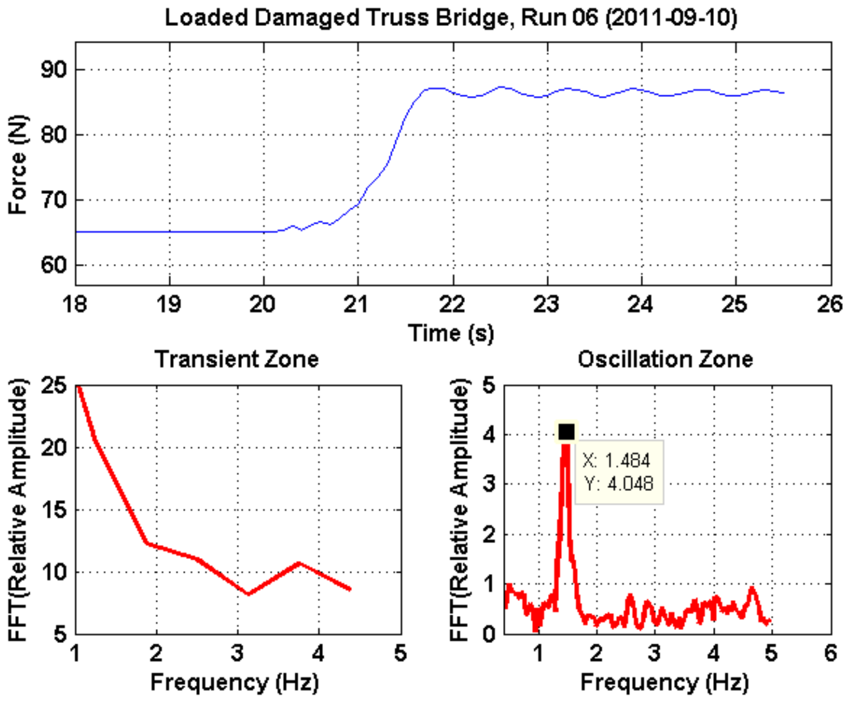
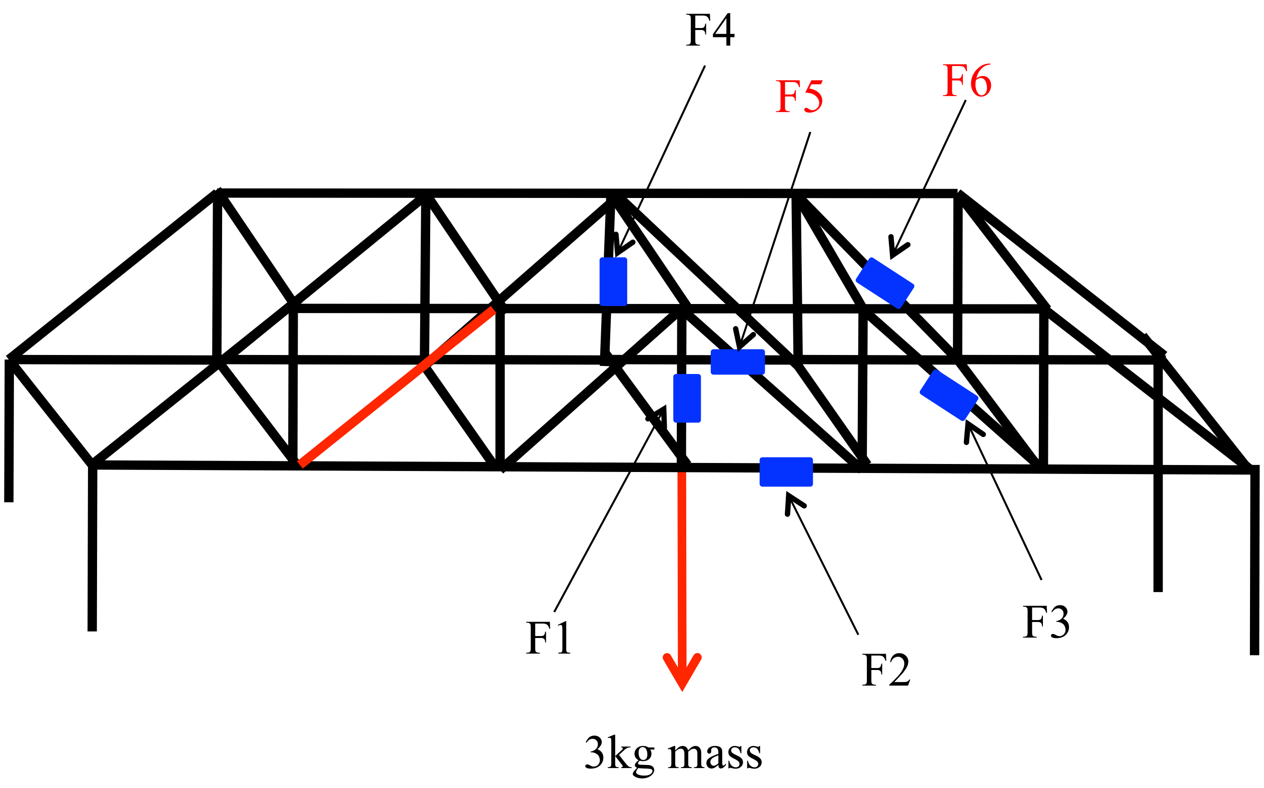


Figure B-6: Physical Experiment: Loaded damaged truss bridge-Force sensor 6 (F6)

Simulation & Experimental Results

- Schematic of loaded damaged truss bridge:



Simulation & Experimental Results

- Simulation results-intact and damaged truss bridge

Table1C: Natural frequency of Intact and damaged truss bridge

Sensor #	Intact Truss Bridge Natural Frequency	Damaged Truss Bridge Natural Frequency
1	1.68	1.484
2	1.68	1.484
3	1.68	1.484
4	1.68	1.484
5	1.68	-
6	1.68	1.484

Outline

- Introduction
  - Motivation of research study
  - Structural health monitoring (SHM)
- Literature Review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research Findings
- Reference
- Acknowledgement

Summary

- Numerical models were simulation using SAP2000®
- Three simulation cases were observed namely; unloaded, loaded intact, and loaded damaged truss bridge.
- Artificial damage was introduced to the truss bridge by reducing the area of a truss member at 20% intervals. The displacement and natural frequency were observed.
- Model truss bridge was numerically simulated (Physical experiment).
- Three loading cases were considered namely; unloaded intact, loaded intact , and loaded damaged truss bridge
- Artificial damage was introduced to the bridge truss by removing a truss member.
- From the result obtained the FFT of the physical experiment, we can conclude that the natural frequency is independent of sensor location.
- Both approaches are reliable tools in damage identification and damage location when given a baseline for monitoring the health of a structure.

Outline

- Introduction
  - Motivation of research study
  - Structural health monitoring (SHM)
- Literature Review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research Findings
- Reference
- Acknowledgement

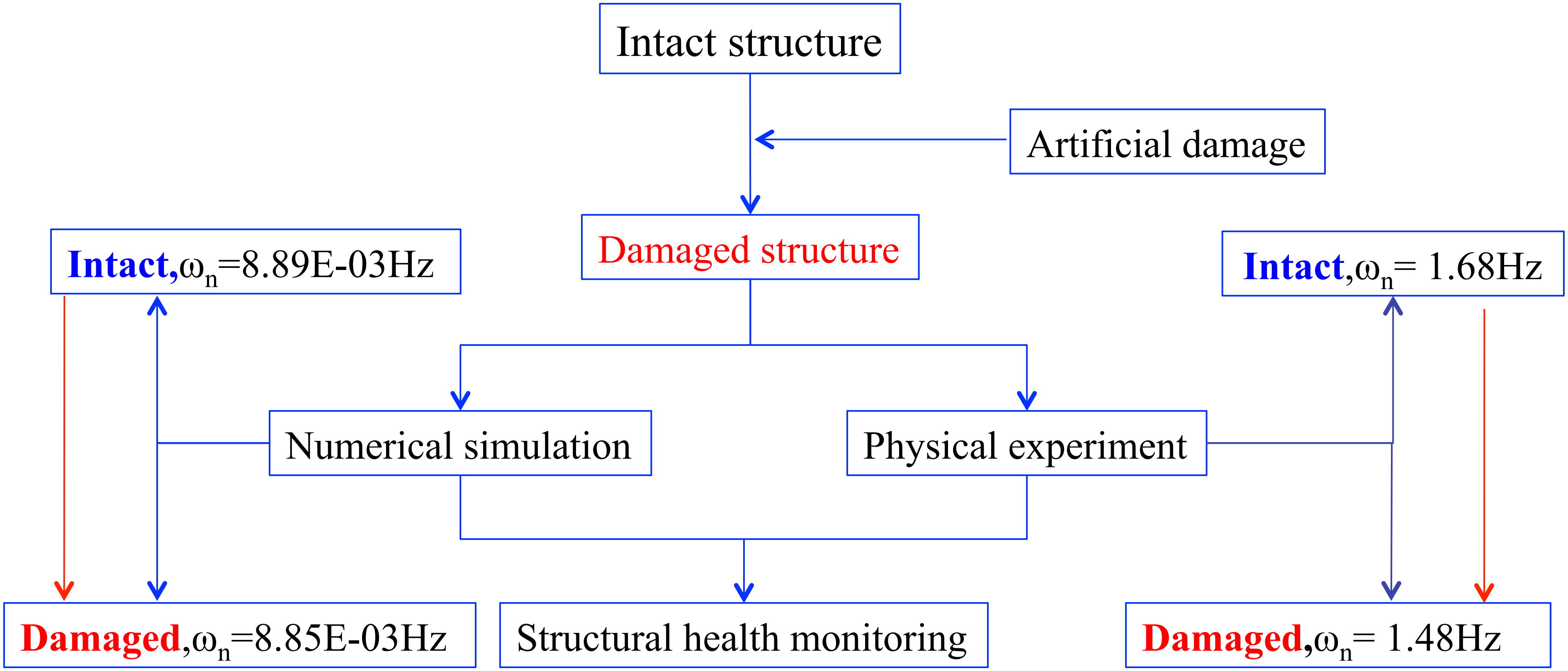
Research Findings

- In the ideal world the output of the unloaded truss bridge model should be start from zero due to the force of gravity, but it is not so in the real world (Force of gravity ≠ o).
- The response for the unloaded truss bridge should be a prefect straight line, it is not the case in the real world. This phenomenon is due to background vibration noise and electronic noise in the measuring equipment such force sensor.
- Comparing the output data from the loaded response of the intact structure to the one of the damaged structure, there are some changes in the internal force in the members.
- It is observed that the natural frequency is independent of sensor location.
- Data from the harmonic zone was preferred to that of transient zone (because the harmonic zone produces a clearly presentation of the frequency response) for frequency analysis.

Research Findings (cont.)

- From the results obtained in Figure 1A, it is observed as the cross-sectional area of a member reduces, the nature frequency reduces.
- From Figure 1B, it is observed as the cross-sectional area of a member reduces stiffness of the structure reduces.
- Since change in stiffness is directly related to the degree of damage, we can use this information to identify the presence of damage in a structure, also the degree of damage in the structure and with different sensor location scenarios we can eventually predict the location of damage.

Research Findings



Intact structure

Artificial damage

Damaged structure

Intact,ω_n=8.89E-03Hz

Intact,ω_n= 1.68Hz

Numerical simulation

Physical experiment

Damaged,ω_n=8.85E-03Hz

Structural health monitoring

Damaged,ω_n= 1.48Hz

Outline

- Introduction
  - Motivation of research study
  - Structural health monitoring (SHM)
- Literature Review
- Research Approach
- Numerical Simulation
- Physical Experiment
- Simulation and Experimental Results
  - Effect of Change in Area-SAP2000
  - Effect of Change in Area-Bridge model
- Summary
- Research Findings
- Reference
- Acknowledgement

Reference

1. Chang, Peter C., Alison Flatau, and S. C. Liu. "Review Paper: Health Monitoring of Civil Infrastructure." *Structural Health Monitoring* (2003): 257. 1 Sept. 2003. Web. 11 Feb. 2011.
2. Khoo, Lay M., P. R. Mantena, and Prakash Jadhav. "Structural Damage Assessment Using Vibration Modal Analysis." *Structural Health Monitoring* 3.2 (2004): 177-94. June 2004. Web. 5 Mar. 2011.
3. Majumder, Luna, and C. S. Manohar. "A Time-domain Approach for Damage Detection in Beam Structures Using Vibration Data with a Moving Oscillator as an Excitation Source." *Journal of Sound and Vibration* 268 (2003): 699-716. *Science Direct*. 21 Nov. 2002. Web. 10 Mar. 2011.
4. Sohn Hoon, Charles R. Farrar, Francois Hemez, and Jerry Czarnecki. "A Review of Structural Health Review of Structural Health Monitoring Literature 1996-2001." 1 Jan. 2002. Web. 13 Jan. 2011.
5. Transportation statistics annual report, U.S. department of transportation, bureau of transportation statistics, 2008.

Acknowledgement

I would like to thank:

- Prof. Tzu-yang Yu for guidance in conducting my thesis research
- Prof. Donald Leitch and Prof. Faraji for their help in reviewing my thesis and also for offering me the opportunity to present my thesis
- UMass Science and Technology Office (S&T) for their financial support to this research
- National Institute of Standards and Technology (NIST) for partially supporting this research.

THANK YOU!

Questions?