Benchmark Studies For Structural Health Monitoring Using Analytical And Experimental Models

2005

Jason Lee Burkett
University of Central Florida

Find similar works at: https://stars.library.ucf.edu/etd

University of Central Florida Libraries http://library.ucf.edu

Part of the Civil Engineering Commons

STARS Citation


This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
BENCHMARK STUDIES FOR STRUCTURAL HEALTH MONITORING USING ANALYTICAL AND EXPERIMENTAL MODELS

by

JASON LEE BURKETT
B.S. University of Central Florida, 2003

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil and Environmental Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Summer Term
2005
ABSTRACT

The latest bridge inventory report for the United States indicates that 25% of the highway bridges are structurally deficient or functionally obsolete. With such a large number of bridges in this condition, safety and serviceability concerns become increasingly relevant along with the associated increase in user costs and delays. Biennial inspections have proven subjective and need to be coupled with standardized non-destructive testing methods to accurately assess a bridge’s condition for decision making purposes.

Structural health monitoring is typically used to track and evaluate performance, symptoms of operational incidents, anomalies due to deterioration and damage during regular operation as well as after an extreme event. Dynamic testing and analysis are concepts widely used for health monitoring of existing structures. Successful health monitoring applications on real structures can be achieved by integrating experimental, analytical and information technologies on real life, operating structures. Real-life investigations must be backed up by laboratory benchmark studies. In addition, laboratory benchmark studies are critical for validating theory, concepts, and new technologies as well as creating a collaborative environment between different researchers.

To implement structural health monitoring methods and technologies, a physical bridge model was developed in the UCF structures laboratory as part of this thesis research. In this study, the development and testing of the bridge model are discussed after a literature review of physical models. Different aspects of model development, with respect to the physical bridge model are outlined in terms of design considerations, instrumentation, finite element modeling, and simulating damage scenarios. Examples of promising damage detection methods were
evaluated for common damage scenarios simulated on the numerical and physical models. These promising damage indices were applied and directly compared for the same experimental and numerical tests. To assess the simulated damage, indices such as modal flexibility and curvature were applied using mechanics and structural dynamics theory. Damage indices based on modal flexibility were observed to be promising as one of the primary indicators of damage that can be monitored over the service life of a structure.

Finally, this thesis study will serve an international effort that has been initiated to explore bridge health monitoring methodologies under the auspices of International Association for Bridge Maintenance and Safety (IABMAS). The data generated in this thesis research will be made available to researchers as well as practitioners in the broad field of structural health monitoring through several national and international societies, associations and committees such as American Society of Civil Engineers (ASCE) Dynamics Committee, and the newly formed ASCE Structural Health Monitoring and Control Committee.
To my wife, Jaime for her support, perseverance, and encouragement.
ACKNOWLEDGMENTS

First and foremost, I thank my Lord and Savior Jesus Christ through whom all things are possible. The author also wishes to express sincere appreciation to Dr. F. Necati Catbas for his guidance, assistance, and review of this thesis. His advice has been critical and enabled me to accomplish this research. In addition to the guidance from Dr. Catbas, I would like to recognize the contributions of Dr.’s Juan Caicedo, Shirley Dyke, Lei Zhao, and Manoj Chopra to this thesis through correspondence and review.

Furthermore, I thank my colleagues in Dr. Catbas’s research team and those from the structures laboratory for their invaluable help in construction, instrumentation, teaching, and advising. Mustafa Gul’s contributions in terms of signal processing, system identification, and MATLAB computations were outstanding. Other names, in no particular order are: Melih Susoy, Jose Perez, Kevin Francoforte, Robert Shmerling, Tom Braswell, Tim Clement, and Mike Olka. Steel donations to the structures lab were made by Cato Steel and Surplus Steel, both of which were a pleasure to deal with.

Finally, I thank my wife, family, and friends for their prayers, encouragement, and support. I am forever grateful for the knowledge given to me by my dad and granddad from their experience and teaching in design and fabrication.
TABLE OF CONTENTS

LIST OF FIGURES ...................................................................................................................... xi

LIST OF TABLES ........................................................................................................................ xv

LIST OF ACRONYMS/ABBREVIATIONS .................................................................................... xvi

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW .................................................. 1

  1.1 Background ....................................................................................................................... 1

  1.2 Literature Review ............................................................................................................ 3

    1.2.1 Laboratory Models .................................................................................................... 3

        1.2.1.1 Classification and History ................................................................................... 3

        1.2.1.2 Advantages and Limiting Factors ....................................................................... 6

        1.2.1.3 Examples ............................................................................................................. 7

        1.2.1.3.1 Scaled Models ............................................................................................... 7

        1.2.1.3.2 Benchmark Structures ................................................................................... 9

        1.2.1.3.3 Phenomenological Models .......................................................................... 10

    1.2.2 National Bridge Inventory ......................................................................................... 11

    1.2.3 Recent Bridge Failures ............................................................................................... 12

    1.2.4 Damage Indices ......................................................................................................... 13

  1.3 Objective and Scope of Work .............................................................................................. 16

CHAPTER 2: LABORATORY MODEL DEVELOPMENT ............................................................ 18

  2.1 Design Considerations .................................................................................................... 18

  2.2 Preliminary Finite Element Model .................................................................................. 22

        2.2.1 Static Results ........................................................................................................ 23

        2.2.2 Dynamic Results ................................................................................................. 25
<table>
<thead>
<tr>
<th>2.3</th>
<th>Design Calculations</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>Fabrication Drawings</td>
<td>27</td>
</tr>
<tr>
<td>2.5</td>
<td>Physical Model Details</td>
<td>28</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Primary Structure</td>
<td>28</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Column Supports</td>
<td>29</td>
</tr>
<tr>
<td>2.5.3</td>
<td>Member Connections</td>
<td>30</td>
</tr>
<tr>
<td>2.5.4</td>
<td>Boundary Supports</td>
<td>30</td>
</tr>
</tbody>
</table>

**CHAPTER 3: MODAL ANALYSIS AND TESTING**

<table>
<thead>
<tr>
<th>3.1</th>
<th>Modal Theory</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.1</td>
<td>General Formulations</td>
<td>32</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Parameter Estimation</td>
<td>37</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Modal Assurance Criteria</td>
<td>38</td>
</tr>
<tr>
<td>3.1.4</td>
<td>Dynamically Measured Flexibility</td>
<td>39</td>
</tr>
<tr>
<td>3.1.5</td>
<td>Mode Shape Curvature</td>
<td>41</td>
</tr>
<tr>
<td>3.2</td>
<td>Equipment</td>
<td>42</td>
</tr>
<tr>
<td>3.3</td>
<td>Instrumentation</td>
<td>43</td>
</tr>
<tr>
<td>3.4</td>
<td>Data Needs</td>
<td>45</td>
</tr>
</tbody>
</table>

**CHAPTER 4: BENCHMARK STUDIES**

<table>
<thead>
<tr>
<th>4.1</th>
<th>History</th>
<th>47</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>Motivation</td>
<td>48</td>
</tr>
<tr>
<td>4.3</td>
<td>Overview</td>
<td>50</td>
</tr>
<tr>
<td>4.4</td>
<td>Numerical Simulations</td>
<td>52</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Detailed Finite Element Model</td>
<td>52</td>
</tr>
</tbody>
</table>
4.4.2 Damage Scenarios............................................................................................................. 55
4.4.3 Analysis Procedures........................................................................................................... 58
  4.4.3.1 FE Analysis......................................................................................................................... 58
  4.4.3.2 Data Extraction .................................................................................................................. 60
  4.4.3.3 Matlab Functions .............................................................................................................. 60
4.5 Experimental Simulations ........................................................................................................ 62
  4.5.1 Laboratory Setup............................................................................................................... 62
    4.5.1.1 Instrumentation ............................................................................................................... 63
    4.5.1.2 Acquisition System and Settings ....................................................................................... 65
  4.5.2 Damage Scenarios.............................................................................................................. 67
  4.5.3 Test Procedures.................................................................................................................... 73
  4.5.4 Post-Processing.................................................................................................................... 76

CHAPTER 5: TEST RESULTS AND DISCUSSION ............................................................................. 78
  5.1 Baseline Characterization ...................................................................................................... 78
  5.2 Scour and Settlement ............................................................................................................. 81
    5.2.1 Settlement at Joint 4.......................................................................................................... 82
    5.2.2 Settlement at Joint 7.......................................................................................................... 88
    5.2.3 Loss of Pile at Joint 4........................................................................................................ 92
  5.3 Boundary Support Changes .................................................................................................. 93
    5.3.1 Restrained Rotation at 2 Supports......................................................................................... 94
    5.3.2 Restrained Rotation at 4 Supports......................................................................................... 97
  5.4 Change in Stiffness .................................................................................................................. 98
    5.4.1 Cross-Member Hinges .................................................................................................... 99
LIST OF FIGURES

Figure 1: Collapse of Silver Bridge over Ohio River, 1967 ......................................................... 2
Figure 2: Health Monitoring Diagram .......................................................................................... 15
Figure 3: Anchor Base and Bolt .................................................................................................. 18
Figure 4: Installed Floor Anchor ................................................................................................. 18
Figure 5: Initial Geometry Assumption ....................................................................................... 20
Figure 6: Summary of Design Considerations ............................................................................. 21
Figure 7: General Design Procedure Using the FEM ................................................................. 22
Figure 8: Single Span Preliminary FEM ....................................................................................... 23
Figure 9: Two Span Preliminary FEM ........................................................................................ 23
Figure 10: Vertical Mode Shapes for Single, Two, and Skewed-Span Cases ............................ 26
Figure 11: 3-D CAD Model .......................................................................................................... 28
Figure 12: Typical Support Column ............................................................................................ 29
Figure 13: Anchor Detail for Support Columns ........................................................................... 29
Figure 14: Moment Connection .................................................................................................. 30
Figure 15: Shear Clips .................................................................................................................. 30
Figure 16: Boundary Support ...................................................................................................... 30
Figure 17: Single DOF System .................................................................................................... 33
Figure 18: FRF of a single DOF System ....................................................................................... 35
Figure 19: IRF of a Single DOF System ....................................................................................... 35
Figure 20: CMIF Plot .................................................................................................................. 38
Figure 21: Accelerometers .......................................................................................................... 43
Figure 22: Measured Force Inputs ............................................................................................... 43
Figure 23: Proposed Instrumentation Plan ................................................................. 44
Figure 24: Laboratory Monitoring Setup ................................................................. 45
Figure 25: FEM for International Benchmark Study .............................................. 51
Figure 26: Detailed FEM of Grid .......................................................... 53
Figure 27: Pinned Support ........................................................................ 54
Figure 28: FEM Released DOF's .............................................................. 54
Figure 29: FEM DOF Labels ................................................................... 55
Figure 30: General Grid Identification ................................................ 56
Figure 31: Load Cases ........................................................................ 59
Figure 32: Numerical Analysis Procedure .................................................... 62
Figure 33: PCB 393C (ICP/Seismic) ............................................................... 63
Figure 34: PCB 3700 (Capacitive) ................................................................. 63
Figure 35: Horizontal Mount .................................................................... 64
Figure 36: Channel Wiring (Vertical Impact) .................................................. 64
Figure 37: Accelerometer Placement ............................................................... 65
Figure 38: Signal Conditioning ................................................................. 66
Figure 39: Data Acquisition ................................................................... 66
Figure 40: Joint 4 Settlement Scenario ............................................................ 69
Figure 41: Joint 7 Settlement Scenario ............................................................ 69
Figure 42: Joint 4 Pile Loss Scenario ............................................................... 70
Figure 43: Joints 7 and 14 Restrained Scenario ........................................... 71
Figure 44: Joints 4, 7, 11 and 14 Restrained Scenario ..................................... 71
Figure 45: Joints 3 and 10 Loss of Stiffness .................................................... 72
Figure 46: Joint 3 Loss of Stiffness ................................................................. 72
Figure 47: Sensor Arrangement for Various Tests ........................................... 74
Figure 48: Test Procedure and Acquisition Scheme ........................................ 75
Figure 49: Damage Scenario Reconfiguration ............................................... 75
Figure 50: Experimental Analysis Scheme ..................................................... 77
Figure 51: Numerical and Experimental Mode Shape Comparison ................. 79
Figure 52: Baseline Experimental Mode Shapes ............................................. 80
Figure 53: Sensor Resolution Issues .............................................................. 81
Figure 54: Settlement/Scour Damage Scenarios ............................................. 82
Figure 55: Experimental MAC Values .......................................................... 82
Figure 56: Experimental Difference Between Damaged and Baseline Flexibility Matrices .... 83
Figure 57: Pseudo-Flexibility Loads .............................................................. 86
Figure 58: Experimental Displacement Profiles .......................................... 86
Figure 59: Experimental Curvature Distribution .......................................... 87
Figure 60: Mode Shape with Support Movement ........................................... 88
Figure 61: Inspection of Supports ................................................................. 88
Figure 62: Support Gap .............................................................................. 89
Figure 63: Support Contact Issues ............................................................... 89
Figure 64: Load Case 1, Experimental Displacement Profiles ....................... 91
Figure 65: Non-Symmetric Curvature .......................................................... 91
Figure 66: Change in Flexibility Matrices .................................................... 92
Figure 67: New Mode from Loss of Pile ....................................................... 93
Figure 68: Restrained Supports Damage Scenarios Typical Details ............ 94
Figure 69: Change in Displacement Comparison ................................................................. 95
Figure 70: Numerical vs. Experimental Deflection for Two Restraints ......................... 96
Figure 71: Curvature Distribution Issues ........................................................................ 97
Figure 72: Displacement Comparison ............................................................................ 98
Figure 73: Stiffness Change Damage Scenarios .............................................................. 99
Figure 74: Experimental Change in Curvature ............................................................... 101
Figure 75: Strain Comparison ...................................................................................... 102
Figure 76: Change in Displacement Comparisons ......................................................... 103
Figure 77: Change in Curvature Comparisons .............................................................. 104
**LIST OF TABLES**

Table 1: Damage Detection Matrix................................................................. 16

Table 2: Static Analysis Results From Critical Load Cases .......................... 25

Table 3: Dynamic Design Properties ............................................................ 26

Table 4: Dynamic Sensors Currently Instrumented on Grid .......................... 45

Table 5: Static Sensors Instrumented on Grid ................................................. 45

Table 6: Numerical Damage Scenarios.......................................................... 56

Table 7: Channel Assignments ...................................................................... 65

Table 8: Data Acquisition Parameters .......................................................... 67

Table 9: Experimental Damage Scenarios...................................................... 68

Table 10: Experimental Mode Comparisons ................................................ 84

Table 11: Experimental Mode Comparisons ............................................... 90

Table 12: Experimental Mode Comparisons ............................................... 94

Table 13: Experimental Mode Comparisons ............................................... 99
**LIST OF ACRONYMS/ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-D</td>
<td>Three-Dimensional</td>
</tr>
<tr>
<td>$(A_{pq})_r$</td>
<td>Residue of the $r^{th}$ mode</td>
</tr>
<tr>
<td>AASHTO</td>
<td>American Association of State Highway Transportation Officials</td>
</tr>
<tr>
<td>ACI</td>
<td>American Concrete Institute</td>
</tr>
<tr>
<td>ASCE</td>
<td>American Society of Civil Engineers</td>
</tr>
<tr>
<td>B(s)</td>
<td>System impedance</td>
</tr>
<tr>
<td>BHM</td>
<td>Bridge Health Monitoring</td>
</tr>
<tr>
<td>BMS</td>
<td>Bridge Management Systems</td>
</tr>
<tr>
<td>C</td>
<td>Damping coefficient</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>CMIF</td>
<td>Complex Mode Indicator Function</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>EFRF</td>
<td>Enhanced Frequency Response Function</td>
</tr>
<tr>
<td>$f$</td>
<td>Force</td>
</tr>
<tr>
<td>$f(t)$</td>
<td>Force as a function of time</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>FRF</td>
<td>Frequency Response Function</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fiber Reinforced Polymer</td>
</tr>
<tr>
<td>h</td>
<td>Height</td>
</tr>
<tr>
<td>$H(\omega)$</td>
<td>Frequency Response Function</td>
</tr>
<tr>
<td>I</td>
<td>Second moment of inertia</td>
</tr>
<tr>
<td>IABMAS</td>
<td>International Association for Bridge Maintenance and Safety</td>
</tr>
<tr>
<td>IASC</td>
<td>International Association of Structural Control</td>
</tr>
<tr>
<td>ISHMII</td>
<td>International Society for Structural Health Monitoring of Intelligent Infrastructure</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$K$</td>
<td>Stiffness coefficient</td>
</tr>
<tr>
<td>$L$</td>
<td>Length</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass constant, Bending moment</td>
</tr>
<tr>
<td>MAC</td>
<td>Modal Assurance Criteria</td>
</tr>
<tr>
<td>$N$</td>
<td>Total number of degrees of freedom of a system</td>
</tr>
<tr>
<td>NDE</td>
<td>Non-Destructive Evaluation</td>
</tr>
<tr>
<td>$p$</td>
<td>Response point</td>
</tr>
<tr>
<td>$q$</td>
<td>Reference point</td>
</tr>
<tr>
<td>$r$</td>
<td>$r^{th}$ mode of vibration of a system</td>
</tr>
<tr>
<td>SDOF</td>
<td>Single Degree of Freedom</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural Health Monitoring</td>
</tr>
<tr>
<td>SHMC</td>
<td>Structural Health Monitoring and Control</td>
</tr>
<tr>
<td>St-Id</td>
<td>Structural Identification</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular Value Decomposition</td>
</tr>
<tr>
<td>$t$</td>
<td>Distance from neutral axis to extreme fiber</td>
</tr>
<tr>
<td>$x$</td>
<td>Displacement</td>
</tr>
<tr>
<td>$\dot{x}$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$\ddot{x}$</td>
<td>Acceleration</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Curvature</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Displacement</td>
</tr>
<tr>
<td>$\Delta_{max}$</td>
<td>Maximum deflection</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>strain</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Mode shape vector or element</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Pole or eigenvalue of the characteristic equation</td>
</tr>
<tr>
<td>$\mu \varepsilon_{max}$</td>
<td>Maximum micro-strain</td>
</tr>
<tr>
<td>$\theta_{max}$</td>
<td>Maximum rotation</td>
</tr>
<tr>
<td>$\sigma_{max}$</td>
<td>Maximum stress</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Variable of frequency, (rad/sec)</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Background

It is difficult to travel any significant distance without crossing a bridge structure. To be classified as a bridge, the clear span must be greater than 20 feet. With the rapid growth of cities and the ever increasing population of drivers, overpasses, interchanges, and water-spanning bridges are being constructed and expanded to meet the demand. Bridges are a significant and critical component of the highway transportation system. Many of the 595,000 highway bridges existing today were constructed from 1950 to 1970 for the interstate system. As a result of this boom in construction, these bridges are either approaching or have surpassed their design life. Although not in danger of collapse, older bridges are likely to be load-posted to prevent heavy trucks from crossing the bridge. Highway agencies are struggling to keep up with the increasing demands on their highways and deteriorating bridges are becoming severe choke points in the system. In 2004, about 151,000 (25.4%) bridges were rated as structurally deficient or functionally obsolete (FHWA 2005). This is clearly a problem that funds can not alleviate by replacing all these bridges. With a rapidly aging infrastructure, the key to improving and maintaining highways will be the use of advanced materials, and innovative inspection, monitoring, and testing technologies. Furthermore, design procedures and construction methods will improve as these technologies improve the common understanding of bridges.

As a result of the 1967 collapse of the Silver Bridge over the Ohio River, Figure 1, the American Association of State Highway and Transportation Officials (AASHTO) developed a set of highway bridge inspection criteria. The National Bridge Inspection Standards mandated
this comprehensive bridge safety inspection program. A fundamental weakness in this current bridge management approach is that bridges are rated based on visual inspection that is subjective and could lead to inaccurate condition assessment. Three major bridge collapses in four years, the 1983 collapse of the Mianus River Bridge in Connecticut, the 1985 collapse of the Chikasawbogue Bridge in Alabama and the 1987 collapse of the Schoharie Creek Bridge in New York, indicates that current bridge inspection techniques need improvement. The complexities and costs associated with preserving the nation's bridge infrastructure demand innovative and unified approaches to inspection, collection, analysis and archival of data, to better define bridge needs and to find effective solutions.

Figure 1: Collapse of Silver Bridge over Ohio River, 1967

Appropriately, the U.S. Congress has mandated the implementation of Bridge Management Systems (BMS), such as Pontis, to promote more cost-efficient maintenance, management, and planning. Non-Destructive Evaluation (NDE) technologies of a rigorous and objective nature are sought to quantitatively identify and evaluate the "global" condition or health of highway structures based upon appropriate features or indices, which need to be established by research.
In order to develop effective and reliable inspection/condition assessment techniques, the dynamic properties of a bridge should be incorporated into the condition assessment process. Objective data acquired through on-site field-testing can provide quantitative and damage-sensitive information about a bridge. The use of objective data throughout condition assessment is therefore intended to optimize maintenance, rehabilitation, and repair operations.

1.2 Literature Review

The following sections give a brief overview of laboratory models, the national bridge inventory, recent bridge failures, and damage indices.

1.2.1 Laboratory Models

1.2.1.1 Classification and History

The ACI Committee 444 defines a structural model as, “Any physical representation of a structure or a portion of a structure. Most commonly, the model will be constructed at a reduced scale.” It should be noted that “most”, not all, models need to be scaled and will be further discussed in later sections. A variety of structures may be modeled, including building, bridges, dams, towers, reactor vessels, shells, aerospace and mechanical engineering structures, undersea structures, etc. Applied forces may represent static, seismic, thermal, and wind loads. Depending on the function of a model, it can be classified into one of several widely accepted groups. The following discussion gives an overview of some of the most popular classes of models but does not necessarily include all classes.
Elastic Models, as their name indicates, are used specifically for behavior in the elastic range of the material. The geometry of the model and prototype are similar while the material does not necessarily resemble the prototype but should be homogeneous. Elastic models using low modulus of elasticity materials are particularly useful for demonstration of structural behavior to students.

Indirect Models are basically used to determine the influence diagrams for reactions and internal shear, bending moment, and axial force. Loads applied to the model have no correspondence to the actual loads expected in real life. Furthermore, there is no need for physical resemblance between the model and prototype but such properties as flexural stiffness should correspond if the behavior is controlled by this quantity.

Direct Models are both geometrically and loaded similar to the prototype. Therefore, strains and other measurable quantities will be representative for the give load application on the prototype. Elastic models can also be a direct model.

Strength Models also called ultimate strength or realistic models are a direct model that is made of materials similar to the prototype materials such that the model will predict prototype behavior for all loads up to failure. Modeling the behavior up to the point of failure is clearly an advantage but a major problem is in finding the proper materials and fabrication techniques for the models.

Wind Effect Models are further classified into shape/rigid and aeroelastic categories. The shape and rigid models are used to measure the forces or wind pressures at various points on the structure. Aeroelastic models on the other hand use shape and stiffness properties of the prototype so that wind-induced stresses, deformations, and dynamic interaction may be measured on the model.
Dynamic Models are used to study vibration or dynamic loading effects on structures.

One popular method for seismic simulation is the use of shake tables. The model used for testing in this thesis is considered to fall in this category of models but uses some unique methods for testing.

Harris and Sabnis’s (1999) comprehensive overview of structural modeling lists the following specific examples that are suitable for structural modeling studies in the design phase.

- Shell roof forms of complex configuration and boundary conditions
- Tall structures and other wind-sensitive structures for which wind tunnel modeling is indicated
- New building structural systems involving the interaction of many components
- Complex bridge configurations such as multicell prestressed concrete box girder highway bridges
- Nuclear reactor vessels and other reinforced and prestressed concrete pressure vessels
- Ordinary framed structures subjected to complex loads and load histories, such as wind and earthquake forces
- Structural slabs with unusual boundary or loading conditions, or with irregular geometry produced by cutouts and thickness changes
- Dams
- Undersea and offshore structures
- Detailing

Small-scale models date back hundreds and even thousands of years ago. The earliest models were much different than present day in that they were used primarily for planning and
constructing purposes. In fact, they can be compared to the architectural models produced currently. The reason these early models are not comparable to today’s structural models is that strain, displacement, and force were not measurable quantities at the time. Therefore, some of the earliest structural modeling includes the Hoover Dam built in 1930 and the other great dams of that era built by the Bureau of Reclamation, Denver, CO (Harris and Sabnis 1999).

1.2.1.2 Advantages and Limiting Factors

The outstanding advantage of physical models over analytical models is their complete behavior characterization to the point of failure. Computer analysis programs have advanced tremendously over the years, but failure capacity of three-dimensional structures under complex loads remains difficult, if not impossible to predict.

Cost is an ever relevant issue for modeling and experimental studies. Scaled models provide savings on materials, fabrication labor, sensors, preparation, disposal, facilities, and laboratory equipment. A good example of cost savings is demonstrated by the fact that a concentrated load is reduced in proportion to the square of the geometric scale factor of the model.

However, despite the cost savings and behavioral advantages of using physical models, they do not fit in very well to typical design environments. Analytical models are typically less expensive and faster. For this reason, physical models are more suitable for special cases where analytical models are not adequate or feasible. Research institutes and facilities are one of the places that most commonly implement physical models. The research application that is most relevant to this thesis is the development of experimental data for verification of the adequacy of proposed analytical methods which will be expanded in later sections.
1.2.1.3 Examples

The following sections will give a brief overview of several physical models implemented for various purposes around the world. Starting with scaled models, the examples progressively include models that are relevant and contributed to the ideas incorporated into the model that is the subject of this thesis.

1.2.1.3.1 Scaled Models

To study changes in dynamic properties with respect to controlled damage, Ren and De Roeck (2002) developed a simple model of a reinforced concrete beam. Their efforts focused on applying analysis techniques to experimental data because of problematic differences from numerical simulations. The governing design objective was to have the lower modal frequencies to correspond to typical civil engineering structures like bridges which fall in the 0-20 Hz range. Since the natural frequencies of a beam are proportional to $h/L^2$, the height ($h$) and length ($L$) of the beam were adjusted to 0.2 m and 6 m respectively, resulting in a first frequency of about 20 Hz. To eliminate the effects of boundary conditions it was decided that a free support, test setup would be adopted whereby the beam would be supported by flexible springs that resulted in rigid-body eigen-frequencies. The reinforcement ratio was designed and checked to be within a realistic range at 1.4%. One drawback of the free test setup is that the static load test, which introduced damage by cracking and yielding, needed a different test configuration.

Lee et al (2003) developed a 1/15 scale model of Korea’s, Yeongjong Bridge floor system for the purpose of investigating local damage detection. Lee’s experiment illustrates an example of modeling a portion of a larger suspension bridge structure. The scale model dimensions were approximately 11 ft. by 8 ft. in plan view. Laboratory space, fabrication
convenience, and materials were a limiting factor in considering how to create the model. The model scale was chosen in reverse logic based on availability of materials. Steel was the material of choice, using tube and custom-fabricated channel sections in combination with plate. An interesting feature of the model is that 10 elastomeric bearings were used to simulate the hanger-suspension cable system. The model specimen was constructed and tested in the Structural Engineering and Earthquake Simulation Laboratory at the State University of New York, Buffalo. 48 channels of dynamic strain were instrumented to correspond to the in-situ structural instrumentation scheme. Using an impact hammer the structure was excited to examine 12 different damage cases. The damage cases included different levels of connection loosening, bearing removal (hanger failure), chord removal (chord fracture), and deck section loss (deck through-cracks). Damage detection was approached using a neural network and signal anomaly index. Overall, their damage detection methods were able to positively identify most damage cases, with the exception of a few false-positives (identifying damage that does not exist) and false-negatives (not identifying damage that exists).

Motavalli and Gsell (2004) aim to close the gap between complex, real-world applications and simplified laboratory experiments with a 1/1 scale model, cable stayed GFRP-bridge. Due to complexities in scaling a structure, the decision was made to design a 1/1 model which was most practical for a footbridge. Due to the large volume of laboratory space the 63 ft. long by 5 ft. wide footbridge was able to be constructed, not to mention its 25 ft. height. While the pylons and cables are made of steel material, both the girders and deck modules are glass fiber reinforced polymer (GFRP). Such a model aligns itself to current trends in civil engineering that focus on lightweight and slender bridges. The design considerations included bolted connections so that members can be replaced with pre-damaged members and loosening of
connections to simulate damage. This laboratory structure currently exists at the EMPA-laboratory, Switzerland where it serves as a research platform for the following topics and subprojects:

- Passive, semi-active and active vibration mitigation
  - Cable vibration mitigation using controlled magnetorheological fluid dampers
- Structural health monitoring
  - Fault detection by curvature estimation with fiber optic sensors
- Distributed, integrated and smart sensing
  - Adaptive tuned mass damper
  - Smart wireless sensing
- Advanced materials in structural elements

1.2.1.3.2 Benchmark Structures

Some of the ideas for the UCF bridge model are based on the work of Dyke et al. (2001) who tested a four story, two bay by two bay steel frame at the University of British Columbia. This scale model was the focus of a series of benchmark structural health monitoring (SHM) problems in damage detection that progressively increased in difficulty. Measuring 2.5m x 2.5m in plan and 3.6m tall, hot rolled steel sections were used construct this model. Excitation to the structure was provided by an electro dynamic shaker for which floor slabs were placed on each floor of the frame to provide more realistic mass distribution. A total of six damage cases were induced to the structure by loosening bolts and removing braces. The benefit of these benchmark studies is that several algorithms are being applied to the same structure and may be compared
side-by-side. Research in SHM aims to find the algorithms that will work most dependably for different types of structures whereby standardized methods may be implemented in the future.

More recently Dyke et al. (2003) published the problem definition for the first generation of benchmark structural control problems for the Bill Emerson Memorial, cable-stayed bridge. The goal of the study was to provide a testbed for the development of strategies for the seismic response control of cable-stayed bridges. In addition, the second phase of this benchmark problem for cable-stayed bridges was also published by Caicedo et al. (2003). For the second phase, more complex behavior was considered, including multi-support and transverse excitations.

Yoshida and Dyke (2004) also addressed the third-generation benchmark problem on structural control, and focused on the control of a full-scale, nonlinear, seismically excited, 20-story building. A semi-active design was developed in which magnetorheological (MR) dampers were applied to reduce the structural responses of the benchmark building. In addition to this paper, Ohtori et al. (2004) present the problem definition and guidelines of a set of benchmark control problems for seismically excited nonlinear buildings, focusing on three typical steel structures, 3-, 9-, and 20-story buildings designed for the SAC project for the Los Angeles, California region. All the papers just mentioned are linked by the common fact that they are geared toward benchmark studies.

1.2.1.3.3 Phenomenological Models

Two phenomenological models were created at the University of Cincinnati and Drexel University to the study the barriers obstructing successful SHM applications (Ciloglu et al. 2001). These plane grid models also represent the early generations of the bridge model that has
been developed at UCF. Phenomenological models are good for studying a broad population of structures. Specifically, the Cincinnati and Drexel grid are representative of the large population of medium-span, simply supported, steel stringer bridges. These models are very similar in that 3 x 2 x 3/16 in. steel tube sections were used for girders and cross-members. The Drexel grid was lengthened to 20ft compared to the 12ft Cincinnati grid. The general layout of the grid models includes three longitudinal girders that are supported at their ends, with six intermediate bays separated by cross members. One of the main thrusts behind the research on these models is to quantify the effects and controlled mechanisms of uncertainty. Many real life structures have been instrumented for the purpose of structural identification (St-Id) but have been mostly unsuccessful at answering real, practical questions and concerns of infrastructure owners and operators. St-Id methods were applied to both models concerning neoprene pads (Cincinnati) and composite action of a deck (Drexel). In addition to this specific study, the models were also developed as flexible structures that are able to be configured to simulate various damage scenarios. The abundance of bolted connection provides a wide range of opportunity for simulating a variety of real-life damage scenarios for bridge structures. To conclude this section of the literature review, the UCF grid model is the third generation of its kind to be designed, tested, and analyzed by the writer’s advisor and his colleagues (Aktan et al. 2000; Catbas et al. 2004b; Ciloglu et al. 2004).

### 1.2.2 National Bridge Inventory

The 2004 bridge inventory report for the United States indicates that 25.4% of the highway bridges are functionally obsolete or structurally deficient. Functionally obsolete bridges generally don’t meet the current criteria for deck geometry, load carrying capacity, clearance or
alignment. Structurally deficient bridges on the other hand, fall into one of the following three categories:

1. Restricted to light vehicles
2. Closed
3. Require immediate rehabilitation to remain open.

With such a large number of bridges in this condition, safety concerns become increasingly relevant along with the associated increase in user costs and delays.

One of the promising features of SHM techniques is that visual inspections may be complemented in a way that will drastically improve the reliability of the nation’s bridge infrastructure. Biennial inspections have proven subjective due to the nature of human error as well as weaknesses in the methods and qualification (Moore et al. 2001). It is recommended that visual inspections be coupled with standardized non-destructive testing methods to accurately assess a bridge’s condition. With advances in the condition assessment methods for bridges better decision making will result. Whereas an inspector may not be able to physically see micro-cracks, SHM instrumentation techniques are promising for detecting of such hidden problems. One of the main objectives of SHM is to detect, locate, and quantify possible damage before any type of failure so that critical decisions may be made using reliable information.

1.2.3 Recent Bridge Failures

To effectively conduct research in a laboratory setting, real problems should be identified and studied on realistic models. One premise for constructing the UCF bridge model is to identify methods and algorithms that will advance the state of the art in identifying structural failure caused by real-life damage scenarios. While the safety of the public is most important, there are several promising aspects of SHM that will save time, money, and improve future
A study by Wardhana and Hadipriono (2003) shows the distribution of 503 bridge failures between 1989 and the year 2000. Leading all other categories by far, hydraulics contributed to 53% of all bridge failures. The other categories and their respective percentages are: Collision (12%), overload (9%), deterioration (9%), earthquake (4%), fire (3%), construction (3%), ice (2%), fatigue-steel (1%), design (1%), soil (1%), and storm/hurricane (1%). It should be noted that failure of a bridge refers to either collapse or distress, which means the superstructure of bridge may or may not fall down. Statistically, these findings show how the majority of the problems with bridges came from incidents like scour, flooding, and collisions. These facts provide an excellent platform from which to build laboratory benchmark studies.

### 1.2.4 Damage Indices

Many of practiced damage detection methods involve visual inspection or localized experimental techniques. Major disadvantages to these methods include their vulnerability to subjective error and the inability to positively identify all damage locations. There is a fundamental need for damage detection methods that quantify the condition of a structure based on vibration characteristics that have global properties embedded them. While research efforts have shifted away from insensitive properties like the frequencies, changes in mode shape are promising for reliable damage detection. The four main points of damage detection are:

1. Detect damage
2. Locate damage
3. Quantify damage
4. Reliability-based decision making

Doebling et al. (1996) give a comprehensive overview of damage identification techniques used for structures and mechanical systems to detect changes in the vibration
characteristics. In this literature review, methods using modal frequencies, mode shapes, mode shape derivatives, and flexibility coefficients are summarized. These and other methods are applicable to a wide range of structures including beams, trusses, plates, shells, bridges, offshore platforms, civil structures, aerospace structures, and composite structures. There is also an updated version of this report (Sohn et al. 2003). The updated literature review is organized following the statistical pattern recognition paradigm reported in Farrar and Doebling (1999). This paradigm can be described as a four-part process: (1) Operational Evaluation, (2) Data Acquisition, Fusion, and Cleansing, (3) Feature Extraction and Information Condensation, and (4) Statistical Model Development for Feature Discrimination. Figure 2 shows a schematic of the processes of SHM.
Figure 2: Health Monitoring Diagram

\[
[f_{i,j}] = [U] [\Omega] [U]^T
\]


1.3 **Objective and Scope of Work**

The objective of this thesis is to develop a phenomenological laboratory model to serve as a platform for a wide range of research needs that include collaborative efforts among different researchers around the world. One such need is to demonstrate and compare state of the art technologies in sensors and acquisition systems. Coupled with the latest technology is the objective to use experimental data to validate theory in structural dynamics and evaluate promising damage indices. Benchmark studies are to be formulated both on a local level as well as an organized problem for researchers at other universities. After the mastery of these concepts and procedures, deployment for field studies should be a realistic action for individuals new to SHM.

**Table 1: Damage Detection Matrix**

<table>
<thead>
<tr>
<th>Damage Condition</th>
<th>Characteristics</th>
<th>Sensor Needs</th>
<th>Data Needs</th>
<th>Condition Evaluation Methods/Algorithms</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Healthy)</td>
<td>n/a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scour</td>
<td>o Small Settlement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Large Settlement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Loss of Pile Support</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss of Stiffness</td>
<td>o Reduce Girder Inertia</td>
<td></td>
<td></td>
<td>TBD*</td>
</tr>
<tr>
<td></td>
<td>o Semi-Rigid Connection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Hinge Formation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restrained Supports</td>
<td>o Worn Pads</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Corroded Bearings</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*TBD-To Be Determined

The scope of work includes the design of a plane grid model using steel members, bolted connections, and interchangeable parts to make a highly flexible test bed. Details will be given
for the design considerations, design calculations, fabrication drawings, and the instrumentation of the laboratory specimen. A brief review of structural dynamics and modal analysis will precede an overview of the damage and condition indices evaluated on the grid model. A detailed finite element model was generated for comparative analyses with the experimental procedures. Experimental and numerical studies include the simulation of real-life damage scenarios that have caused recent bridge failures and maintenance problems. Table 1 shows an incomplete damage detection matrix that may be partially completed using the findings of this thesis.
CHAPTER 2: LABORATORY MODEL DEVELOPMENT

2.1 Design Considerations

From the conceptual phase it was decided that a grid model would be an ideal structure to implement in the UCF structures laboratory. Knowing the type of structure desired, specifying the details of the laboratory model is critical. Basically, many different ideas were compiled and then implemented to the design specifications. A summary of the design considerations discussed in the following paragraphs is provided in Figure 6.

Since the model was not designed to replicate a specific structure, the dimensions were not assigned on a scaled order. Rather, the model was developed to explore the phenomena related to structural health and performance. The length and width of the model were designed to match the anchor points in the strong floor of the laboratory as well as conform to the space limitations of a laboratory setting. Figure 3 and Figure 4 show the anchor point provisions.

Figure 3: Anchor Base and Bolt
Figure 4: Installed Floor Anchor
Boundary supports were designed such that conditions across the spectrum would be modeled. Whatever the cause may be, supports can very easily deteriorate from a “freely” rotating pin or roller to some high-friction mechanism that transfers large moments. This is one of the many examples to be listed that the writers are seeking to model and detect using health monitoring techniques.

One of the most practical ways of making a structure changeable is to use bolted connections. As bolted connections are used in real-life structures, problems occur with fatigue, cracking, and other issues that cause a loss of stiffness. Using both moment connections and shear connections provides plenty of opportunity to loosen bolts and remove certain components to vary levels of damage and uncertainty. Scenarios like hinges and semi-rigid connections can be easily simulated.

To accommodate researchers working on the structure, a minimum height of 3 ft. was established for comfortable working conditions. In the future, a deck may also be added to the grid model. Since the same section is being used for all members the top of the grid will provide a good surface for deck support, with the exception of the plates which may be modified.

Some of the most important aspects of the laboratory model are in terms of its dynamic and static properties. To properly simulate phenomenon associated with short to medium span bridges, a frequency range of 1 to 40 Hz should not be exceeded for the lower modes. It is intuitive that the two main factors for this property are mass and stiffness. One challenge of choosing a good section for the girders and cross members was that the two-span case proposed only had 9ft spans, thus increasing the stiffness significantly over the single-span case.

Concerning the static outputs the controlling factor was determining if currently available sensors were capable of reading the respective quantities. For example, strain gage reading
should at least exceed 10 micro-strain and be read in no less than 1 micro-strain increments. The same principles go for the displacements and rotations.

After considering the previous issues in designing the grid model it was decided that an 18ft by 6ft structure would work well in the laboratory. To provide lateral stability, seven cross members were selected at 3ft spacing. In addition to the plan dimensions, 42in was specified for the column height in order to allow for workable space. The structure is long enough to simulate both single and two span bridges yet does not exceed the physical limitations in the laboratory. Single, two, and even skewed spans may be considered using the interchangeable column supports. As presented in the next section, the initial geometry assumption must be further verified in terms of how the structure will behave for given element cross sections available from steel suppliers. Figure 5 shows the initially assumed dimensions and layout of the grid.

Figure 5: Initial Geometry Assumption
Flexibility
- Simple supported, single span
- Continuously supported, two span
- Bolted connections
  - Simulate deterioration
  - Simulate damage
- Removable cross member connection plates
  - Moment connection
  - Shear connection

Boundary Conditions
- Rollers
- Pins
- Fixed

Loading
- Static weights
- Dynamic
  - Electro-Seis shaker
  - Impact Hammer
  - Ambient

Measurement
- Critical measurement locations
- Space for sensor attachment

Deck
- Accommodate deck connection
- Smooth surface for deck to rest on

Measurable Results
- Stresses and strains
- Deflection
- Mode shapes
- Frequencies

Able to Manufacture
- Constructability
- Available materials
- Physical limitations

Anchor Points
- 3 ft grid pattern of anchor points on strong floor
- Design of connection to rigid column

Strength Calculations Using LRFD
- Moment
  - Girders
  - Cross Members
  - Connection Plates (tension)
- Shear
  - Connections
  - Bolts
  - Coped ends
- Bearing plate requirements

Figure 6: Summary of Design Considerations
2.2 Preliminary Finite Element Model

Since the model specimen to be developed is for phenomenological studies, the behavior of the grid needed to be checked for the dynamic and static properties listed in the previous section. To check these quantities a simple finite element model (FEM) was started using the defined layout. The general logic of checking the FEM is presented in Figure 7.

- Choose model geometry
- Assign frame elements
- Assign support restraints
- Define load cases
- Assign standard loads
- Define static and dynamic analysis cases
- Run analysis cases
- Check outputs
  - Static (deflection, strain, rotation, stress)
  - Dynamic (frequencies, mode shapes)
- Record critical outputs
- Repeat for different frame sections and support conditions

Figure 7: General Design Procedure Using the FEM

The general design procedure was carried out using SAP2000 finite element (FE) software. Since the objective of using this model is only for estimating the behavior of the grid structure, the design FEM is considered to yield nominal results. It was determined that the grid would be defined by a length and width of 18ft and 6ft, respectively after considering the layout of the laboratory floor space and the ability to anchor to the floor. Figure 8 and Figure 9 show the
single and two span design models respectively. Beam elements were the elements of choice while no additional details were included in terms of accounting for additional inertia and mass from various sensors, bolts, and connection plates. Furthermore, the boundary support conditions assume that whatever is designed will act rigidly in the axial direction up to the point of support. In actuality W12x26 column supports are specified in the design for column supports.

Even though a purely analytical study of an FEM yields results for certain sections, material availability is always an issue. It was clear from the beginning of the design phase that one of the smallest sections available would be preferable but other alternatives arose. One such case was a company offering discounted prices for using particular wide flange sections. Therefore, specific analyses were compared to see if these sections would work, in addition to the general analyses for the other sections.

2.2.1 Static Results

Design loads consisted of 100 lb point loads at various nodes. The details of the load cases are not shown here due to the large number of cases and their intuitive nature. To give a brief
summary, the negative moments and stresses were found by loading both spans while the positive moments, rotations, and deflection by loading one span.

100 lb nodal loads were chosen because of weights that actually exist in the lab. It would not be realistic to place multiple 600 lb loads due to the impossibility of actually carrying this out with currently available or expected equipment. Furthermore, if an increased load is used in the future, the static results may be linearly interpolated if the steel stresses remain in the linear region.

Although the experiments of this thesis focus on dynamic testing, static results remain an important factor in the design of this laboratory specimen. The first reason for finding the static responses is to determine if the structure will sustain any design loads. As previously mentioned, this bridge model is different than most in that ultimate load testing is not of interest, yet lesser loads may still be applied. More important to the objectives of this thesis was to determine the resolution and measurement ranges required for the accelerometers, strain gages, tilt meters, and displacement transducers. In this particular case, a variety of sensors, to be described later, were already available for which their specifications were verified with the static results. The two most insensitive quantities were deflection and rotation for the two-span case due to the relatively short spans and high stiffness.

Selected results from the critical load cases are displayed in Table 2. Looking at the deflection column of Table 2 it is noticeable how much more flexible the single-span case is. The trend remains the same, where the single span results are of the largest magnitude. Of course, the large stress should be carefully noted for design purposes, but the smaller values are of more interest for ensuring quality data can be collected with purchased sensors. After consulting the manufacturer’s specifications for various sensors, it was determined that these values would be
sufficient, although near the minimum end of range and resolution. A quick example shows that the micro-strain levels of Table 2 are well within the 3000 micro-strain range of the Geokon vibrating wire strain gage, model 4100. Additionally, any incremental loads of 25 or 50 lbs will cause strain levels to fluctuate well over the 0.1 micro-strain resolution.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\Delta_{\text{max}}$ [in]</th>
<th>$\theta_{\text{max}}$ [deg]</th>
<th>$\sigma_{\text{max}}$ [ksi]</th>
<th>$\mu\varepsilon_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Span</td>
<td>0.051</td>
<td>0.01</td>
<td>-2.93</td>
<td>-101.1</td>
</tr>
<tr>
<td>Skewed</td>
<td>0.158</td>
<td>0.23</td>
<td>3.9</td>
<td>134.5</td>
</tr>
<tr>
<td>Single-Span</td>
<td>1.142</td>
<td>0.95</td>
<td>10.87</td>
<td>374.7</td>
</tr>
</tbody>
</table>

### 2.2.2 Dynamic Results

To check the dynamic properties of the grid model, modal analysis cases were run using SAP2000. Using the restraints, geometric, and material properties of the grid, SAP2000 is able to run an eigenvalue analysis to determine the modal frequencies. Once again, the objective of these preliminary analyses was to ensure that the frequency band of the model was not too high and unrealistic for short to medium-span bridges. Before running the analyses, the goal was to keep the lower modes less than 40 Hz, which turned out to be satisfied. Table 3 shows how the first three vertical modes for all three cases are less than 40 Hz. The single and two-span cases even contain four vertical modes that are less than 40 Hz. These preliminary results again reinforce the notions that the model was being designed in a practical and realistic manner.
Table 3: Dynamic Design Properties

<table>
<thead>
<tr>
<th>Mode</th>
<th>Two-Span [Hz]</th>
<th>Skewed [Hz]</th>
<th>Single-Span [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.66</td>
<td>16.54</td>
<td>5.81</td>
</tr>
<tr>
<td>2</td>
<td>22.80</td>
<td>22.70</td>
<td>5.96</td>
</tr>
<tr>
<td>3</td>
<td>34.84</td>
<td>34.85</td>
<td>22.66</td>
</tr>
<tr>
<td>4</td>
<td>34.95</td>
<td>51.33</td>
<td>22.80</td>
</tr>
<tr>
<td>5</td>
<td>93.53</td>
<td>71.20</td>
<td>51.35</td>
</tr>
</tbody>
</table>

![Modal Frequency Diagrams](image)

Figure 10: Vertical Mode Shapes for Single, Two, and Skewed-Span Cases
2.3 **Design Calculations**

After the preliminary FEM analyses were iteratively run and updated, hand calculations were performed to verify that the selected sections were adequate for the prescribed loads. The lab specimen will not be tested to its ultimate strength which makes the design process more of a verification procedure. Typical quantities of bending moment and shear are checked for the members. Some of special details that were checked include the coped ends of the cross members and bolted connections. All design calculations were made using specifications from the *AISC Manual of Steel Construction, LRFD 3rd edition*. The details of the calculations can be found in Appendix A.

2.4 **Fabrication Drawings**

The last step before erection of the physical structure in the laboratory was to have the parts fabricated. To ensure the practicality and quality of the finished product, several companies were consulted both about the material specifications and fabrication techniques. An interesting situation came up during the consulting process when a local steel fabricator suggested that the steel sections could be donated if they were of a particular size that was stocked. Unfortunately, particular details did not enable this offer to be taken. Once the fabrication details were agreed upon, a set of CAD drawings was given to the company awarded the job. A complete set of the fabrication drawings are available in Appendix B.
2.5  **Physical Model Details**

2.5.1  **Primary Structure**

Similar to an overpass one might see while driving along the interstate, the grids main configuration has two clear spans with the beams remaining continuous across the middle supports. As seen in Figure 11, the model has two 18 ft. girders in the longitudinal direction to transfer the loads to the supports. Lateral stability is provided by transverse bracing at 3 ft. intervals from end to end of the grid. Each member of the test structure has the same cross-section. After analyzing the same geometry for many different cross-sections, a S3 x 5.7 was found to be the most desirable in terms of modal frequencies, deflections, rotations, stresses, and strains that are representative for typical short to medium span highway bridges. In addition, the structure is doubly symmetric with typical parts that are interchangeable. For example, if unrepairable damage is to be simulated on a cross-member, a new piece may be easily inserted after the test.

Figure 11: 3-D CAD Model
2.5.2 Column Supports

Another example of interchangeable parts on the grid is the column supports. The two middle columns can be easily removed to analyze a simply supported structure or repositioned to any other connection point that would simulate unequal or skewed spans. These different scenarios are possible due to the typical bolt patterns and sizes around the grid. Figure 12 shows a typical column that is 42 in. tall. Each column was designed to rigidly support the grid superstructure. To simulate a “fixed” restraint at the floor, 1 in. steel plate was specified. Coupled with W12x26 column and 2 ½ in. diameter anchor bolt, the 18 in. length of steel plate provides sufficient rigidity to prevent rotations at the floor level. A close-up of the column base and anchor detail can be seen in Figure 13.

Figure 12: Typical Support Column
Figure 13: Anchor Detail for Support Columns
2.5.3 Member Connections

Each cross member is connected to the girders by two angle clips and two cover plates, using a total of 30, ¼ in. bolts for each typical connection. One special detail that had to accommodated was that the inside face of the flanges are sloped and therefore require a special, beveled washer. An interesting note is that the beveled washers accounted for 2/3 of the cost of all the nuts, bolts, and washers. The angle clips provide a “shear connection” while the cover plates on top and bottom form a “moment connection.” The advantage to this connection is that there are many bolts to loosen and even remove to analyze scenarios such as zero moment transfer and “semi-rigid” connections. As previously stated, the connections are bolted together with several bolts so that the stiffness may be changed in multiple degrees. Detecting any damage to connections is very important since they are often referred to as the “weak link.” Typical connections can be seen in Figure 14 and Figure 15.

![Figure 14: Moment Connection](image1.png) ![Figure 15: Shear Clips](image2.png) ![Figure 16: Boundary Support](image3.png)

2.5.4 Boundary Supports

With the designed supports of Figure 16, almost any boundary condition can be modeled. The supports were machined specifically for the structure and special consideration was taken
into account in choosing the boundary support because of the availability of parts and cost of machine shop labor. Other options included factory made bearings but the translation degree of freedom (DOF) becomes harder to accommodate. The advantages to using this type of mechanism is its ability to be easily reconfigured and the fact that they have been used in other studies where their effectiveness has already been proven (Ciloglu et al. 2001).

Examples of the different restraints include pin supports, rollers, fixed support, semi-fixed support, and any type of elastic material like neoprene pads. Although the round bar is placed between the grid and column, bolts may be extended through from top to bottom for restraining translation or rotation. To fully ensure a restraint on rotation the rollers may be removed and then place bolts through the top and bottom roller blocks. If elastomeric pads are to be used, then the rollers and blocks may be removed altogether so that a pad is the only medium between the grid and columns. This versatility will provide many opportunities for exploration and documentation of corresponding behavior of the grid system. Any proposed methods in SHM need to be verified on boundary conditions that range from transparent to uncertain because of the significant effects that are imposed to a bridge’s dynamic and static behavior (Catbas and Aktan 2002).
CHAPTER 3: MODAL ANALYSIS AND TESTING

3.1 Modal Theory

Modal analysis is considered one of the most powerful techniques in determining the actual state of a structure using modal parameters. Modal parameters of a system refer to frequencies, damping factors, modal vectors, and modal scaling. While the modal parameters may be determined analytically or experimentally, sometimes the system is too complex for analytical methods. If a system’s modal parameters are not well understood, experimental data may be used to verify or calibrate the analytical model. The details of a modal test setup will be given in subsequent chapters of this thesis. For complete coverage of structural dynamics and modal analysis the indicated sources should be referred to since this discussion is limited to the basic concepts (Allemang 1999; Chopra 2001).

Modal analysis uses different domains, which must be carefully understood, to describe the characteristics and response of a system. Typically, the time, frequency (Fourier), and Laplace domains are used. The relationship between these domains and the systems are integral transforms (Fourier and Laplace) that reflect the information contained by the governing differential equations transformed to each domain (Aktan et al. 1997).

3.1.1 General Formulations

To start, the single DOF system of Figure 17 will be considered. As with most complex methods, understanding the basic case enables one to grasp the advanced applications, which are
multiple DOF systems in this case. Despite the trivial solution of a single DOF system, linear superposition of them can create a multiple DOF system.

![Figure 17: Single DOF System](image)

Recall from structural dynamics that the general equation of motion for a single DOF system is represented as follows:

\[
[M] \ddot{x} + [C] \dot{x} + [K] x = f \]

Equation 3-1

Where,

- \( M \) = Mass
- \( C \) = Damping
- \( K \) = Stiffness

Note that for single DOF systems, the matrices and vectors of Equation 3-1 are 1x1 (scalar).

The Laplace transform of this equation assuming all initial conditions are zero yields:

\[
[s^2[M] + s[C] + [K]]X(s) = \{F(s)\}
\]

Equation 3-2

Where the Laplace domain (s domain) can be thought of as complex frequency (s = \( \sigma + j\omega \)).
Let,

\[ B(s) = [s^2[M] + s[C] + [K]] \]

Then Equation 3-2 can be written as,

\[ [B(s)][X(s)] = \{F(s)\} \]

where \([B(s)]\) is referred to as the system impedance matrix or just the system matrix.

Premultiplying Equation 3-3 with the inverse of \([B(s)]\) yields:

\[ [B(s)]^{-1}\{F(s)\} = \{X(s)\} \]

Then,

\[ [H(s)][F(s)] = \{X(s)\} \]

Defining the transfer function as the inverse of the impedance matrix:

\[ [B(s)]^{-1} = [H(s)] \]

The frequency response function is the transfer function (surface) evaluated along the \(j\omega\) (frequency) axis. Then,

\[ [H(s)]_{j\omega} = [H(\omega)] \]

A sample frequency response function (FRF) for a single DOF system is shown in Figure 18. The time domain representation of a single DOF system is an impulse response function (IRF). Figure 19 shows an example of an IRF. Comparing the FRF and IRF, they are system responses in different domains.
One of the most commonly used practices in experimental modal analysis applications is to use FRF’s. FRF’s between different spatial input and output degrees of freedom are measured...
with designed temporal information. The relationship between input and output is given in the formulation as:

\[ \{H\} \{F(\omega)\} = \{X(\omega)\} \]  

Equation 3-6

A FRF can be given in partial fraction form as follows (Aktan et al. 1997):

\[ H_{pq}(\omega) = \sum_{r=1}^{N} \left[ \frac{(A_{pq})_{r}^*}{j\omega - \lambda_r} + \frac{(A_{pq})_{r}}{j\omega - \bar{\lambda}_r} \right] \]  

Equation 3-7

Where,

- \( N \) = Total number of DOF of the system
- \( r \) = \( r \)th mode of vibration of the system
- \( p \) = Response point
- \( q \) = Reference point
- \( \lambda_r = S_r + j\omega_r \), \( r \)th pole or eigenvalue of the characteristic equation
- \( (A_{pq})_r = \) Residue of the \( r \)th mode

For an \( N \) DOF system with \( N \) distinct modes and the value of an FRF at a particular frequency can be expressed in partial fraction form as follows:

\[ H_{pq}(\omega) = \frac{(A_{pq})_{1}^*}{j\omega - \lambda_1} + \frac{(A_{pq})_{1}}{j\omega - \bar{\lambda}_1} + \frac{(A_{pq})_{2}^*}{j\omega - \lambda_2} + \frac{(A_{pq})_{2}}{j\omega - \bar{\lambda}_2} + \ldots + \frac{(A_{pq})_{N}^*}{j\omega - \lambda_N} + \frac{(A_{pq})_{N}}{j\omega - \bar{\lambda}_N} \]

From an experimental perspective, the above equation dictates that FRF’s are evaluated for an \( N \) degree of freedom system at \( i \), number of frequencies. For example, a FRF \( H_{23} \) (response \( p \), at point 2 and input \( q \), at point 3) acquired with an 800 frequency spacing (i.e. \( \omega_1 \ldots \omega_{801} \)) for an \( N=15 \) DOF system can be expressed as:
Parameter estimation methods can be grouped as Time Domain Algorithms, Frequency Domain Algorithms, or Spatial Domain Algorithms. Complex Mode Indicator Function (CMIF) is a robust method that is relatively new and provides a more objective method to system identification. The following paragraph gives a brief overview of the CMIF method and it should be noted that CMIF is method used for parameter estimation of the test results presented in this thesis. To further understand the details of CMIF refer to (Catbas et al. 2004a).

The CMIF method is a spatial domain method where the eigenvectors are estimated directly by using Singular Value Decomposition (SVD) of the measured FRF matrix. A plot of the singular values of the FRF matrix (CMIF Plot) is used to determine the location and number of eigenvalues in a set of data. Peaks in the CMIF plot are locations of the eigenvalues. Figure 20 shows an example of a CMIF plot. Obviously, picking the points from the CMIF plot requires some manual process. At the peaks the singular value vector (CMIF vector) is the best least squares estimate of the eigenvector for the selected peak. The CMIF vector is used as a spatial filter to compute an Enhanced Frequency Response Function (EFRF) from weighted average of the FRF matrix. The resulting EFRF in the vicinity of the selected peak looks like the FRF.
measured on a Single Degree of Freedom (SDOF) system. A simple SDOF estimation algorithm can be used to estimate the eigenvalues (frequency and damping) and the modal scale factor.

Figure 20: CMIF Plot

3.1.3 Modal Assurance Criteria

For different modal tests, i.e. damage cases or time variant reasons, extracted mode shapes are often compared using what is commonly termed Modal Assurance Criteria (MAC). Though a structure may yield similar modal frequencies for two separate tests, the mode shapes should be checked for their correlation. If the two modes are identical a value of one will result
when checked by the MAC. On the other hand, if the modes are totally unrelated a value of zero will result. The MAC that compares mode i and j has the form

\[
MAC_{i,j} = \frac{\left| \sum_{k=1}^{n} (\phi_i)_k (\phi_j)_k \right|^2}{\sum_{k=1}^{n} (\phi_i)_k (\phi_i)_k \sum_{k=1}^{n} (\phi_j)_k (\phi_j)_k},
\]

Equation 3-8

where \( (\phi)_k \) is an element of the mode-shape vector and the asterisk denotes complex conjugate. Typically, a value greater than 0.9 indicates two modes are correlated (Farrar and Jauregui 1996). MAC is not affected by scalar multiples.

### 3.1.4 Dynamically Measured Flexibility

First developed by Maxwell in 1864, the flexibility is a displacement influence coefficient of which the inverse is stiffness. Flexibility is a significant quantity due to the importance of mass, stiffness, and damping to the characterization of a structure.

To find the modal flexibility of a structure one can use modal parameters from experimental testing. Flexibility has been proposed as a reliable signature reflecting the existing condition of a bridge (Catbas and Aktan 2002). For this reason, flexibility methods in bridge health monitoring are promising. In a comparative fashion, the difference between two sets of flexibility can be observed from two different modal tests. The transformation of the natural frequencies and mode shapes to a unit load flexibility matrix is given by the expression:

\[
[f_{i,j}] = [U][\Omega][U]^T
\]
\[
\begin{bmatrix}
  f_{1,1} & f_{1,2} & \cdots & f_{1,n} \\
  f_{2,1} & f_{2,2} & \cdots & f_{2,n} \\
  \vdots & \vdots & \ddots & \vdots \\
  f_{n,1} & f_{n,2} & \cdots & f_{n,n}
\end{bmatrix}
\begin{bmatrix}
  \phi^1(1) & \phi^2(1) & \cdots & \phi^m(1) \\
  \phi^1(2) & \phi^2(2) & \cdots & \phi^m(2) \\
  \vdots & \vdots & \ddots & \vdots \\
  \phi^1(n) & \phi^2(n) & \cdots & \phi^m(n)
\end{bmatrix}
\begin{bmatrix}
  \frac{1}{\omega_1^2} & 0 & \cdots & 0 \\
  0 & \frac{1}{\omega_2^2} & \cdots & 0 \\
  \vdots & \vdots & \ddots & \vdots \\
  0 & 0 & \cdots & \frac{1}{\omega_m^2}
\end{bmatrix}
\begin{bmatrix}
  \phi^1(1) & \phi^2(1) & \cdots & \phi^m(1)^T \\
  \phi^1(2) & \phi^2(2) & \cdots & \phi^m(2) \\
  \vdots & \vdots & \ddots & \vdots \\
  \phi^1(n) & \phi^2(n) & \cdots & \phi^m(n)
\end{bmatrix}_{n \times m}
\]

\[
f_{i,j} = \sum_{i=1}^{m} \frac{\phi^k(i)\phi^k(j)}{\omega_k^2}
\]

Equation 3-9

Where,
- \( m \) = Total number of modes identified experimentally
- \( n \) = Total number of measurement points
- \( \phi^k(i) \) = Modal vector coefficient at the \( i^{th} \) measurement point of the \( k^{th} \) unit mass-normalized mode vector
- \( f_{i,j} \) = Flexibility coefficient at the \( i^{th} \) point under the unit load at the point \( j \)
- \( \omega_i \) = \( i^{th} \) frequency (rad/sec)

This formula is an approximation to the real flexibility matrix because of the truncated number of modes obtainable in practice. Modal truncation effect should be minimized with an appropriate number of experimental modes identified. It is necessary to study the truncation effect of modal number in the above formula as the mode number obtained from the experiment is always limited.

Bernal and Gunes (2004) describe a flexibility based damage characterization technique and its performance applied to Phase 1 of the benchmark study developed by the IASC-ASCE SHM Task Group. Catbas et al (2005) also use modal flexibility to evaluate the condition of two real-life bridges using pseudo-flexibility loads along the girders. In this paper, the modal flexibility is obtained from the frequency response measurements.
3.1.5 Mode Shape Curvature

To detect damage, mode shape curvature is one index that examines the modes shape vectors. Any change in structural behavior may be reflected in the dynamic properties of the modal vectors. Going back to mechanics theory, curvature, bending strain, and deflection are related by the following equation:

\[
\frac{d^2 v}{dx^2} = M/EI = \frac{\varepsilon}{t}
\]

Equation 3-10

where \( v'' \) is the curvature at a section, \( M \) is the bending moment, \( E \) is the modulus of elasticity, \( I \) is the second moment of inertia, and \( \varepsilon \) is the strain at \( t \) from the neutral axis at that section.

Since curvature is a function of stiffness, any reduction in this property from damage should be evidenced by an increase in curvature at a particular location. This behavior can be detected through examination mode shapes, which are really just displacement vectors. Although this concept has been introduced in the context of modal vectors, this damage index will be implemented in this thesis in terms of displacement vectors resulting from uniform loads applied to dynamically derived flexibility matrices. The details of the analysis will be explained in later sections. To calculate the curvature of the displacement vectors, a numerical derivation technique is used. Specifically, the central difference approximation is used as follows:

\[
v_{q,i}'' = \frac{v_{q-1,i} - 2v_{q,i} + v_{q+1,i}}{\Delta x^2}
\]

Equation 3-11

where \( q \) represents the elements of the \( i^{th} \) displacement vector and \( \Delta x \) is the length between measured displacement points.
3.2 Equipment

To conduct modal testing, the only required sensors are accelerometers for the response and a load cell for the input force. A few examples of sensors for measuring input and output can be seen in Figure 21 and Figure 22. One consideration for large-scale, civil infrastructure is that generating enough energy to excite the structure may be impractical or costly. Therefore, modal methods are becoming more reliant on measured outputs from ambient vibrations which are not measurable. Although accelerometers can be used alone, additional sensors like high-speed strain gages are being used in combination for various condition assessment indices. To record and view the actual data from these sensors, appropriate data acquisition hardware is required that can often be specific to different types of sensors. For a complete listing of available sensors in the laboratory and their specifications, see Appendix C.

The sensors and input equipment in the following figures are samples of the technology being implemented on the grid model. Figure 21 shows various accelerometers that are some of the top of line technology in terms of resolution and practical usage. The seismic accelerometer to the left is capable of measuring up to 800 Hz. Although the capacitive and wireless sensor may not have such a wide frequency band, they are still advantageous for applications where space and connectivity is restricted. When conducting modal tests, the impact hammer and shaker are important tools. For typical input-output tests the hammer is a widely used method to input energy to the structure to excite the resonant frequencies over a finite band. The limitation of the hammer in real life applications is its mass and tip hardness. When larger quantities energy are required the shaker becomes more ideal and can also be used to verify specific modes. Exciting a particular mode only involves tuning a sine wave with the respective frequency.
To begin dynamic testing of the laboratory model, an instrumentation plan was needed. Taking into consideration both the available sensors and behavior of the grid, sensors were strategically placed to monitor the mode shapes, strains, and displacements. For example, accelerometers should not be primarily placed at locations where only nodal points are observed in the mode shapes (supports…). After studying the dynamic behavior of the FEM, the
The instrumentation plan shown in Figure 23 was proposed and then partially implemented as the various sensors became available. Figure 24 shows the existing setup for the bridge model in the UCF structures laboratory. Included are accelerometers, hammer, electro-seis shaker, shaker amplifier, signal conditioners, signal digitizer, and desktop computer. Table 4 and Table 5 show some of the characteristics of the sensors being used in on the grid model and other SHM projects in the laboratory.

![Figure 23: Proposed Instrumentation Plan](image-url)
Table 4: Dynamic Sensors Currently Instrumented on Grid

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Quantity</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB 393 Accelerometer</td>
<td>13</td>
<td>High Frequency Vibrations (0.01-1200 Hz)</td>
</tr>
<tr>
<td>PCB 3700 Series Accelerometer</td>
<td>3</td>
<td>Low Frequency Vibrations (0-150 Hz)</td>
</tr>
<tr>
<td>Wireless Accelerometer</td>
<td>3</td>
<td>Low Frequency Vibrations, Rotations</td>
</tr>
<tr>
<td>Sony Video Camera</td>
<td>1</td>
<td>High Resolution Imaging</td>
</tr>
</tbody>
</table>

Table 5: Static Sensors Instrumented on Grid

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Quantity</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geokon 6” VW Strain Gage</td>
<td>8</td>
<td>3000με range, 0.1με resolution</td>
</tr>
<tr>
<td>Geokon 3” VW Strain Gage</td>
<td>6</td>
<td>3000με range, 0.1με resolution</td>
</tr>
<tr>
<td>Geokon VW Tiltmeter</td>
<td>2</td>
<td>+/- 10 deg. range, +/- 10 arc sec sensitivity</td>
</tr>
</tbody>
</table>

Figure 24: Laboratory Monitoring Setup

3.4 **Data Needs**

Essential to a good test plan, whether in the field or laboratory, is a detailed document that specifies the data requirements. Obviously, data will continuously stream in from the various sensors such as accelerometers and just stating that acceleration data needs to be stored is far less than required. For the individual or groups of sensors, all details should be spelled out clearly as
to the sampling frequency, voltage range, time, etc… (Table 8). In addition to the acquisition settings for the sensors, consideration should be given to the file format for which the data will be saved in. If the data is given to particular parties then the data files and processed information should be compatible to their computer software.

Pertaining to the actual data, a file structure may be suggested or required. Subsequent use of that data should also be outlined in terms any digital signal processing techniques. For example, different types of windows may be used or excluded. Different dynamic properties may also be specified in terms of dynamic properties (modal frequency, damping values, mode shape vectors, and modal scaling).

Finally, emphasis should be placed on labeling cables and channels in a logical and organized manner, making sure that all details are documented. Each sensor should be assigned to a spatial location on the structure, global measurement direction, and acquisition channel. Predefined locations and quantities of sensors should be explicitly documented for the use of the test group. In the end, the file structure, cable labels, and sensor documentation make for a successful test. Without this essential aspect of organization and specifications, massive amounts of data will be impossible to understand and draw conclusions from. The details of the test plan for the experimental studies are discussed in the next chapter.
CHAPTER 4: BENCHMARK STUDIES

4.1 History

To address the many needs of Bridge Health Monitoring (BHM) the Bridge Health Monitoring committee was formed under the auspices of the International Association for Bridge Maintenance and Safety (IABMAS). They met collectively for the first time during the 2004 IABMAS Conference in Kyoto, Japan. The three focus areas of the committee are 1) current BHM applications, 2) synergies between bridge management and health monitoring, and 3) research needs for the development of a benchmark study in BHM. In this committee, there is a strong participation from the Far East as well as from Europe. In addition, there are members of ASCE Engineering Mechanics Dynamics Committee, the newly formed ASCE Structural Health Monitoring and Control (SHMC), International Association of Structural Control (IASC) and International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII). This wide spectrum of participation will provide different perspectives and also help reconcile different approaches.

Individuals were selected to lead the efforts in these areas and have since made varying levels of progress in research, drafting documents, and requesting valuable feedback from agencies like DOT. The members of focus area 3 have established a benchmark problem for BHM of which a numerical component is the first phase. An experimental component of the benchmark study will come in later phases. While obtaining results in a timely manner is important, the general procedure will be approached very carefully so that sufficient detail is
given to every aspect of the study for thoroughness. Reports on progress, research studies, and findings will be made during the 2006 IABMAS meeting in Porto, Portugal.

4.2 **Motivation**

This benchmark problem will enable community participation in applying multiple approaches to one specific problem. Each investigator’s methods will be objectively compared and contrasted for realistic but progressively more challenging damage scenarios. Benchmark studies have also proven effective to identify limitations in current state of the art techniques, providing valuable information to define future research efforts. Previous studies include several ASCE benchmark studies such as the 4 story steel frame located at the University of British Colombia, Vancouver ([http://wuscel.cive.wustl.edu/asce.shm/](http://wuscel.cive.wustl.edu/asce.shm/)) (Dyke et al. 2001) and other examples include the 91/5 highway over-crossing in southern California ([http://www.ruf.rice.edu/~nagaraja/](http://www.ruf.rice.edu/~nagaraja/)). In Europe, a study on the Swiss Z24 bridge (Kramer et al. 1999) brought several researchers together for collaboration. The laboratory studies at Drexel University provided data to interested researchers (Ciloglu et al. 2004). *The aim is not to repeat past studies, but to demonstrate accumulated knowledge in solving realistic problems in BHM and to enhance the currently available techniques.*

As previously mentioned, many challenges separate the theory and successful practice of BHM. Several relevant issues pertaining to real-life application of BHM are listed below and should be examined within the context of this benchmark problem.

- **Decision-making**: One fundamental challenge in the application of this technology is the question of whether or not the information provided is suitable for guiding the bridge
owner on the best action to take, or if the results of the analytical methods need to be framed in a different way.

- **Effectiveness of BHM methods for non-stationary inputs**: Typically considered are either ambient response data or forced response data in applying a BHM technique to detect structural damage as well as to monitor the operating condition. However, short-span bridge structures are subjected to traffic loading, which is immeasurable and can often dynamically interact with the structure itself. Are the responses due to traffic useful for BHM? Should ambient responses be used?

- **Model development and updating**: The bridge system response (static as well as dynamic) is time variant. What are the methods to best characterize the structure e.g. with one average model, or upper/lower bounds or multiple models? The capabilities of current model-updating techniques should be investigated due to the fact that recommendations on repair and retrofit priorities for the bridge owners will be based at least in part on the future capacity of the structure and the expected remaining lifetime. Decisions such as these may require updating the state of the model to provide an accurate snapshot of the structure at given point in time for performance evaluation and simulations.

- **Impact of uncertainties in BHM**: Realistic sources of uncertainty should be investigated. For instance, frequencies and mode shapes cannot be precisely measured experimentally under real-world conditions. Nonlinearities, sensor noise, boundary conditions, environmental factors, non-stationary inputs, etc will all contribute to errors in the final results. Unknown/uncertain construction and structural details and modeling errors will also contribute to uncertainty in the information used for damage detection. What are the impacts of these issues for real-world damage detection?
- **Indeterminate structures**: Many bridges are statically indeterminate. It is documented that the indeterminacy poses problems especially when coupled with environmental effects. What are means for overcoming these problems for the analysis and evaluation with various experimental and analytical techniques?

- **Sensor, data acquisition selection**: A variety of sensors and data acquisition systems may be suitable for measuring the static/dynamic responses of a typical highway bridge. Different sensors and data acquisition might provide varying levels of information and accuracy. Thus, an evaluation of several sensors and analytical methods in terms of noise levels, bandwidth, sensitivity, usefulness etc should be conducted to establish the effectiveness of each sensor. Additionally, combinations of several methodologies using different responses may be implemented for redundancy and to test for the presence of false positives.

- **Implementation issues**: Standardization of available methods is critical for practical implementation. Data analysis, data fusion and information management should be examined to tie all of these issues together to develop systems that can meet the needs of the bridge owners.

### 4.3 Overview

Chosen for the initial phase of the benchmark problem is the bridge model at the University of Central Florida. Details of the structure were described in previous sections and can be obtained from [http://people.cecs.ucf.edu/catbas/](http://people.cecs.ucf.edu/catbas/). Data will also be made available at the same website for the participants. This benchmark problem will start as a simple problem using numerical studies on a finite element model (Figure 25) of the laboratory specimen. The use of
numerical models allows one to control the problem and isolate each issue regarding implementation of the problem. Then experimental studies can be pursued with greater confidence. This was previously found to be a particularly helpful approach, especially for encouraging investigators new to this area to participate.

An overview of the benchmark problem to be distributed world-wide has just been described in previous paragraphs. Although the official benchmark problem has not been distributed, the writer has been able to conduct a trial run of the numerical and experimental simulations with damage detection applications for this thesis. The numerical studies conducted by the writer have contributed significantly to the development of the numerical phase soon to begin in terms of numerical, geometric, technology, and structural properties of the grid. Even though the experimental phases have not been formulated, the experimental data that has been
generated within the scope of this thesis may be used in the future. Eventually, studies will expand to real life bridges as an extension of this initial phase of the benchmark studies.

### 4.4 Numerical Simulations

As the first step in applying damage detection methods, the following numerical study was conducted on the two-span grid model in the UCF structures laboratory. The benefit of numerical studies can not be emphasized enough in how they bring about a better understanding of the problem and applicable methods. First, the FEM’s of the structure were developed, and then the selected damage simulations were run to determine if any detectable changes occurred. Results will not be presented in the following section but are reserved for the next chapter.

#### 4.4.1 Detailed Finite Element Model

SAP2000 was the FEM software of choice for the numerical studies, as used in the design model. The main differences from the design model and detailed model shown in Figure 26, are that the joint regions were discretized and columns added. For the entire structure, beam elements were used for respective elements. To better characterize the joint region, small elements were added to include the effects of the connection plates. For a simple assumption, only the area of the plates that contact the S3x5.7 beams were taken to contribute to the structural behavior. The small elements were just S3x5.7 sections with a modified flange thickness and cross-section depth. These assumptions neglect any slippage between the girders and connection plates for the composite behavior. It is important to recognize the limitations and implications of each assumption, but issues related to model calibration and optimization for the grid model are under investigation by a colleague and are not in the scope of this thesis.
Another issue for the joint region under consideration is any additional mass that exists in reality but is not included in the model. After thinking carefully about the physical model, it was determined that mass should be included for the excess plate areas, connection bolts, and accelerometers. These are three sources that may not be significant by themselves but are quite significant when added together. To account for these masses, lumped masses were added to the girder and cross-member intersections of the grid. Mass and stiffness are the main factors to drive the dynamic response of the structure, so these details prove to be important. Detailed calculations for these quantities can be found in Appendix D.

Several additional details were considered for the numerical model that were not in the design model. Some of these have just been described, but the remaining detail of the numerical model is the interaction between the columns and grid superstructure with the round bar and plates as a medium. It was decided that the column supports should be included in the model.
despite their relatively rigid behavior in comparison to the grid superstructure. Starting at the strong floor level, the anchor was assumed to enforce a fixed type behavior. This assumption can be justified by the large steel plates that extend from either side of the bolt creating a sufficient moment arm for resistance. Secondly, the interaction of the superstructure and columns were idealized by releasing the moment, torsion, and shear resistance in the respective directions of Figure 28. Obviously, some DOF’s must be restrained to maintain stability. In actuality the scalloped bearing support provided stability to the grid in addition to bolts inserted through the top and bottom plates to create a “pin” support. The bolts just mentioned are placed on the contracting side of the support and not tightened so that rotational movement is still allowed. Figure 27 shows the physical condition of a pin-type connection on the grid.

![Figure 27: Pinned Support](image)

![Figure 28: FEM Released DOF's](image)

To more efficiently work with the outputs from the FE software, each node in the model was labeled strategically. For example, the nodes corresponding to DOF of interest were labeled consecutively so that tabular results could be extracted easily. The node labels are not shown here due to the relevance, but Figure 29 shows the DOF’s and their labels that are considered for damage detection. The importance of these DOF’s will become more apparent in the analysis procedures where the outputs need to be processed with respect to the flexibility matrix.
As indicated in the literature review, many problems plague the national bridge population and create challenges for the inspectors responsible for evaluating these structures. To evaluate some promising damage indices the damage scenarios listed in Table 6 will be simulated on the FEM. Although the damage scenarios are not all-inclusive, they aim to represent the immediate needs indicated by Department of Transportation (DOT) officials across the nation. The spatial locations that correspond to both numerical and experimental damage locations can be referred to in Figure 30.

Damage detection essentially has two approaches, comparing the present state to a previous or new condition and looking at the current condition for abnormal behavior. The first approach is more straight-forward whereby a structures “health” may be continuously or discretely compared to a previous state with particular changes signifying possible damage.
Obtaining baseline data is the ideal case but for older bridges, which are of primary concern this is not possible. Therefore, both approaches will be used for the damage detection studies in this thesis.

![General Grid Identification](image)

Table 6: Numerical Damage Scenarios

<table>
<thead>
<tr>
<th>Damage Scenarios</th>
<th>Damage Characteristic</th>
<th>FEM Application</th>
<th>Damage Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Healthy/Baseline</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2) Scour</td>
<td>Pile Loss</td>
<td>Remove column element</td>
<td>Jt. 4</td>
</tr>
<tr>
<td>3) Boundary Support Change</td>
<td>A.) Restrained Rotation and Translation</td>
<td>Restrain moment and shear between column and grid</td>
<td>Jts. 7, 14</td>
</tr>
<tr>
<td></td>
<td>B.) Restrained Rotation and Translation</td>
<td>Restrain moment and shear between column and grid</td>
<td>Jts. 4, 7, 11, 14</td>
</tr>
<tr>
<td>4) Reduced Stiffness</td>
<td>A.) Cross-Member Hinge</td>
<td>Release moments at both ends of cross-member, set joint elements to S3x5.7</td>
<td>Jts. 3, 10</td>
</tr>
<tr>
<td></td>
<td>B.) Reduced girder inertia and cross-member hinge</td>
<td>Release moments at one end of cross-member, set joint elements to S3x5.7</td>
<td>Jt. 3</td>
</tr>
</tbody>
</table>

To complete this discussion of the damage scenarios and their application to the FEM, each characteristic simulated in Table 6 will be explained in brief detail. Simulating the effects of scour/pile loss was easy in that the column frame element at joint 4 only needed to be deleted.
This is an extreme damage case but the applications may be less obvious in that the real-life event only needs microscopic clearance between the pier and superstructure. In fact, the pile may even still be physically constrained to a pile cap yet have lost soil friction.

Other settlement levels were considered for the numerical case but the structure’s dynamic characteristics were unaffected due to the relatively low dead weight of the structure. Several attempts to model varying levels of settlement were made using the FE software. First, a continuous beam problem was investigated due to its similarity to the grid. Extreme cases of settlement were modeled with still no effect on the stiffness matrix. All these cases assumed that only one support was restrained from translation. If multiple supports are restrained from translation, the stiffness matrix begins to change very quickly with large levels of settlement due to the axial effects. This issue with regard to the FEM should be investigated further under the scope of a different study. On the other hand, these additional settlement cases were included in the experimental damage cases and proved to change the dynamic characteristics of the grid model.

Again, modeling the boundary support restraints were relatively quick and simply. FE models have proven effective in their ability to give insight to various issues with less effort and more economical than physical testing and instrumentation. Fixing the connectivity between the columns and grid basically required that the connectivity between the columns and grid be restored to the FE software default whereby all internal forces are continuous through the joint. The difference in the restrained boundary condition scenarios is that only two end supports are restrained for one case while middle supports are also restrained for the other case. Older bridges that used a roller and bearing-pin connections are of particular interest for these damage cases.
due to their susceptibility to corrosion. Furthermore, boundary restraints are known to induce uncertainties and significant changes in the dynamic behavior (Ciloglu et al. 2001).

Fatigue cracking, bolt shear, and corroded elements all pose threats to the integrity of bridges in that the local stiffness of elements are changed in ways that change the structure’s behavior. The reduced stiffness damage scenarios correspond to these problems yet were designed such that the physical model is repairable and not permanently damaged for the experimental cases. For the FEM the cross-member linking joints 3 and 10 was released of it’s moment transfer to the girders for case 4-A. Moment releases were applied to both ends of the cross member in addition to reducing the small joint elements back to S3x5.7 since the composite action of the plate is removed for the cross member, not the girders.

4.4.3 Analysis Procedures

For each damage scenario previously described, the respective FEM was run using a standardized analysis procedure. Despite the varying models, aspects such as load cases, analysis options, data extraction, and post-processing were generalized for application to all models. One good aspect of conducting the numerical study first is that the process of damage detection becomes streamlined for the experimental component. Each step of the analysis procedure is described in the following with an outline provided in Figure 32.

4.4.3.1 FE Analysis

The FE analysis marks the beginning of the analysis procedure. Starting with the FEM for each respective damage scenario, the analyses were run using special analysis options. With SAP2000 beta version the beta solver was utilized for obtaining the mass and flexibility matrix.
directly. Rather than process a finite number of mode shapes to obtain the dynamic flexibility matrix, the flexibility matrix was obtained directly for the numerical benchmark study. As will be seen in the experimental studies, the dynamic formulation of the flexibility matrix will be required for the post-processing methods to be described later.

Furthermore, three uniform load cases are assigned to the structure. These three load cases are visualized in Figure 31. Load cases are assigned to the FEM even though the stiffness matrix is obtained and used for the actual deflection calculations in MATLAB. Creating these load cases in the FEM enables other static outputs like bending moment to be obtained more easily and provides an opportunity to verify some of the displacement results externally calculated. The reason for using three load cases will be evident in the results.

![Figure 31: Load Cases](image)

To cover the dynamic options of the analysis, a modal analysis case was specified to run with 20 modes set as an upper limit. Due to the 3-dimensional nature of the structure, all DOF’s were activated. The result of activating all DOF’s is that vertical, lateral, and longitudinal modes are possible. As a result of this option more processing was required to filter out some modes
that were not of interest. For these studies, vertical modes are of primary interest due to practical applications of modal analysis on bridge structures in the field.

4.4.3.2 Data Extraction

Once the FE analysis is run the next step is to extract the various results for further processing and damage detection. Specifically, the stiffness and mass matrices were of primary importance since the basis for the experimental benchmark studies in damage detection is to use dynamic outputs to obtain static properties. Also of interest were the bending moment values from discrete locations at the 14 joints on the grid. These moment values are used to make some comparisons between static and dynamically calculated strain, as will be seen in the results.

With respect to the dynamic outputs two main components were needed, frequencies and mode shapes. Although frequency is a very global property that is not sensitive to local damage, significant structural change can be found in addition to seeing new modes introduced. When comparing frequencies, the mode shapes should be correlated using the MAC values presented in the theory section of this thesis. Since MAC values are based on mode shapes, the mode shapes are thus needed. The mode shapes are also normally used for finding the flexibility matrix, but are not for this numerical study due to the convenience of SAP2000’s beta solver which gives the stiffness matrix as a direct output file. Data extraction for the numerical cases is considerably more straight-forward than the experimental component where parameter estimation is required.

4.4.3.3 Matlab Functions

After the required data is extracted from the FE analysis a series of MATLAB function were formulated to evaluate the raw data. For example, the mass and stiffness matrices output by
SAP2000 are rearranged for the efficiency of the solver. This caused initial problems but was resolved by writing a code that utilizes another information file from SAP2000 to organize the matrices according to the DOF labels. Recall how the importance of initial joint labeling was emphasized. Furthermore, the DOF needed to be reduced from the 312 coming from the FEM. Again recalling the DOF’s of interest in Figure 29 another code was written to reduce the 312 DOF flexibility and mass matrices to the dimensions 28x28.

Another computation using MATLAB was to compare the difference between the baseline and damaged flexibility matrices in the form of a 3-D surface. Also, the damaged flexibility matrix was multiplied by the three previously described load cases of Figure 31 to obtain the displacement vectors of the girder lines. Using the displacement vectors of the individual girders, the curvature was evaluated for the discrete joints between the end supports. To compare the mode shapes, a small code also evaluates the mode shape matrices of two different cases to obtain the MAC values. The MAC values had to be manually reviewed before modes from different damage cases could be compared. The results of these analysis steps will be displayed in the next chapter as well as the appendix.
1. FE Analysis
   a. Model selection
   b. Load cases
   c. Analysis options

2. Data Extraction
   a. Stiffness and mass
   b. Bending moment for strain correlation
   c. Frequencies
   d. Mode shapes

3. MATLAB Functions
   a. Reorganize/reduce stiffness and mass matrices
   b. Change in flexibility matrices
   c. Girder displacement profiles
   d. Girder line curvature
   e. MAC values for mode shapes

Figure 32: Numerical Analysis Procedure

4.5 Experimental Simulations

Conducting the experimental phase of this benchmark study proved to be complimentary to the numerical studies. Through the experimental simulations, real-life challenges were exposed and addressed regularly. Examples of the challenges range from fabrication errors to software issues. Starting with the laboratory setup, the following sections will explain the experimental testing process and respective details. Particular challenges will be addressed as they relate to the discussion, including in the results chapter.

4.5.1 Laboratory Setup

To see the actual test setup for the experimental simulations, refer to Figure 24. Basically, the same geometric setup was used compared to the numerical cases. The two-span configuration was used for baseline comparisons. All the details of the grid are described in the model
development sections, the contents of this section will focus on the test preparation and instrumentation aspects.

4.5.1.1 Instrumentation

A total of 16 accelerometers were used on the grid, using capacitive and ICP technology, see Figure 33 and Figure 34. The ICP accelerometers were used primarily for measuring the vertical acceleration, whereas the capacitive accelerometers were used for the horizontal measurements. One exception is that an ICP accelerometer was used for horizontal acceleration to more completely characterize the horizontal mode shapes, see Figure 35. Mounting the accelerometers required 3 different methods: hot glue, wax, and one magnet.

Figure 33: PCB 393C (ICP/Seismic)  
Figure 34: PCB 3700 (Capacitive)
Conducting these laboratory experiments required a lot of labor hours in terms of mounting sensors, making cables, labeling cables, and assigning channels, and setting up the acquisition software. All the cables running into the acquisition system were made with coaxial cable and BNC connectors. One exception is that a short length of factory micro-dot cable extends from the ICP and capacitive accelerometers. Before cutting the cables, the instrumentation plan was reviewed to find out the maximum length of cable required for any sensor. All cables were cut to 30 ft. lengths based on this maximum length requirement and then adding some extra to be conservative. Figure 37 shows each accelerometer’s placement and is referred to by Table 7 for the channel assignments that correspond to the different excitation types to be described in the test procedure. Note in Table 7 how there are actually 17 sensors including the hammer and only 16 channels to operate on at any given time. This condition required some wiring swapping between tests, but did not pose much of a problem other than keeping track of wires carefully.
Table 7: Channel Assignments

<table>
<thead>
<tr>
<th>Channel</th>
<th>Vertical</th>
<th>Ambient</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hammer</td>
<td>-</td>
<td>Hammer</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>-</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td>15</td>
<td>16</td>
</tr>
</tbody>
</table>

Quality assurance is easily controlled with labeled wires. Each wire used in the instrumentation plan was labeled at both ends so that its start and end points are known at all times. In the case where cables were switched to different channels for various tests, channel assignments could become confusing, to say the least. After all the wires were hooked up to the sensors and acquisition system, a simple demo run was made to verify that each sensor was working properly and assigned to the right channel. Another reason to label wires is that when cables go bad they can easily be replaced. During the experimental testing for this thesis the hammer cable went bad and needed immediate repair before continuing.

4.5.1.2 Acquisition System and Settings

To record the structural response, an acquisition system from VXI and Agilent Technologies is being used. From the accelerometers, the continuous electrical signal is conditioned (Figure 38) before being discretized into finite values by the digitizer. After the
signal is digitized, the PC link (Figure 39) enables the data to be stored to the computer. The MTS-Test software package was used for acquisition control. MTS is a very robust and powerful software package that enhanced the testing experience, despite the initial learning curve to get comfortable using the impact test features and settings.

There are two cards that plug into the VXI mainframe. As mentioned previously one is the digitizer and the other links to the PC via IEEE 1394 fire wire. Currently, the digitizer card is limited to 16 channels but provides similar constraints to real-life monitoring whereby instrumentation must be limited due to time and economic reasons. One of the most powerful aspects of this digitizer and acquisition system is that all the time data is collected simultaneously as opposed to a finite difference in each channels recording history. In addition to collecting data, the PC link card is also used as the controller for the electro-seis shaker. The shaker cable connects to the PC link and then the settings are configured with the testing software. No further details will be given for the shaker since it is not part of these experimental tests.

Figure 38: Signal Conditioning

Figure 39: Data Acquisition
Table 8: Data Acquisition Parameters

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Vertical</th>
<th>Ambient</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Frequency [Hz]</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Number of Spectral Lines</td>
<td>801</td>
<td>-</td>
<td>801</td>
</tr>
<tr>
<td>Length of Time Record [sec]</td>
<td>10.24</td>
<td>300</td>
<td>10.24</td>
</tr>
<tr>
<td>Trigger on Hammer Input</td>
<td>10%</td>
<td>-</td>
<td>10%</td>
</tr>
<tr>
<td>Trigger Delay [sec]</td>
<td>0.05</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Windows</td>
<td>Exponential</td>
<td>-</td>
<td>Exponential</td>
</tr>
<tr>
<td>Impact Window Width</td>
<td>1%</td>
<td>-</td>
<td>1%</td>
</tr>
<tr>
<td>Exponential Window Decay Rate</td>
<td>0.1%</td>
<td>-</td>
<td>0.1%</td>
</tr>
<tr>
<td>Noise Reduction Method</td>
<td>H1</td>
<td>-</td>
<td>H1</td>
</tr>
<tr>
<td>Blocksize</td>
<td>2,048</td>
<td>2,048</td>
<td>2,048</td>
</tr>
<tr>
<td>Number of Samples</td>
<td>4096</td>
<td>120,000</td>
<td>4096</td>
</tr>
<tr>
<td>Number of Averages</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Hammer Range [V]</td>
<td>+/- 0.1</td>
<td>-</td>
<td>+/- 0.2</td>
</tr>
<tr>
<td>Max. Accelerometer Range [V]</td>
<td>+/- 2</td>
<td>+/- 0.5</td>
<td>+/- 2</td>
</tr>
<tr>
<td>Hammer Tip</td>
<td>Med. (Red)</td>
<td>-</td>
<td>Med. (Red)</td>
</tr>
</tbody>
</table>

As mentioned in previously in this section, MTS software was used for controlling the data acquisition system. Actually, MTS also has signal processing techniques built in to average data, apply windows, and reduce noise. Acquisition parameters used for this test are in Table 8.

### 4.5.2 Damage Scenarios

Without repeating the general remarks of the damage scenarios applied to the numerical benchmark study, the implementation of the experimental cases will be explained in this section. Table 9 displays the damage scenarios used for the experimental testing cases, while Figure 30 can still be used to reference the damage locations. The only difference between the numerical and experimental damage scenarios is the addition of two settlement cases for reasons indicated in the section on numerical damage scenarios.

Simulating these damage scenarios on the grid required thinking through a lot of practical issues, especially regarding the settlement and boundary support changes. It is much easier to
discuss changing the laboratory model than actually implementing the physical changes. All these practical issues were worked out in the design phase and thankfully no major surprises happened during the tests.

Table 9: Experimental Damage Scenarios

<table>
<thead>
<tr>
<th>Damage Scenarios</th>
<th>Damage Characteristic</th>
<th>Grid Configuration</th>
<th>Damage Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Healthy/Baseline</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2) Scour/ Settlemen</td>
<td>A.) 3/4” Settlement</td>
<td>Insert 3/4” shims to other supports</td>
<td>Jt. 4</td>
</tr>
<tr>
<td></td>
<td>B.) 3/4” Settlement</td>
<td>Insert 3/4” shims to other supports</td>
<td>Jt. 7</td>
</tr>
<tr>
<td></td>
<td>C.) Pile Loss</td>
<td>Remove round bar at support</td>
<td>Jt. 4</td>
</tr>
<tr>
<td>3) Boundary Support Change</td>
<td>A.) Restrained Rotation and Translation</td>
<td>Insert bolts through top and bottom support blocks and tighten</td>
<td>Jts. 7, 14</td>
</tr>
<tr>
<td></td>
<td>B.) Restrained Rotation and Translation</td>
<td>Insert bolts through top and bottom support blocks and tighten</td>
<td>Jts. 4, 7, 11, 14</td>
</tr>
<tr>
<td>4) Reduced Stiffness</td>
<td>A.) Cross-Member Hinge</td>
<td>Loosen 8 bolts through both ends of cross-member</td>
<td>Jts. 3, 10</td>
</tr>
<tr>
<td></td>
<td>B.) Reduced girder inertia and cross-member hinge</td>
<td>Remove connection plates</td>
<td>Jt. 3</td>
</tr>
</tbody>
</table>

Starting with scour/settlement damage scenarios, the details of each damage scenario in Table 9 will be explained in terms of the physical implementation during the testing process. To simulate ¾ in. of settlement at joint 4 of the grid all other supports in the grid were raised ¾ in using shims made of steel plate, visible in Figure 40. The only problem with simulating settlement on the grid was that the dead weight of the superstructure is not sufficient to force the “settled” joint back down in contact with the round bar (Figure 41). Looking at Figure 40, one can see the stack of 1 in. thick steel plates to bring the grid back in contact. For the joint 4 settlement case approximately 250 pounds of steel was used at joint 4. Although adding mass to a structure will significantly change the dynamic response, the weight added for these settlement cases was concentrated to the supports by resting on the connection bolts which transferred the
load through the joint region. Examination of the results verified that the mass did not contribute to a change in dynamic behavior, but will be further discussed in the results section. Also seen in Figure 40 is the ICP accelerometer mounted on top of the weight stack. At first this detail was doubted, but the data collected from this sensor proved to be reading similar to the adjacent support on the other girder line.

Joint 7 settlement was induced the same way as joint 4 with the exception that additional weight was needed at both ends of the gird because the middle support (jt. 4) was acting as a pivot point. Figure 41 One good aspect of this settlement case was that only 80 pounds of weight
was needed at the two end supports. Although not related to this study, it is intuitive that less weight would be required due to the cantilever nature of the problem as opposed to the simple beam case of settlement at joint 4.

Simulating the pile loss damage was the simplest scenario in terms of physical labor and time to reconfigure. As seen in Figure 42 the round bar was simply removed since this still allowed sufficient clearance for the modal testing.

Moving on to the boundary support restraints, two cases were simulated. For the first case only joints 7 and 14 were restrained using through-bolts shown in Figure 43. The ability to extend the ¼ in. bolts through the top and bottom simultaneously was planned for in the design and was facilitated by the oversized holes (5/16 in.). One consideration for commenting on the results might be that the bolts have some flexibility that may not restrain rotation infinitely. Looking closely at Figure 43 one can see that the settlement shims are still in place, but are installed for all supports. Rather than remove all shims, it was easier to insert the one that was removed for the settlement cases. Just to clarify, there were no interaction between settlement and restrained support damage cases. The same explanations cover the damage case where 4 supports are restrained as shown in Figure 44.

Figure 42: Joint 4 Pile Loss Scenario
Simulating a loss of stiffness was made convenient by the bolted plate connections. Despite the insensitivity of the response to the loosening of a single bolt, more significant damage scenarios like the shearing of a bolt group is tested by removing the bolts that connect the cross-member to the girders. Figure 45 shows the details of the damaged connection where 8 bolts were removed for both joints 3 and 10. One assumption of the FEM is that no frictional force would develop between the disconnected portion of the plate and cross-member.

![Figure 43: Joints 7 and 14 Restrained Scenario](image)

![Figure 44: Joints 4,7,11 and 14 Restrained Scenario](image)
The main function of the plates is to link the two girders with the cross-member. Their contribution to the stiffness of the girder can not be neglected though. This detail was included in the FEM and then tested for the loss of stiffness damage scenario. For this case damage was focused to joint 3 where all the bolts in the moment connection were removed, including the plates (Figure 46). As seen from the figure the shear connection is still in tact. Relating to the FEM, the shear connection is not capable of moment resistance. Note the exposed bolt holes in the connection region that seem to reduce the stiffness of the girder. According to the design calculation, these holes do not cause a reduction in strength of the section.
4.5.3 Test Procedures

In general there were three components of data collection to each damage scenario in the testing procedure. These three components are vertical, horizontal and ambient excitation. Vertical and horizontal data were collected using an impact hammer as the measured input while recording the response of the accelerometers. Ambient data on the other hand had three subcomponents of light, moderate and support excitation. Note that analyses and results from the horizontal and ambient data collection will be neglected in this thesis due to its absence from the scope. The horizontal and ambient data will be used for other on-going studies within the research group. Basically, acceleration data was collected in three separate sets from the assigned channels of Table 7. The locations and sensors selected for data acquisition during the 3 test components are visualized in Figure 47.

Focusing on the vertical excitation component, 4 joint locations (2, 5, 6, and 12) were chosen as impact points for the hammer. Using a medium-hardness tip the grid was struck 5 consecutive times for averaging purposes, leaving sufficient time intervals for vibrations to cease. Each of the five impacts triggered the data acquisition system to begin collecting data. Collecting data using multiple input locations enables different modes to be excited in the event that an impact location corresponds with a nodal point of a mode shape. Reciprocity can also be checked from two different input locations. After the data set is collected, the user has the option of accepting or rejecting. Only data that appears reasonable and free from overloaded channels should be accepted. Overloading a channel is related to the voltage settings whereby the continuous voltage signal is discretized. The voltage signal should sufficiently use the range assigned in the acquisition parameters of Table 8.
A brief overview of the horizontal and ambient data collection process will also be covered here. Figure 47 shows the position of the horizontal sensors which averaged the response of 5 consecutive hammer impulses for the 3 input locations (2, 3 and 6). Notice how the input locations do not correspond to any of the sensor locations because of physical limitations. Ideally, driving point measurements should be taken whereby the impact location corresponds with the sensor location and measurement axis. This criterion was more easily satisfied for the vertical measurement cases. Ambient data was collected by simply tapping the grid with a hand or a glove. Additional ambient data was collected by exciting the column supports.

![Figure 47: Sensor Arrangement for Various Tests](image)

After the three components of data were collected for each damage scenario, the time history and FRF data sets were exported to a universal file format to be used for further post-processing. Data processing began immediately after each damage case simulation. Once the first set of data was processed, the procedure was streamlined. The purpose of processing the data for each damage scenario before continuing was to prevent going back and collecting data after the grid was changed. Once the data was successfully exported and saved to the prescribed folder directory, reconfiguration of the grid began for the next damage scenario.
As imagined after seeing the damage scenario pictures, a variety of tools and methods were required for reconfiguring the grid damage scenarios. Figure 49 shows a few snapshots of the work required to install and remove the shim plates. The 20 ton overhead crane is a handy asset for lifting heavy objects like the grid superstructure which weighs approximately 500 lbs.

The previous discussion aimed to give an overview of the test procedure. The actual test plan, which is summarized in these sections, can be found in Appendix D.
4.5.4 Post-Processing

The system identification method used is a robust modal parameter estimation technique that has been developed over ten years of research by Catbas, et al. This method has been used in other laboratory studies and many medium-span bridges as well as long-span bridges. As mentioned previously, the method used for parameter estimation is CMIF. This method is run in MATLAB in conjunction with additional algorithms for modal scaling and flexibility. When run in the MATLAB command window, the algorithm name appears as MODALCIS. After identifying the modal parameters and flexibility using MATLAB the frequencies, mode shapes, and flexibility matrix were compared and further evaluated similar to the numerical benchmark study. To help prevent the possibility of using bad data, the dynamic results were checked before moving to the static calculations, for the experimental cases. Since the flexibility matrix is computed from the modal data, proceeding to the displacement based indices first could lead to illegitimate results.

First, the mode shapes were plotted and labeled for visual inspection. Using MAC values the damaged mode shapes were then compared to the baseline mode shapes. A table was then constructed to numerically compare frequencies and MAC values for different modes. This is where new modes can be positively identified in addition to modes that are missed.

Understanding any changes in the static behavior of the structure was first approached by looking for changes in the flexibility matrix. To see these changes, the damaged flexibility matrix was simply subtracted from the baseline matrix and then plotted as a two and three-dimensional mesh for detailed inspection. These plots will be shown in the results section. Finally, the displacement profiles and curvature distributions were computed for the two girder lines using the dynamically measure flexibility matrix, with an additional plot of the strain
correlation to the FEM. As stated in the numerical section, the reason for using three different load cases will become evident in the results. Briefly though, the three load cases enable damage detection of members contributing to lateral load distribution. A summary of the experimental analysis procedures is shown in Figure 50.

**Figure 50: Experimental Analysis Scheme**
CHAPTER 5: TEST RESULTS AND DISCUSSION

The objective of this chapter is to summarize the results of the numerical and experimental benchmark studies. Analyses were performed as an investigational study to find the advantages and disadvantages of different indices. Time history data was collected for the grid structure and processed to obtain FRF’s, modal frequencies, mode shapes, flexibility matrix, displacement, and curvature. Further investigation of specific details may be recommended based on the finding in this chapter.

Results of the baseline structure and each damage scenario will be discussed separately in the following sections. For each case representative figures and tables will be shown to adequately explain the results. Within each section the numerical and experimental damage results will be explained in relation to their baseline results as well as cross correlation between the numerical and experimental results. Many plots, tables, and figures were generated during the post-processing stage due to the explorative aspect of this study, many of which need further evaluation beyond the scope of this study. Although a limited sample of results are contained in this chapter, the comprehensive results for the numerical and experimental benchmark studies may be referenced in Appendix F and Appendix G, respectively.

5.1 Baseline Characterization

To start, the first few mode shapes of the baseline condition will be examined for consistency between the experimental and FEM results. A good understanding of the vibration characteristics will provide insight for future cross correlation and comparison. As seen in Figure 51 the modal frequencies for the three vertical mode shapes have a good correlation in their
shape. The first and third modes have a difference of less than 4%, but the second modal frequency varies by slightly more than 12%. For higher frequencies some new modes were found from the experimental results that differ from the FEM results. It should be clear that any differences and new modes affect the calculated flexibility used for the damage indices in the following sections. All the baseline experimental mode shapes are displayed in Figure 52.

<table>
<thead>
<tr>
<th>Finite Element/Numerical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Mode 1 – 22.23 Hz Vert. Bending" /></td>
<td><img src="image2" alt="Mode 1 – 22.37 Hz Vert. Bending" /></td>
</tr>
<tr>
<td><img src="image3" alt="Mode 2 – 23.58 Hz Vert. Torsion" /></td>
<td><img src="image4" alt="Mode 2 – 27.00 Hz Vert. Torsion" /></td>
</tr>
<tr>
<td><img src="image5" alt="Mode 3 – 34.65 Hz Vert. Bending" /></td>
<td><img src="image6" alt="Mode 3 – 33.38 Hz Vert. Bending" /></td>
</tr>
</tbody>
</table>

Figure 51: Numerical and Experimental Mode Shape Comparison
Baseline Experimental Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>27.00</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>

Figure 52: Baseline Experimental Mode Shapes
FEM updating and calibration of the grid are issues being investigated by a colleague. Future sections will not discuss the differences between results with respect to FEM calibration issues. Another general statement for all the experimental mode shapes is that the resolution of the accelerometers greatly affects the results. Experimental mode shapes that look the same but have distinguished frequencies are a result of the sensor resolution as shown in Figure 53.

![Figure 53: Sensor Resolution Issues](image)

### 5.2 Scour and Settlement

As mentioned previously, numerical results were not computed for the two settlement cases. Therefore, the first two sections will only present results using experimental data. The third scour damage case of pile loss will be correlated to the numerical model. All the settlement damage scenarios are visually summarized in Figure 54 for reference while reviewing these results.
5.2.1 Settlement at Joint 4

As a first damage scenario, without a numerical comparison, most of the results computed will be displayed as a representative example of the post-processing analysis. Other damage scenarios will be discussed using fewer figures. Remember that all of the tables, plots, and figures are available in the Appendices.

<table>
<thead>
<tr>
<th>Baseline Modes</th>
<th>Jt 4 Settlement Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00 0.08 0.01 0.01 0.13 0.06 0.00 0.98 0.02 0.08 0.04 0.05 0.09 0.11 0.00 0.01 0.02</td>
</tr>
<tr>
<td>2</td>
<td>0.07 1.00 0.01 0.03 0.34 0.28 0.00 0.05 0.03 0.05 0.00 0.02 0.01 0.01 0.02 0.03 0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.00 0.00 1.00 0.12 0.02 0.01 0.00 0.03 1.00 0.05 0.02 0.00 0.15 0.20 0.05 0.03 0.05</td>
</tr>
<tr>
<td>4</td>
<td>0.00 0.00 0.06 0.98 0.06 0.06 0.04 0.04 0.05 0.00 0.05 0.02 0.01 0.01 0.03 0.00 0.01</td>
</tr>
<tr>
<td>5</td>
<td>0.01 0.04 0.00 0.04 0.84 0.91 0.12 0.02 0.01 0.09 0.01 0.99 0.94 0.27 0.99 0.01 0.04</td>
</tr>
<tr>
<td>6</td>
<td>0.00 0.02 0.00 0.05 0.14 0.07 0.93 0.02 0.04 0.06 0.13 0.05 0.30 0.79 0.05 0.91 0.90</td>
</tr>
<tr>
<td>7</td>
<td>1.00 0.06 0.01 0.05 0.14 0.09 0.00 0.98 0.03 0.06 0.03 0.06 0.08 0.11 0.01 0.01 0.02</td>
</tr>
<tr>
<td>8</td>
<td>0.00 0.02 1.00 0.06 0.04 0.03 0.01 0.03 1.00 0.02 0.01 0.00 0.15 0.20 0.05 0.02 0.05</td>
</tr>
<tr>
<td>9</td>
<td>0.01 0.02 0.02 0.00 0.26 0.29 0.02 0.20 0.01 0.99 0.03 0.11 0.05 0.02 0.07 0.03 0.04</td>
</tr>
<tr>
<td>10</td>
<td>0.02 0.00 0.03 0.08 0.01 0.09 0.15 0.01 0.05 0.01 0.98 0.03 0.11 0.13 0.04 0.08 0.09</td>
</tr>
<tr>
<td>11</td>
<td>0.03 0.00 0.00 0.01 0.88 0.80 0.10 0.01 0.00 0.07 0.10 0.99 0.92 0.31 1.00 0.06 0.09</td>
</tr>
<tr>
<td>12</td>
<td>0.01 0.02 0.11 0.05 0.18 0.03 0.94 0.01 0.07 0.04 0.07 0.02 0.27 0.89 0.02 0.96 0.96</td>
</tr>
<tr>
<td>13</td>
<td>0.05 0.01 0.10 0.05 0.28 0.06 0.92 0.05 0.07 0.00 0.14 0.11 0.15 0.90 0.11 0.93 0.94</td>
</tr>
<tr>
<td>14</td>
<td>0.01 0.02 0.00 0.06 0.18 0.05 0.95 0.02 0.04 0.05 0.10 0.01 0.26 0.86 0.00 0.96 0.96</td>
</tr>
<tr>
<td>15</td>
<td>0.06 0.02 0.08 0.06 0.33 0.13 0.91 0.05 0.05 0.04 0.09 0.19 0.10 0.91 0.19 0.95 0.96</td>
</tr>
</tbody>
</table>

Figure 54: Settlement/Scour Damage Scenarios

Figure 55: Experimental MAC Values
Looking first at the MAC values shown in Figure 55, the relationship between the damage scenario and baseline mode shapes can be more easily understood. Recalling that values of unity mean the modes are the same, the lower bound criteria was set at 90%. For a MAC matrix like the one displayed in Figure 55 it seems logical that the diagonal terms should theoretically be the modes most highly correlated. However, when new mode shapes are introduced or baseline modes are missed, off-diagonal terms become correlated. Using Figure 55 as an example, modes 5, 13, and 15 are new modes compared to the baseline findings. Furthermore, new and missed modes are the reason for blank spaces in Table 10. Notice how relatively close the frequencies are for modes 12 and 13 of the baseline and damaged cases, respectively, yet they are not correlated looking at the MAC value of 27%. Distant, off-diagonal terms may also be observed in Figure 55, which is again explained by the sensor resolution and graphically in Figure 53. Table 10 summarizes the mode shapes and frequencies which are observed to change less than 3% in the maximum case.

Figure 56: Experimental Difference Between Damaged and Baseline Flexibility Matrices
To observe any changes in the flexibility matrix, the damaged flexibility matrix is subtracted from the baseline and then plotted as the colored meshes shown in Figure 56. Looking at the changes from a qualitative point of view, the changes are sporadic and don’t seem to be helpful in locating the damage, especially if the damage case is not known. These meshes begin to make more sense when compared to the displacement profiles in Figure 58.

The six displacement plots correspond to the two girder lines and 3 pseudo-flexibility load cases shown again in Figure 57. Three load cases are used to distinguish changes resulting from cross-member contributions. Suppose a cross-member was removed, the effect would not be seen in terms of deflection if both girder lines were loaded simultaneously. For this settlement case, some interesting results occur when only one girder is loaded; the adjacent girder deflects in the upward direction. Theoretically, this behavior does not make sense. Rather, these are numerical errors in the flexibility matrix.

<table>
<thead>
<tr>
<th>Table 10: Experimental Mode Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
</tr>
<tr>
<td>Mode</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>13</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>15</td>
</tr>
</tbody>
</table>
Another significant result from the displacement plots is the displacement profile for load 2, girder 1. It appears that joint 4 is flexible, which corresponds to the joint that was purposely settled. There are two explanations for this; either this is truly an indication of the settled joint in an obscure way or this behavior is the result of stacking weight on the joint and placing an accelerometer at the top. Not enough weight may have allowed some vibration at the middle support. Aside from the settled joint issue, the load 3, girder 2 plot agrees with intuition in that the girder deflection should increase due to the inability of the cross-members to resist until the girder comes back to the same elevation level. In other words, the stored energy in the cross members from the joint settlement adds to deflection in the girder line 2.

Taking the second derivative of the displacement vectors for each girder using the central difference method, the curvature was plotted for the discrete measurement points. One consideration for experimental testing is that the first and last measurement point will not be able to have a corresponding curvature value due to the numerical approximation of the central difference formula. For this damage case the curvature at the ends was assumed to be zero because these are known damages. When the curvature is plotted for the fixed boundary condition damage scenarios, one will notice how the plot lines end at joints 6 and 13 for girder 1 and 2 respectively. A finer resolution of sensors would yield more accurate results in terms of curvature, but cost is always an issue for instrumentation of a bridge. One last general statement about the curvature results is that they should not be used as a direct indication of changes in the girder stiffness due to the redundancy of the structure, whereby cross-members and such also contribute to this curvature value.
Figure 57: Pseudo-Flexibility Loads

Figure 58: Experimental Displacement Profiles
When looking at the curvature plots of Figure 59 significant changes are not really noticeable except for girder 2 when loaded with case 3. The curvature values at distances 36, 108, and 180 inches change by 29%, 31%, and 43%, respectively. Again, this goes back to the discussion on the change in displacements for this case. Therefore, the settlement at joint 4 on girder line 1 became evident not from girder 1 results, but more so from girder 2 results. This is a good example of why loading one girder at a time is beneficial for damage assessment.
5.2.2 Settlement at Joint 7

Before going into details of the settlement results for this damage case, attention should be given to some irregularities in experimental mode shapes and flexibility matrices. It has been noted previously that the supports showed flexible behavior when the flexibility matrix was multiplied by a force vector. In Figure 60 the support movement that affects the flexibility matrix is obvious in the experimental mode shape. Upon viewing these results, immediate inspection was warranted to determine why this behavior might occur.

After investigating all the boundary supports, it was realized that fabrication errors led to non-level column surfaces or laterally sloped scallops that were a result of the machine shop. Figure 62 shows a picture of the small gap at the end of the roller. To further explain this issue CAD drawings shown in Figure 63 were generated. Basically, the problem is that one end of the roller contacts the plates at a finite location. Looking at the where the center-line of the accelerometer passes through the support, there is clearly a gap. This clear space along the centerlines of the accelerometers is the reason that significant vibrations were recorded.

Figure 60: Mode Shape with Support Movement  
Figure 61: Inspection of Supports
Figure 62: Support Gap

Figure 63: Support Contact Issues

Settlement at joint 7 changed the mode shapes compared to both the baseline and the previous damage of settlement at joint 4. A total of 4 modes were introduced or missed for the previous damage case, but now there are 9 modes that do not correlate. Table 11 gives a summary of the joint 7 settlement mode shapes and their frequency differences compared to the baseline. For the most part the modes are highly correlated and differ by less than 1.5%, with the
exception of modes 13 and 14 that change by 12.9% and 10.67%, respectively. Overall, these modal findings can be summarized in that lower modes were not immediately affected.

For the static load cases using the dynamically measured flexibility matrix, Figure 64 depicts two changes of 13% and 11%. Literature indicates that changes less than 10% should not be immediately taken as damage for deteriorated and redundant structures (Catbas et al. 2005). Since the laboratory model is not classified as deteriorated or subject to temperature changes, changes even less 10% could be attributed to damage and further validates the 11% and 13% changes found for this case.

One of the advantages to the displacement and curvature indices is that damage can even be detected without baseline data. A 22% difference in curvature for two symmetric ordinates can be observed in Figure 65. Although the percentage difference may not be the location

### Table 11: Experimental Mode Comparisons

<table>
<thead>
<tr>
<th>Mode</th>
<th>Baseline Frequency [Hz]</th>
<th>Jt 7 Settlement Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>1</td>
<td>0.51%</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>2</td>
<td>0.60%</td>
<td>0.999</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>3</td>
<td>0.84%</td>
<td>0.998</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>4</td>
<td>1.29%</td>
<td>0.998</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>5</td>
<td>0.88%</td>
<td>0.991</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>6</td>
<td>0.45%</td>
<td>0.927</td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>8</td>
<td>0.03%</td>
<td>0.999</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>10</td>
<td>99.88</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>11</td>
<td>1.48%</td>
<td>0.910</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td>12</td>
<td>12.89%</td>
<td>0.981</td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>13</td>
<td>10.67%</td>
<td>0.952</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td>14</td>
<td>151.89</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
indicator for damage, the change is very visible in the plot and can lead to further investigation in terms of data processing or visual inspection like shown in Figure 61.

![Image of Displacement Profile](image1)

**Figure 64: Load Case 1, Experimental Displacement Profiles**

![Image of Non-Symmetric Curvature](image2)

**Figure 65: Non-Symmetric Curvature**

91
5.2.3 Loss of Pile at Joint 4

Both the change in flexibility and mode shapes show undisputable changes directly indicating and locating the damage (Figure 66). There is not a comparison for a change in frequency due to the introduction of a new first mode. The new mode is shown in Figure 67 for both the numerical and experimental results. Such catastrophic structural change is bound to yield results like these. Some may begin to think that these changes may be obvious and quickly detected through vision, but in fact may not due to the unseen loss of pile friction below ground or water. This type of severe damage may be well suited for the onset of new technologies like sensors that will process the data before the output is recorded (Chang et al. 2003). If a new first mode is easily identified without even requiring data collection or post-processing, understanding and locating the problem may be quickly addressed.

Comparing the quantitative difference between the numerical and experimental results, the two studies are in good agreement for not being calibrated. The second modes differ by 0.5%
for the numerical and experimental cases. Further results may be viewed in the appendix but will not be further discussed in this section due to the obvious success of identifying the damage with the first steps of modal parameter identification.

<table>
<thead>
<tr>
<th>Numerical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Numerical Model" /></td>
<td><img src="image2.png" alt="Experimental Model" /></td>
</tr>
<tr>
<td>Mode 1 – 5.78 Hz Vert. Bending</td>
<td>Mode 1 – 6.21 Hz Vert. Bending</td>
</tr>
<tr>
<td>Mode 4 – 22.23 Hz Vert. Bending</td>
<td>Mode 2 – 22.35 Hz Vert. Bending</td>
</tr>
</tbody>
</table>

Figure 67: New Mode from Loss of Pile

### 5.3 Boundary Support Changes

Corresponding to deterioration and other phenomenon of boundary supports, first two supports were restrained, then four. Joints 4, 7, 11, and 14 were restrained using the typical details shown in Figure 68.
5.3.1 Restrained Rotation at 2 Supports

Boundary support conditions have proven to be one of the major causes for modal frequencies to change on a structure, also seen in Table 12. The first two modal frequencies increase by about 10%, followed by the next two at around 9%. This table only contains the first few lines of the whole table because it is the first four correlated modes that significantly change in their frequencies. On the other hand, the higher modes are not affected greatly by the restrained supports.

Table 12: Experimental Mode Comparisons

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>1</td>
<td>24.60</td>
<td>10.00%</td>
<td>0.970</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>2</td>
<td>29.85</td>
<td>10.54%</td>
<td>0.969</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>3</td>
<td>36.41</td>
<td>9.07%</td>
<td>0.966</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>5</td>
<td>44.45</td>
<td>8.64%</td>
<td>0.960</td>
</tr>
</tbody>
</table>
Displacement profile plots for this damage scenario also appear as expected in that one span should deflect more than the other due to the redistributed moments (Figure 69). Changes in displacement are obvious in these results ranging from 11% to 65% including both the numerical and experimental case. If the damage scenario were not known, as the case in real life, this behavior would be a clear sign of asymmetric load distribution and cause for further investigation.

Figure 69: Change in Displacement Comparison

Points a, b, c, and d are important to understanding one difference between the numerical and experimental results in Figure 70. The fact that point “a” deflected further than point “c” could mean one of two things; either the physical structure is stiffer or restraints 7 and 14 are not fully fixed. The conclusion for these results is that the supports were not fully restrained in the experimental test. Considering the ratios $a/b=3.3$ and $c/d=1.5$, they should be more similar even if not exact for the same boundary restraints but different cross-sections. Notice there is a small measure of deflection at the middle support, but this is still not a complete explanation for the difference between the ratios $a/b$ and $c/d$. 

95
As the number of sensors decreases, so does the certainty when calculating the curvature. When calculating the curvature using the central difference method, the number of outputs will be two less than the inputs. In other words, the curvature values at the supports are not known. For most of the results in this study, the curvature at the supports was assumed as zero if the ends were free to rotate. However, in this damage scenario a curvature value was not plotted for the restrained ends because of this limitation (Figure 71). This issue is a disadvantage of using curvature as a damage index when boundary conditions may not be free to rotate. One recommendation is to use a finer resolution of accelerometers in the support regions, if available. While the end value of curvature will still not be available, a trend like the one in Figure 71 may be more obvious.

Figure 70: Numerical vs. Experimental Deflection for Two Restraints
5.3.2 Restrained Rotation at 4 Supports

The first difference noticed between the numerical and experimental results is that the MAC matrices were extremely different. For the numerical analysis, none of damaged vertical modes were found to correlate with the baseline. On the other hand, the experimental analysis correlated the first 11 modes and then the 15\textsuperscript{th} modes. This is a strong statement as to how different the experimental and numerical models behaved dynamically. Refer to the Appendix F and G to see the MAC matrices and modal frequency comparisons.

Again, the change in displacement for the second span of the grid indicates a severe change in structural behavior. The interior measurement points of the second span change by 40\% and 57\% for the numerical results (Figure 72). Experimental results compare slightly different but still significant at 42\% and 40\%, respectively.
The experimental displacement profile of Figure 72 also verifies the previous conclusion about non-fixity of the supports at joints 7 and 14. If in fact the support was fully fixed, points A and B would deflect the same distance as shown in the numerical plot. Looking closer at point A one can see that the deflection value compares well with the numerical result, further indicating that the end support had the ability to rotate.

Figure 72: Displacement Comparison

5.4 Change in Stiffness

Changes in the stiffness of structural elements and joints are a very local behavior that have proven difficult to detect in the field using dynamic tests. The damage scenarios of this section are in fact, local changes in stiffness that do not drastically change the properties of the structural elements. Figure 73 gives a brief visual review of the damage scenarios implemented for problems of stiffness.
5.4.1 Cross-Member Hinges

Both the numerical and experimental MAC values agreed unanimously that the mode shapes did not change for damage of releasing moment resistance at the cross-member hinges. There were only two experimental modes that didn’t correlate and none of the modal frequencies changed more than 0.5%. It’s clear the dynamic properties do not indicate the simulated damage.

Table 13: Experimental Mode Comparisons

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>1</td>
<td>22.38</td>
<td>0.04%</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>2</td>
<td>27.02</td>
<td>0.05%</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>3</td>
<td>33.33</td>
<td>0.13%</td>
<td>1.000</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>4</td>
<td>40.92</td>
<td>0.02%</td>
<td>1.000</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>5</td>
<td>64.68</td>
<td>0.39%</td>
<td>0.995</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>6</td>
<td>67.01</td>
<td>0.38%</td>
<td>0.998</td>
</tr>
<tr>
<td>7</td>
<td>68.27</td>
<td>7</td>
<td>68.27</td>
<td>0.05%</td>
<td>1.000</td>
</tr>
<tr>
<td>8</td>
<td>94.21</td>
<td>8</td>
<td>94.16</td>
<td>0.05%</td>
<td>0.999</td>
</tr>
<tr>
<td>9</td>
<td>96.56</td>
<td>9</td>
<td>96.52</td>
<td>0.04%</td>
<td>0.999</td>
</tr>
<tr>
<td>10</td>
<td>103.58</td>
<td>10</td>
<td>103.54</td>
<td>0.04%</td>
<td>1.000</td>
</tr>
<tr>
<td>11</td>
<td>120.65</td>
<td>11</td>
<td>120.23</td>
<td>0.35%</td>
<td>0.999</td>
</tr>
<tr>
<td>12</td>
<td>126.41</td>
<td>12</td>
<td>126.28</td>
<td>0.10%</td>
<td>0.999</td>
</tr>
<tr>
<td>13</td>
<td>137.25</td>
<td>13</td>
<td>137.22</td>
<td>0.02%</td>
<td>0.999</td>
</tr>
<tr>
<td>14</td>
<td>141.94</td>
<td>14</td>
<td>145.71</td>
<td>0.35%</td>
<td>0.983</td>
</tr>
<tr>
<td>15</td>
<td>145.71</td>
<td>15</td>
<td>148.09</td>
<td>0.03%</td>
<td>0.999</td>
</tr>
</tbody>
</table>
Intuitively, the hinged cross-members should only affect the out of phase behavior of the grid. In other words, uniformly loading both girders should not induce detectable changes. Contrary to these statements, Figure 74 shows a 10% change in curvature at the point of damage for girder 2 while both girders are loaded. The lower plot of Figure 74 should actually yield the significant results indicating damage, since it is the only girder loaded and resisted less by the damaged cross-member. The 8% change in the lower plot is still an indicator but it’s just misleading how the first plot indicates more change. This is a good opportunity to point out how the curvature reported is not explicitly related to the inertia of the girder. In this case there was no change induced to the girders, yet a change occurred in the girder curvature. This is a result of moment redistribution. One final note on the curvature is that the numerical results did not yield any changes. In addition, displacement profiles were not a good indicator either.

Another damage detection approach related to strain was also investigated. Multiplying the curvature obtained from the second derivative of displacement by the distance from the neutral axis to the extreme fiber yields an approximation to strain. The advantage to this concept is that strain is a directly measurable quantity that does not require a reference, like displacement. Therefore, experimental strain measurements can be correlated those calculated from dynamic flexibility/curvature. Comparing the results of Figure 75 one can see a relatively good correlation despite the lack of a direct relationship. If the middle support had not of recorded high levels of vibration the experimental plot may look even better over the interior support. But then again, the FEM and experimental results should not be compared too rigorously since it is not calibrated.
Figure 74: Experimental Change in Curvature
5.4.2 Reduced Inertia and Hinge

Both the numerical and experimental modal results for removing the plates resembled those of the cross-member hinges. Again, all the numerical modes correlate in the MAC matrix, while 3 modes are uncorrelated for the experimental modes. In addition, all modes are subject to change less than 1%, which is not considered significant for real SHM applications.

Flexibility coefficients proved effective for this damage scenario. Numerical and experimental changes in displacement differed by 6.5% and 5.7%, respectively compared to the baseline data (Figure 76). These differences are not as high as the 10% criteria mentioned previously, but definitely identify the damage location. The only drawback to the change in displacement plots is that there were some false positives for the other experimental load cases that would be difficult to identify as insignificant if the damage condition were not known. Some abnormal behavior seemed to result from the uniform load on both girders, while the results from uniformly loading one girder at a time compared much better to the numerical model.
Although the percent differences of the displacement changes were less than 10%, the curvature changes in Figure 77 show its advantage. For the same measurements, the curvature quantity appears to be more sensitive. The numerical differences were 17% while the experimental were 16% and 19%, all of which fall in a reasonably close range. Once again, the issue of false positives arises when looking at the right side of the first experimental graph in Figure 77. The change at joint 6 along girder 1 for load 1 is calculated as 4%. In addition to these damage indices, others may be needed to reject false positives when the damage case is not known.
Errors may stem from two main sources, either testing or post-processing. Testing is also considered to be a part of the numerical problem as well. FEM are susceptible to user input errors. Testing errors could also include the sensor mounting, boundary support connectivity, channel assignments, wiring, or acquisition settings. From the post-processing side, errors may include choosing FRF peaks, mode shapes, or windows. Furthermore, taking numerical derivatives to obtain curvature is a possible source of error. For every number input or function run, there is a chance that some input error may occur. Thankfully, a lot of system identification methods, like CMIF are automated and relatively easy to run. The results just presented are subject to error, but have been obtained with utmost care to prevent any misleading findings.
5.6 **Results Summary**

The numerical benchmark study can be termed a *forward problem* because any changes in the structural behavior could be positively linked to the simulated damage. Although other stages of damage location and quantification may still be challenging, the detection part is relatively easy for the FEM. Damage detection procedures were more difficult on the grid model, which makes it closer to the real life *inverse problem* (Catbas et al. 1998). The Lab model provided an intermediate step to real life problems with increased uncertainty, particularly the issues with the supports not in full contact.

Modal frequencies were relatively insensitive to the stiffness and settlement damage cases with the exception of the higher modes of settlement at joint 7. As expected, the frequencies changed significantly for global damages like the loss of a pile and restraining boundary supports, particularly the lower modes. One advantage to monitoring frequencies and mode shapes is that the introduction of new modes, especially the first or second, indicates a major change occurring in the structure. These results can be obtained relatively easy and maybe completely by the sensor in the near future.

Flexibility-based indices of displacement and curvature were a good indicator and locator for damage with and without baseline data. Using principles of structural analysis and symmetry, damage is easy to detect and then the location can be determined based on the asymmetrical changes. Some of the flexibility results were plagued from high levels of vibrations at the supports. A significant difference was found between the behavior of the numerical and experimental restrained boundary supports. The experimental boundary restraints were not completely restraining rotations due to either flexibility or micro-looseness of the bolts.
Curvature proved to be more sensitive for some cases where the displacement results were questionable. Another error to be cautious of is numerical errors taking the second derivative and finding percent differences of small numbers. While not always locating damage, flexibility based indices certainly give further direction as to where further investigation should take place with either visual inspection or other damage indices. The major disadvantage to using curvature for damage cases where the end supports may have some degree of restraint is that curvature is not obtainable at the end point using the central difference method.
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Laboratory Model Development

Fundamental knowledge needs, technology needs, and socio-organizational challenges make up the backbone of SHM and the basis for developing a laboratory benchmark model. The first objective of this study was met in the development and instrumentation of a phenomenological laboratory model that currently serves a wide range of research needs as well as having served the immediate needs of this study. The structure developed was an 18 ft. by 6 ft. steel grid that was designed, drafted, procured, and assembled in the UCF Structures Laboratory. It’s static and dynamic characteristics were designed and have been experimentally verified as being representative of short to medium span bridges which make up the majority of the U.S. bridge population. Details were included such that several categories and levels of damage that currently plague the U.S. bridges can be simulated without permanently affecting the models performance. Different aspects of the model such as connection elements, bolts, supports, and boundary conditions may be easily reconfigured for respective damage or structural geometry.

6.2 Laboratory Test Set-Up of Sensors and Acquisition System

Using state of the art technologies in sensors and acquisition systems, the grid has been instrumented with a realistic, yet dense array of accelerometers as well as displacement transducers and strain gages which were not in the scope of this study. More accelerometers could be used for better characterization of the laboratory model, but using the currently available supply created a more life-like process whereby a test plan was devised that used a
minimum sensor distribution and even required moving sensors and switching channels between various tests. Designing, planning, and setting up the data acquisition system and installing sensors all made for an excellent exercise in preparing for a real life SHM application. Test groups must be well equipped and prepared for many obstacles when deployed to the field to set up a SHM system.

6.3 **Benchmark Studies**

Within the scope of this thesis was to run both numerical and experimental damage scenarios as benchmark studies to investigate and verify some promising damage indices. First a FEM was developed using SAP2000 to accurately represent the physical model using frame elements. Appropriate adjustments were made for varying inertias and additional mass from external components. Careful attention was given to the numbering and labeling of elements due to the output of stiffness and mass matrices for post-processing. A slightly varied version of this FEM is also being used in conjunction with the world-wide benchmark study whereby the geometric and structural properties of this model are used.

The numerical benchmark study can be termed a *forward problem* because any changes in the structural behavior could be positively linked to the simulated damage. Results from the FEM were always clean and behaved predictably because of the lack of signal noise. Noise is a known challenge in real-life applications.

Damage detection procedures were more difficult on the grid model, which makes it closer to the real life *inverse problem*. The Lab model provided an intermediate step to real life problems with increased uncertainty, particularly the issues with the supports not in full contact. Fabrication and construction errors must be fully expected when conducting experimental modal
tests. After collecting each experimental data set it was crucial to analyze the data to a preliminary stage so that any obvious blunders or phenomena could be immediately identified and addressed. For example, after collecting all the data for the pile loss case, it was realized that the 5 vertical impacts were conducted at intervals that were too short. Because of the missing support the girder was vibrating for a longer period of time which ended up being an addition to the vibration from the subsequent impacts. The result was that the flexibility matrix ended up being more flexible than actuality. At first, the girder was deflecting 7 inches under the uniform load, but after recollecting the data it reduced to approximately 1 inch, which was expected. This example of not waiting long enough to impact the grid caused a girder deflection 7 times the expected.

To detect damage, indices of frequency, mode shape, flexibility, deflection, and curvature were employed. Modal frequencies were found to be relatively insensitive to the stiffness and settlement damage cases with the exception of a few high modes of settlement at joint 7. Typically, local damage is smeared into the global behavior of the structure (Catbas et al. 1998). As expected, the frequencies changed significantly for global damages like the loss of a pile and restraining boundary supports, particularly the lower modes. One advantage to monitoring frequencies and mode shapes is that the introduction of new modes, especially the first or second, indicates a major change occurring in the structure. These results can be obtained relatively easy and hopefully by sensors in the near future.

Flexibility-based indices of displacement and curvature were a good indicator and locator for damage with and without baseline data. Using principles of structural analysis and symmetry, damage is easy to detect while the location can be partially determined based on the asymmetrical changes. Damage locations may not always be pin-pointed just be looking at the
deflected shape. If changes occur due to the supports or damage in a member providing lateral load distribution, further investigation would be required to find the exact problem.

Some of the flexibility results were skewed from high levels of vibrations at the supports. After investigating the support conditions, finite contact was observed whereas continuous contact was assumed in the sensor placement. This problem represents practical issues in fabrication and construction whereby, supports do not always behave linear and rigid. A significant difference was found between the behavior of the numerical and experimental restrained boundary supports. The experimental boundary restraints were not completely restraining rotations most likely due to flexibility of the bolts.

Curvature proved to be advantageous for some cases where the displacement results were questionable. Specifically, observing the change in curvature provided significant findings for the loss of stiffness at joint 3 case. Curvature seemed to be a more sensitive quantity when looking for changes in reference to the baseline. When only using one set of measured data, curvature did not prove superior to displacement in that displacement was just as good in indicating non-symmetry. Caution must be taken when computing the second derivative and finding percent differences of small numbers, due to numerical errors.

While not always locating damage, flexibility based indices certainly give further direction as to where further investigation should take place with either visual inspection or other damage indices. The major disadvantage to using curvature for damage cases where the end supports may have some critical information is that curvature is not obtainable at the end points using the central difference method. Additional methods may need to be investigated to further address this issue.
Overall, this study was a success in that a laboratory SHM system has been developed, instrumented, and tested both numerically and experimentally. The completion of this study has now prepared and positioned the graduate research team more in depth studies and deployment to the field. Other issues remain to be studied in relation to field testing, like time variant conditions. One of the main challenges in using dynamic test data is that the dynamic properties, especially frequencies, shift due to environmental effect for redundant structures. Issues like these have been previously studied and succeeded, but nonetheless exist (Catbas et al. 2005).

6.4 Recommendations

After completing this study, the author recommends the following, in no particular order:

1. Studies should be conducted with additional mass added to the grid. With added mass, the structure will become more flexible and possibly reduce chatter from the loose supports.
2. Support connectivity should be improved to characterize the model’s horizontal modes. Horizontal data was collected during the testing process, but not analyzed in this study. The data has a significant amount of noise due to the chattering of the roller supports.
3. A static test should be conducted to verify the displacement vectors computed using the dynamically measure flexibility. Additional measurements may include strain and its correlation to the dynamic-based curvature.
4. More accelerometers need to be instrumented near the end supports to better characterize the curvature trend without the end measurement.
UCF Grid Model Strength Design

**Design Checks**

1. Flexure
2. Shear
3. Connections
   a. Shear Clips
   b. Moment Plates
   c. Bolts
4. Bearing Plates

**Given**

\[
\text{(kip ksi psi)} := \left( \frac{1000 \text{lb}}{\text{in}^2} \right)
\]

\[
\left( \phi_w \phi_b \phi_v \phi_r \right) := (1.0 \ 0.9 \ 0.9 \ 0.75)
\]

*Note: The following properties and calculations are based on AISC LRFD Manual 3rd ed.*

**S3x5.7 Section Properties**

\[
\begin{pmatrix} F_y & F_u & F_r & E \end{pmatrix} := (36 \ 58 \ 10 \ 29000) \text{ksi}
\]

\[
\begin{pmatrix} d & t_w & b_r & t_f & k \end{pmatrix} := (3 \text{in} \ 0.17 \text{in} \ 2.33 \text{in} \ 0.26 \text{in} \ 0.625 \text{in})
\]

\[
\begin{pmatrix} A_g & I_x & S_x & Z_x & r_x & r_y \end{pmatrix} := \left( 1.66 \text{in}^2 \ 2.5 \text{in}^4 \ 1.67 \text{in}^3 \ 1.94 \text{in}^3 \ 1.23 \text{in} \ 0.518 \text{in} \right)
\]

\[
\begin{pmatrix} \lambda_f & \lambda_w & X_1 & X_2 \end{pmatrix} := \left( 4.48 \ 11 \ 6430 \text{ksi} \ 89 \times 10^{-6} \text{ksi}^{-2} \right)
\]

**Flexural (check 3 limit states)**

1. **Yielding**

\[
M_p := \begin{cases} 
a & \leftarrow F_y \cdot Z_x \\
b & \leftarrow 1.5F_y \cdot S_x \\
b & \text{if } a > b \\
a & \text{otherwise}
\end{cases}
\]

\[
M_{n1} := M_p
\]

\[
M_{n1} = 69.84 \text{kip-in}
\]
2. Lateral Torsional Buckling

\[ F_L := F_Y - F_t \]

\[ L_p := 1.76 r_Y \frac{E}{F_Y} \]

\[ L_T := \frac{r_Y X_1}{F_L} \sqrt{1 + \frac{L}{L_T^2}} \]

\[ M_r := F_L S_x \]

\[ L_{b1} := 3 \text{ft} \quad \text{(unbraced length for girder is equal to x-member spacing)} \]

\[ L_{b2} := 6 \text{ft} \quad \text{(unbraced length for x-member is equal to grid width)} \]

\[ C_b := 1.0 \quad \text{(1.0 is a conservative assumption)} \]

\[ M_{n2} := \begin{cases} a & \text{if } a \leq M_p \\ M_{n1} & \text{otherwise} \end{cases} \]

\[ M_{n3} := \begin{cases} a & \text{if } a \leq M_p \\ M_{n1} & \text{otherwise} \end{cases} \]

3. Flange and Web Local Buckling

Criteria

\[ \lambda_{pw} := 3.76 \frac{E}{F_Y} \]

\[ \lambda_{pw} = 106.717 \]

\[ \lambda_{pf} := 0.38 \frac{E}{F_Y} \]

\[ \lambda_{pf} = 10.785 \]

Check

\[ \lambda_w \leq \lambda_{pw} = 1 \quad \text{(True, OK)} \]

\[ \lambda_f \leq \lambda_{pf} = 1 \quad \text{(True, OK)} \]

Therefore, FLB and WLB are not an issue
**Flexural Design Strength**

\[ \phi_b M_n = \phi_b M_n^f \]

(LTB controls for girders because \( M_n^2 < M_n^1 \))

\[ \phi_b M_n^3 = 55.854 \text{kip}\cdot\text{in} \]

(LTB controls for x-members because \( M_n^3 < M_n^1 \))

**Factored Loads for Flexure** (includes self-weight)

**Simply Supported**

Using SAP2000, 6 pt. loads of 440 lbs. were found to be acceptable

\[ M_u = 60.9 \text{kip}\cdot\text{in} \]

**Continuously Supported**

Using SAP2000, 2 pt. loads of 2700 lbs. were found to be acceptable

\[ M_u = 59.28 \text{kip}\cdot\text{in} \]
Using SAP2000, 4 pt. loads of 2900 lbs. were found to be acceptable

\[ M_u := -58.5 \text{kip in} \]

Cross Member Specification

\[ P_u := \frac{4M_{n3}}{L_{b2}} \quad P_u = 3.448 \text{kip} \]

(Concentrated Load at Midspan of x-memb.)

*The cross member load will actually be controlled by the connection detail*

Shear

Qualifications:
- *Unstiffened Web*
- *Doubly Symmetric Shape*

\[ \lambda_w \leq 260 = 1 \quad \text{(true)} \]

\[ \lambda_w \leq 2.45 \sqrt{\frac{E}{F_Y}} = 1 \quad \text{(true)} \]

\[ A_w := d \cdot t_w \]

\[ V_n := 0.6 F_Y \cdot A_w \quad \Rightarrow V_n = 11.016 \text{kip} \]

**Shear Design Strength**

\[ \phi V_n = 9.914 \text{kip} \]

*The shear capacity of the S3x5.7 can not be obtained because the flexural capacity controls.*
Bearing Plate Requirements

Assume, \( N := 0 \text{in} \)

1. **Web Yielding**

Supports

\[
R_{n1} := \phi_w(2.5k + N)F_y \cdot t_w
\]

\( R_{n1} = 9.563 \text{kip} \)  \[K1-3\]

Load Points

\[
R_{n2} := \phi_w(5k + N)F_y \cdot t_w
\]

\( R_{n2} = 19.125 \text{kip} \)  \[K1-2\]

2. **Web Crippling**

\[
\frac{N}{d} = 0 \quad \frac{N}{d} \leq 0.2
\]

Supports

\[
R_{n3} := \phi_Y 0.4t_w \left[ 1 + 3 \left( \frac{N}{d} \right) \left( \frac{t_w}{t_f} \right)^{1.5} \right] \sqrt{\frac{E_F y f}{t_w}}
\]

\( R_{n3} = 10.955 \text{kip} \)  \[K1-5a\]

Load Points

\[
R_{n4} := \phi_Y 0.8t_w \left[ 1 + 3 \left( \frac{N}{d} \right) \left( \frac{t_w}{t_f} \right)^{1.5} \right] \sqrt{\frac{E_F y f}{t_w}}
\]

\( R_{n4} = 21.911 \text{kip} \)  \[K1-4\]

\( R_w \cdot R_{n1} = 9.563 \text{kip} \)

(Web Yielding controls for girders because \( R_{n1} < R_{n2,3,4} \))

\( R_u := 2.9 \text{kip} \)

\( R_u \leq \phi_w \cdot R_{n1} \)  \((\text{Bearing plates are clearly not necessary})\)
Shear Connections for Cross Members

1. Coped Beam

\[ h_o := 1.75in \]
\[ l_{net} := \frac{t_w h_o^3}{12} \]
\[ c := \frac{h_o}{2} \]
\[ S_{net} := \frac{l_{net}}{c} \]
\[ e := \left(1.5 + \frac{3}{16}\right)\text{in} \]

Flexural Yielding

\[ \phi_{n5} := \phi_v \frac{F_y S_{net}}{e} \]

Local Buckling

Using conservative approach,

\[ K := 0.7 \quad \text{(from pg. 9-9)} \]
\[ \lambda := \frac{\sqrt{F_y}}{167\sqrt{ksi}} \frac{1}{K} \frac{h_o}{2 t_w} \]
\[ \lambda = 0.264 \]

\[ Q := 1.0 \quad \text{(b/c} \lambda < 0.7) \]

\[ F_{cr} := F_y Q \]
\[ \phi_{n6} := \phi_v \frac{F_{cr S_{net}}}{e} \]

\[ \phi_{n6} = 1.666\text{kip} \]
Shear Yielding

\[ \phi_{R_n7} := \phi_v \cdot 0.6 \cdot b \cdot t_w \cdot F_y \]
\[ \phi_{R_n7} = 5.783 \text{kip} \quad [J5-3] \]

Shear Rupture

\[ \phi_{R_n8} := \phi_v \cdot 0.6 \left( h_o - 2 \cdot \frac{5}{16} \text{ in} \right) \cdot t_w \cdot F_u \]
\[ \phi_{R_n8} = 4.992 \text{kip} \quad [J4-1] \]

Bolt Hole Bearing Strength

\[ \phi_{R_n9} := \begin{cases} 
\phi_v \cdot 2 \left( 1.2 \left( \frac{5}{16} \text{ in} \right) \cdot t_w \cdot F_u \right) & \text{if } a \leq b \\
\phi_v \cdot 2.4 \left( \frac{1}{4} \text{ in} \right) \cdot t_w \cdot F_u & \text{otherwise}
\end{cases} \]
\[ \phi_{R_n9} = 4.437 \text{kip} \quad [J4-1] \]

(this eqt. governs edge distance reqts)

2. Bolts

A307 Bolts
\[ F_v := 24 \text{ksi} \]
\[ A_b := \frac{\pi \left( \frac{.25 \text{ in}}{2} \right)^2}{4} \quad [\text{Table J3.2}] \]

*Threads will be permitted in the shear plane

\[ \phi_{R_{n10}} := \phi_v \cdot F_v \cdot A_b \quad \text{(for each bolt)} \]

Accounting for 2 bolts and 2 shear planes for each connection

\[ 4\phi_{R_{n10}} = 3.534 \text{kip} \]

3. Clip Angles

*Given that the dimensions of the angles are similar to that of the coped beam end, the connection angle strength will far exceed that of the beam because there are 2 angles used with 3/16 in. thickness which is greater than the beam web thickness.

Shear Connection Design Strength

\[ \phi_{R_n5} = 1.666 \text{kip} \quad *\text{Coped end detail controls the connection strength} \]
1. Check Effect of bolt holes in the Girder Flanges

\[ d_b := \frac{5}{16} \text{ in} \quad A_{fg} := t_f b_f \quad A_{fn} := A_{fg} - 2 \cdot \frac{\pi d_b^2}{4} \]

\[ 0.9 F_y \cdot A_{fg} = 19.628 \text{kip} \]

\[ 0.75 F_u \cdot A_{fn} = 19.679 \text{kip} \]

\[ 0.75 F_u \cdot A_{fn} \geq 0.9 F_y \cdot A_{fg} = 1 \quad \text{(True, no deduction in strength req'd)} \]
2. Plate Gross Section

Plate Properties

\[ t_p := \frac{3}{16} \text{in} \quad b_1 := 9\text{in} \quad b_2 := 7.5\text{in} \quad A_{g1} := t_p \cdot b_1 \quad A_{g2} := t_p \cdot b_2 \]

Design Strength

\[ \phi_{Pn1} := \phi_b \cdot F_y \cdot A_{g1} \quad [\phi_{Pn1} = 54.675\text{kip}] \]
\[ \phi_{Pn2} := \phi_b \cdot F_y \cdot A_{g2} \quad [\phi_{Pn2} = 45.563\text{kip}] \]

3. Plate Net Section

Plate Properties

\[ A_{n1} := t_p \cdot b_1 - 4 \left( \frac{\pi d_b^2}{4} \right) \quad A_{n2} := t_p \cdot b_2 - 3 \left( \frac{\pi d_b^2}{4} \right) \]

Design Strength

\[ \phi_{Pn3} := \phi_r \cdot F_u \cdot A_{n1} \quad [\phi_{Pn3} = 60.061\text{kip}] \]
\[ \phi_{Pn4} := \phi_r \cdot F_u \cdot A_{n2} \quad [\phi_{Pn4} = 51.163\text{kip}] \]

3. Bolts

*The same bolts and assumptions are used from the shear connector design

\[ \phi_{Pn5} := 4 \left( \phi_r \cdot F_v \cdot A_b \right) \quad \text{(Accounting for 4 bolts and a single shear plane)} \]
\[ [\phi_{Pn5} = 3.534\text{kip}] \quad \text{(The bolts are the limiting case)} \]

Design Strength

\[ \phi_{M_{up}} := d \cdot \phi_{Pn5} \quad [\phi_{M_{up}} = 10.603\text{kip}] \]

Using a very conservative assumption of fixed end moment capacity

\[ P_{up} := \frac{8 \cdot \phi_{M_{up}}}{72\text{in}} \quad [P_{up} = 1.178\text{kip}] \quad \text{(This Concentrated Load at Midspan controls the x-memb. capacity)} \]
APPENDIX B: FABRICATION DRAWINGS
Grid Model (Elevation View)
Grid Model: (Plan View)

Note: See "Detail A" on following page
Detail A:
Main Beams:

Top Flange: (ALL 8" HOLES)

Bottom Flange: (ALL 8" HOLES)

Notes:
- Spaces change at eyes and middle of bottom flange
- Detail B (pg. 5)
- Detail C, D (pg. 6)
Detail B: (Elevation View)

*NOTE: ALL 3/8" HOLES*
Detail C: (Plan View)

Top Flange: (ALL $\frac{3}{16}$ HOLES)

Detail D: (Plan View)

Bottom Flange: (ALL $\frac{3}{8}$ HOLES)
Cross Members:

Note: See page 8 for "Detail E"

<table>
<thead>
<tr>
<th>Name</th>
<th>M2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>53 x 57</td>
</tr>
<tr>
<td>Qty</td>
<td>7</td>
</tr>
<tr>
<td>Page</td>
<td>7</td>
</tr>
</tbody>
</table>
Coped End Detail:

Elevation View:  
Plan View:

Note: The coped ends may be manufactured by any process as long as the given dimensions are satisfied.
Connection Angles:

*Note: The angles are drilled the same for both legs.

<table>
<thead>
<tr>
<th>Name</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>1(\frac{1}{4}) x 1(\frac{1}{2}) x (\frac{3}{8})</td>
</tr>
<tr>
<td>Qty</td>
<td>30</td>
</tr>
<tr>
<td>Page</td>
<td>9</td>
</tr>
</tbody>
</table>
Shims:

Plan View:

Elevation View:

<table>
<thead>
<tr>
<th>Name</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>PL (\frac{1}{4}^\prime)</td>
<td>6</td>
</tr>
<tr>
<td>S2</td>
<td>PL (\frac{1}{8}^\prime)</td>
<td>6</td>
</tr>
<tr>
<td>S3</td>
<td>PL (\frac{1}{16}^\prime)</td>
<td>6</td>
</tr>
</tbody>
</table>

Page: 10
Boundary Supports:

Plan View:

Elevation View:

<table>
<thead>
<tr>
<th>Name</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>PL 1&quot;</td>
<td>12</td>
</tr>
<tr>
<td>M5</td>
<td>Round Bar 1½&quot;</td>
<td>7</td>
</tr>
</tbody>
</table>

Page: 11
Connection Plates: (5/16" holes only)

P1

P2

P3

*Note: The 1/4" spacing on P2 changed to 1/2" for P1 and P3

<table>
<thead>
<tr>
<th>Name</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>PL 3/8&quot;</td>
<td>4</td>
</tr>
<tr>
<td>P2</td>
<td>PL 1/2&quot;</td>
<td>16</td>
</tr>
<tr>
<td>P3</td>
<td>PL 3/8&quot;</td>
<td>8</td>
</tr>
</tbody>
</table>

Page: 12
Notes:
- Column is to be centered on base plate
- Both plates are to be fully welded to specified locations with 1/4" welds

<table>
<thead>
<tr>
<th>Name</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>PL 2&quot;</td>
<td>6</td>
</tr>
<tr>
<td>C2</td>
<td>PL 1&quot;</td>
<td>6</td>
</tr>
<tr>
<td>C3</td>
<td>W12 X 26</td>
<td>6</td>
</tr>
</tbody>
</table>
Geokon Vibrating Wire Strain Gage
Model 4100

<table>
<thead>
<tr>
<th>Strain Gage</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>3000 µε</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 µε</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.1% FS</td>
<td></td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>-5 to 175°F</td>
<td>-20 to 80°C</td>
</tr>
<tr>
<td>Length</td>
<td>2 in.</td>
<td>51 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermistor</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>-112 to 302°F</td>
<td>-80 to +150°C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.9°F</td>
<td>+/- 0.5°C</td>
</tr>
</tbody>
</table>
Geokon Vibrating Wire Strain Gage
Model 4000

<table>
<thead>
<tr>
<th>Strain Gage</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>3000 µε</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 µε</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.1% FS</td>
<td></td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>-5 to 175°F</td>
<td>-20 to 80°C</td>
</tr>
<tr>
<td>Length</td>
<td>5.875 in.</td>
<td>150 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermistor</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>-112 to 302°F</td>
<td>-80 to +150°C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.9°F</td>
<td>+/- 0.5°C</td>
</tr>
</tbody>
</table>

*Dimensions of the Model 4000.*
# Geokon Vibrating Wire Tiltmeter
## Model 6350

<table>
<thead>
<tr>
<th>Tilt Sensor</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>+/- 15°</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>10 arc seconds</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.1% FSR</td>
<td></td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>-40 to 90°F</td>
<td>-40 to 90°C</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.250 in.</td>
<td>32 mm</td>
</tr>
<tr>
<td>Length</td>
<td>7.375 in.</td>
<td>187 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>1.5 lbs.</td>
<td>0.7 kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermistor</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>-112 to 302°F</td>
<td>-80 to +150°C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.9°F</td>
<td>+/- 0.5°C</td>
</tr>
</tbody>
</table>
ICP® Accelerometer
Model 393C

<table>
<thead>
<tr>
<th>Performance</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (± 15 %)</td>
<td>1000 mV/g</td>
<td>101.9 mV/(m/s²)</td>
</tr>
<tr>
<td>Measurement Range</td>
<td>2.5 g pk</td>
<td>24.5 m/s² pk</td>
</tr>
<tr>
<td>Frequency Range (± 5 %)</td>
<td>0.025 to 800 Hz</td>
<td>0.025 to 800 Hz</td>
</tr>
<tr>
<td>(± 10 %)</td>
<td>0.01 to 1200 Hz</td>
<td>0.01 to 1200 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (Diameter x Height)</td>
<td>2.25 x 2.16 in</td>
<td>57.2 x 54.9 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>31.2 oz</td>
<td>885 gm</td>
</tr>
</tbody>
</table>
3700 Series Capacitive Accelerometer
Model 3701G3FA3G

<table>
<thead>
<tr>
<th>Performance</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (+/- 5%)</td>
<td>1000mV/g</td>
<td>102 mV/(m/s²)</td>
</tr>
<tr>
<td>Measurement Range</td>
<td>+/- 3g</td>
<td>+/- 29 m/s²</td>
</tr>
<tr>
<td>Frequency Range (+/- 5%)</td>
<td>0 to 100 Hz</td>
<td>0 to 100 Hz</td>
</tr>
<tr>
<td>Frequency Range (+/- 10%)</td>
<td>0 to 150 Hz</td>
<td>0 to 150 Hz</td>
</tr>
</tbody>
</table>

**Electrical**

| Spectral Noise (1 Hz)        | 15µg/√Hz         | 145 (µm/s²)/√Hz |
| Spectral Noise (10 Hz)       | 4µg/√Hz          | 39 (µm/s²)/√Hz  |
| Spectral Noise (100 Hz)      | 1µg/√Hz          | 10 (µm/s²)/√Hz  |

**Physical**

| Size (Height x Length x Width) | 0.45 x 0.85 x 0.85 in. | 11.4 x 21.6 x 21.6 mm |
| Weight                        | 0.62 oz.           | 17.5 gm            |
086 Series ICP® Hammer  
Model 086D20

<table>
<thead>
<tr>
<th>Performance</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (± 15 %)</td>
<td>1 mV/lbf</td>
<td>0.23 mV/N</td>
</tr>
<tr>
<td>Measurement Range</td>
<td>± 5000 lbf pk</td>
<td>± 22,000 N pk</td>
</tr>
<tr>
<td>Frequency Range (-10 dB)</td>
<td>1 kHz</td>
<td></td>
</tr>
<tr>
<td>(Hard Tip)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(-10 dB) (Medium Tip)</td>
<td>700 Hz</td>
<td></td>
</tr>
<tr>
<td>(-10 dB) (Soft Tip)</td>
<td>450 Hz</td>
<td></td>
</tr>
<tr>
<td>(-10 dB) (Super Soft Tip)</td>
<td>400 Hz</td>
<td></td>
</tr>
</tbody>
</table>

**Physical**

<table>
<thead>
<tr>
<th>Physical</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer Mass</td>
<td>2.4 lb</td>
<td>1.1 kg</td>
</tr>
<tr>
<td>Head Diameter</td>
<td>2.0 in</td>
<td>5.1 cm</td>
</tr>
<tr>
<td>Tip Diameter</td>
<td>2.0 in</td>
<td>5.1 cm</td>
</tr>
<tr>
<td>Hammer Length</td>
<td>14.5 in</td>
<td>37 cm</td>
</tr>
<tr>
<td>Electrical Connector</td>
<td>BNC Jack</td>
<td></td>
</tr>
</tbody>
</table>
Electro-Seis Shaker
Model 113-F

<table>
<thead>
<tr>
<th>Properties</th>
<th>English</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>0 to 200 Hz</td>
<td></td>
</tr>
<tr>
<td>Force Rating (50% Duty Cycle – ½ hr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dc to 0.1 Hz</td>
<td>30 lb pk</td>
<td>133 N pk</td>
</tr>
<tr>
<td>Above 0.1 Hz</td>
<td>42 lb pk</td>
<td>186 N pk</td>
</tr>
<tr>
<td>Above 20 Hz</td>
<td>Refer to Graph</td>
<td></td>
</tr>
<tr>
<td>Maximum Stroke</td>
<td>6.25 in pk-pk</td>
<td>158 mm pk-pk</td>
</tr>
<tr>
<td>Velocity</td>
<td>30 in/s</td>
<td>762 mm/s</td>
</tr>
</tbody>
</table>

Force Envelope for Model 113 Shaker in the fixed and free body modes
APPENDIX D: CALCULATIONS FOR NUMERICAL FEM
**Joint Inertia**

**Given:**

- **S3x5.7 Beam**
  - \( I_s := 2.52 \text{in}^4 \)
  - \( b_f := 2.33 \text{in} \)
  - \( t_f := 0.26 \text{in} \)
  - \( t_w := 0.17 \text{in} \)

- **3/16" Plate**
  - \( t_{pl} := \frac{3}{16} \text{in} \)
  - \( b_{pl} := 2.33 \text{in} \)

*Cross-Hatched area contributes to additional Inertia*

**Calculate Additional Inertia From Plates**

\[
A_{pl} := t_{pl} \cdot b_{pl} \\
A_{pl} = 0.437 \text{in}^2
\]

\[
y_c := \frac{d}{2} + \frac{l_{pl}}{2} \\
y_c = 1.594 \text{in}
\]

\[
I_{pl} := 2 \left( \frac{b_{pl} \cdot t_{pl} \cdot \frac{3}{12}}{I_{pl}} + A_{pl} \cdot y_c^2 \right) \\
I_{pl} = 2.222 \text{in}^4
\]

**Total Inertia of Composite Joint Section**

\[
I_{tot} := I_s + I_{pl} \\
I_{tot} = 4.742 \text{in}^4
\]
Gross Joint Masses

1. Cover Plates

\[ t_p := \frac{3}{16} \text{ in} \]

\[ A_p := (9.6 - 3.25) \text{ in}^2 \]

\[ A_p = 46.5 \text{ in}^2 \]

\[ V_p := A_p \cdot t_p \]

\[ V_p = 8.719 \text{ in}^3 \]

\[ W_p := \left( \frac{490 \text{ lbf}}{\text{ ft}^3} \right) V_p \]

\[ W_p = 2.47 \text{ lbf} \]

\[ M_p := \frac{W_p}{32.2 \text{ ft}} \]

\[ M_p = 0.0768 \frac{\text{lbf \cdot sec}^2}{\text{ft}} \]

2. 30 Bolts, Nuts, and Washers

\[ d_b := \frac{1}{4} \text{ in} \]

\[ L_b := 2 \text{ in} \]

\[ A_b := \frac{\pi \cdot d_b^2}{4} \]

\[ A_b = 0.049 \text{ in}^2 \]

\[ V_b := A_b \cdot L_b \]

\[ V_b = 0.098 \text{ in}^3 \]

\[ W_b := \left( \frac{490 \text{ lbf}}{\text{ ft}^3} \right) V_b \]

\[ W_b = 0.0278 \text{ lbf} \]

\[ M_b := \frac{30 \cdot W_b}{32.2 \text{ ft}} \]

\[ M_b = 0.0259 \frac{\text{lbf \cdot sec}^2}{\text{ft}} \]

3. Accelerometers

\[ W_a := 2 \text{ lbf} \]

\[ M_a := \frac{W_a}{32.2 \text{ ft}} \]

\[ M_a = 0.062 \frac{\text{lbf \cdot sec}^2}{\text{ft}} \]
Joint Mass (Not included by steel in inertia calc's)

Interior Joints

Regions of extra mass

\[
A_1 := 4 \left( \frac{13}{16} \right) \left( 3 + \frac{11}{16} \right) + 2.5 \left( \frac{11}{16} \right) + \frac{1}{2} (2.5)(3) \] \text{ in}^2
\]

\[A_1 = 33.859 \text{ in}^2\]

\[
M_1 := \frac{A_1 \left( \frac{3}{16} \text{ in} \right) \left( \frac{490 \text{ lbf}}{\text{ ft}^3} \right)}{32.2 \frac{\text{ ft}}{\text{ sec}^2}}
\]

\[M_1 = 0.056 \frac{\text{ lbf} \cdot \text{sec}^2}{\text{ ft}}\]
APPENDIX E: EXPERIMENTAL TEST PLAN
**Test Plan**

**Location:** UCF Structures Lab  
**Specimen:** Grid Model

- **Test Type:** Dynamic testing with impact hammer and ambient vibration  
- **Test Item Description:** Two Span Steel Grid Structure  
- **Creation Date:** 23 June 2005  
- **Test Date:** 27-30 June 2005  
- **Advisor:** Dr. F. Necati Catbas  
- **Authors:** Jason Burkett  
  Mustafa Gul

**BACKGROUND INFORMATION**

There are a number of studies currently in progress at the UCF Structures Laboratory within the Structures and Systems Research Group. At the center of attention in the laboratory is the UCF Grid Model designed and setup by Burkett and Catbas (2004). The grid shown in Figure 2 is 6 ft wide and 18 ft long with cross-members equally spaced at 3 ft intervals, all sections are AISC S3x5.7. Laboratory models like this grid are critical for successful health monitoring of real life structures. Proposed theory and methodologies should be validated before their implementation in the field.

The primary author is working closely with Dr. Catbas on an international benchmark study using the UCF grid. The focus of this study is to use different algorithms, indices, and other methods to detect damage that is induced on the numerical model as a first phase. Later phases, as well as Jason’s current thesis work will include experimental studies using the same methods of the numerical phase. Therefore, the goal of this test plan is to extract the dynamic properties of the grid structure in its baseline and “damaged” conditions. Quality baseline data is also needed from the grid to be used for other comparative analyses. The specific data needs are included in later sections of this test plan.

**TEST OBJECTIVES**

The objective of this test is to positively identify the dynamic and static properties of the UCF Grid using impact and ambient vibration tests. Specialized algorithms, techniques, and software will be used to extract the dynamic properties which will also be used to approximate the flexibility of the structure.
Figure 1: Identification of Grid Joints

Figure 2: Laboratory Setup

Figure 3: Spatial Coordinates

**TEST CONFIGURATIONS**

**Two-Span (9 ft clear spans):** For the two-span configuration, the middle supports shown in Figure 2 must be in place and in contact with the grid so that a total of six supports are influencing the grid. First, baseline data will be collected for the two-span configuration. Several “damage” cases will be tested thereafter, which requires physically changing different components and details of the structure. All details of the baseline and damage, test configurations are specified in the following table.

<table>
<thead>
<tr>
<th>Node</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>72</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>108</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>144</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>180</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>216</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>36</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>72</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>108</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>144</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>180</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>216</td>
<td>72</td>
<td>0</td>
</tr>
</tbody>
</table>
**Table 1: Test Descriptions**

<table>
<thead>
<tr>
<th>Damage Scenarios</th>
<th>Damage Characteristic</th>
<th>Grid Configuration</th>
<th>Damage Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Healthy/Baseline</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2) Scour/Settlement</td>
<td>A.) 3/4” Settlement</td>
<td>Insert 3/4” shims to other supports</td>
<td>Jt. 4</td>
</tr>
<tr>
<td></td>
<td>B.) 3/4” Settlement</td>
<td>Insert 3/4” shims to other supports</td>
<td>Jt. 7</td>
</tr>
<tr>
<td></td>
<td>C.) Pile Loss</td>
<td>Remove round bar at support</td>
<td>Jt. 4</td>
</tr>
<tr>
<td>3) Boundary Support Change</td>
<td>A.) Restrained Rotation and Translation</td>
<td>Insert bolts through top and bottom support blocks and tighten</td>
<td>Jts. 7, 14</td>
</tr>
<tr>
<td></td>
<td>B.) Restrained Rotation and Translation</td>
<td>Insert bolts through top and bottom support blocks and tighten</td>
<td>Jts. 4, 7, 11, 14</td>
</tr>
<tr>
<td>4) Reduced Stiffness</td>
<td>A.) Cross-Member Hinge</td>
<td>Loosen 8 bolts through both ends of cross-member</td>
<td>Jts. 3, 10</td>
</tr>
<tr>
<td></td>
<td>B.) Reduced girder inertia and cross-member hinge</td>
<td>Remove connection plates</td>
<td>Jt. 3</td>
</tr>
</tbody>
</table>

**GENERAL TEST PREPARATION**

1. Install 15 accelerometers at the locations shown in Figure 4. Acceptable methods of attachment include: magnets, thin layer of hot glue, thin layer of wax, or removable epoxy. New sensors do not actually need to be installed since the 15 accelerometers shown in Figure 4 are already installed. For quality assurance the sensor locations and attachment should be verified as a minimum requirement. All arrows represent single-axis accelerometers and the vector along which data shall be collected. Table 3 gives a detailed description of each sensor’s properties while their corresponding locations are in Figure 4.

2. Verify that existing and new cables are labeled in compliance with the preexisting setup and channel information in Table 3. New cables should be labeled at each end, continuing from the highest number that exists in the current setup, so that cables do not get mixed up.

3. After any sensors are installed or rewired according to Table 3, a demo run should be made to verify that data is being collected from each sensor on its correct channel. This step is critical for verifying such errors as discontinuity and misconnections in cables which could lead to lost or unidentified data.

4. Since the number of available channels is 16, it is possible to collect data from every sensor simultaneously. On the other hand, all the vertical response data may not be necessary for the horizontal excitation tests. Only 15 sensors may be used since the hammer is designated to the first channel. Refer to Figure 5 for the diagrams showing which sensors are used for the respective tests and the channel assignments are listed in Table 4.

5. Refer Table 2 for all acquisition settings for the various test procedures. These parameters have been predetermined by both theory and experimental trial.
TEST PROCEDURE

1. Begin Test 1. Set acquisition settings according to vertical acquisition parameters of Table 2. With all grid supports in place and no damage induced, the impact hammer should be used to impact the grid in the vertical direction at joints 2, 5, 6, and 12. All vertical sensors and channels should be activated according to Table 4 and Figure 5. The point of impact should coincide with the vertical sensor axis (i.e. vertical impact points should be on the bottom connection plates of the grid). Five impact repetitions at each specified joint location should be recorded so that a total of 4*5=20 impacts on the grid will take place for the vertical part of Test 1.

Set acquisition settings according to ambient acquisition parameters of Table 2. Instead of using the hammer, provide a light, random input to the structure at various locations and directions for the specified time period.

Set acquisition settings according to horizontal acquisition parameters of Table 2. Deselect the unnecessary channels for horizontal testing as specified in Figure 5 and Table 4. To excite the grid’s horizontal modes, use the hammer to impact joints 2, 3, and 5. Although there are no sensors at joints 2, 3, or 6 it is assumed that the cross-members will act rigidly for the horizontal modes being excited. Again, the impact location should coincide with the horizontal measurement axes (i.e. horizontal impact points should be on the center of the girder web, not the flanges) with 5 repetitions for each specified joint location. End Test 1.

2. Repeat step 1 for each damage scenario in Table 1. A total of 8 tests should be conducted using 3 different excitation methods for each test.
**FINAL DATA REQUIREMENTS**

The modal parameters of the structure will be identified using two methods. First, commercial software will be used. Second, the data will be analyzed by a system identification method. The final test results will be stored according to the file directory shown in Figure 6 and in a compatible electronic file format such as Data Set 55, Universal File, etc. The main dynamic properties to be identified include eigenvalues (modal frequencies and damping values), eigenvectors (mode shapes), modal scaling, and modal flexibility.

The commercial software that will be used in this study is I-DEAS/MTS TEST. The system identification method which will be used is a proven, robust modal parameter estimation technique that has been developed over ten years of research (Catbas et al). This method has been used in laboratory studies and many medium-span bridges as well as long-span bridges.

After the data is processed the final mode shapes will be plotted and modal correlations will be documented for the verification and comparison of experimental and analytical results. In addition, the modal flexibility of the grid will be used for various damage detection indices.
### Table 2: Data Acquisition Parameters

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Vertical</th>
<th>Ambient</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Frequency [Hz]</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Number of Spectral Lines</td>
<td>801</td>
<td>-</td>
<td>801</td>
</tr>
<tr>
<td>Length of Time Record [sec]</td>
<td>10.24</td>
<td>300</td>
<td>10.24</td>
</tr>
<tr>
<td>Trigger on Hammer Input</td>
<td>10%</td>
<td>-</td>
<td>10%</td>
</tr>
<tr>
<td>Trigger Delay [sec]</td>
<td>0.05</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>Windows Exponential</td>
<td>-</td>
<td>Exponential</td>
<td></td>
</tr>
<tr>
<td>Impact Window Width</td>
<td>1%</td>
<td>-</td>
<td>1%</td>
</tr>
<tr>
<td>Exponential Window Decay Rate</td>
<td>0.1%</td>
<td>-</td>
<td>0.1%</td>
</tr>
<tr>
<td>Noise Reduction Method</td>
<td>H1</td>
<td>-</td>
<td>H1</td>
</tr>
<tr>
<td>Blocksize</td>
<td>2,048</td>
<td>2,048</td>
<td>2,048</td>
</tr>
<tr>
<td>Number of Samples</td>
<td>4096</td>
<td>120,000</td>
<td>4096</td>
</tr>
<tr>
<td>Number of Averages</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Hammer Range [V]</td>
<td>+/- 0.1</td>
<td>-</td>
<td>+/- 0.2</td>
</tr>
<tr>
<td>Max. Accelerometer Range [V]</td>
<td>+/- 2</td>
<td>+/- 0.5</td>
<td>+/- 2</td>
</tr>
<tr>
<td>Hammer Tip</td>
<td>Med. (Red)</td>
<td>-</td>
<td>Med. (Red)</td>
</tr>
</tbody>
</table>

### Table 3: Sensor Properties

<table>
<thead>
<tr>
<th>Sensor Label</th>
<th>Serial #</th>
<th>Type</th>
<th>Measurement Direction</th>
<th>Sensitivity [mV/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer 20565</td>
<td></td>
<td>Force Transducer</td>
<td>Variable</td>
<td>0.93*</td>
</tr>
<tr>
<td>1 9272</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>960</td>
<td></td>
</tr>
<tr>
<td>2 8954</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1077</td>
<td></td>
</tr>
<tr>
<td>3 8200</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1101</td>
<td></td>
</tr>
<tr>
<td>4 8782</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1024</td>
<td></td>
</tr>
<tr>
<td>5 9215</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1015</td>
<td></td>
</tr>
<tr>
<td>6 8051</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1114</td>
<td></td>
</tr>
<tr>
<td>7 9211</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>924</td>
<td></td>
</tr>
<tr>
<td>8 8691</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1063</td>
<td></td>
</tr>
<tr>
<td>9 9177</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1040</td>
<td></td>
</tr>
<tr>
<td>10 8567</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1069</td>
<td></td>
</tr>
<tr>
<td>11 8783</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1064</td>
<td></td>
</tr>
<tr>
<td>12 8922</td>
<td>ICP Seis Accel</td>
<td>Vertical</td>
<td>1065</td>
<td></td>
</tr>
<tr>
<td>13 5226</td>
<td>Capacitive Accel</td>
<td>Transverse</td>
<td>1028</td>
<td></td>
</tr>
<tr>
<td>14 5537</td>
<td>Capacitive Accel</td>
<td>Transverse</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>15 5540</td>
<td>Capacitive Accel</td>
<td>Transverse</td>
<td>966</td>
<td></td>
</tr>
<tr>
<td>16 8958</td>
<td>ICP Seis Accel</td>
<td>Transverse</td>
<td>1009</td>
<td></td>
</tr>
</tbody>
</table>

*Note: [mV/lbf]*
Table 4: Channel Assignments for Tests

<table>
<thead>
<tr>
<th>Channel</th>
<th>Sensors</th>
<th>Vertical</th>
<th>Ambient</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hammer</td>
<td>1</td>
<td>-</td>
<td>Hammer</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>12</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>-</td>
<td>13</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td>14</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td>15</td>
<td>16</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 6: Representative Data File Directory
APPENDIX F: NUMERICAL TEST RESULTS
BASELINE GRID

(numerical)
## Dynamic Properties

### Baseline FE Model

![Baseline FE Model Diagram](image)

### Modal Properties

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Period [sec]</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.167</td>
<td>0.055044</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>2</td>
<td>20.650</td>
<td>0.048427</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>3</td>
<td>22.234</td>
<td>0.044976</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>23.580</td>
<td>0.042409</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>5</td>
<td>34.645</td>
<td>0.028864</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>36.692</td>
<td>0.027254</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>41.974</td>
<td>0.023824</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>8</td>
<td>44.125</td>
<td>0.022663</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>9</td>
<td>53.488</td>
<td>0.018696</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>10</td>
<td>55.546</td>
<td>0.018003</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>11</td>
<td>63.492</td>
<td>0.015750</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>12</td>
<td>84.917</td>
<td>0.011776</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>91.372</td>
<td>0.010944</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>14</td>
<td>101.240</td>
<td>0.009877</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>110.140</td>
<td>0.009079</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
Baseline Grid Modes

Mode 1 – 18.17 Hz
Horz. Bending

Mode 2 – 20.65 Hz
Horz. Bending

Mode 3 – 22.23 Hz
Vert. Bending

Mode 4 – 23.58 Hz
Vert. Torsion

Mode 5 – 34.65 Hz
Vert. Bending

Mode 6 – 36.69 Hz
Vert. Bending

Mode 7 – 41.97 Hz
Horz. Bending

Mode 8 – 44.13 Hz
Horz. Bending

Mode 9 – 53.49 Hz
Horz. Bending

Mode 10 – 55.55 Hz
Horz. Bending

Mode 11 – 63.49 Hz
Horz. Bending

Mode 12 – 84.92 Hz
Vert. Bending

Mode 13 – 91.37 Hz
Vert. Bending

Mode 14 – 101.24 Hz
Vert. Bending

Mode 15 – 110.14 Hz
Vert. Bending
PILE LOSS
(numerical)
# Dynamic Properties

## Pile Loss Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.78 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>18.17 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>3</td>
<td>19.27 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>4</td>
<td>22.23 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>5</td>
<td>23.58 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>6</td>
<td>35.63 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>38.24 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>8</td>
<td>44.13 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>9</td>
<td>51.06 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>10</td>
<td>52.86 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>11</td>
<td>55.55 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>12</td>
<td>63.22 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>13</td>
<td>84.92 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>91.37 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>104.84 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>16</td>
<td>126.44 Hz</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
### Baseline Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.522</td>
</tr>
<tr>
<td>6</td>
<td>0.519</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>0.000</td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>0.254</td>
</tr>
<tr>
<td>15</td>
<td>0.254</td>
</tr>
</tbody>
</table>

### Pile Loss Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>0.993</td>
</tr>
<tr>
<td>3</td>
<td>1.000</td>
</tr>
<tr>
<td>4</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>0.064</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>0.073</td>
</tr>
<tr>
<td>10</td>
<td>0.047</td>
</tr>
<tr>
<td>11</td>
<td>0.049</td>
</tr>
<tr>
<td>12</td>
<td>0.000</td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### MAC Values

<table>
<thead>
<tr>
<th>Mode</th>
<th>MAC Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.519</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>0.000</td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Pile Loss</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.17</td>
<td>2</td>
<td>18.17</td>
</tr>
<tr>
<td>2</td>
<td>20.65</td>
<td>3</td>
<td>19.27</td>
</tr>
<tr>
<td>3</td>
<td>22.23</td>
<td>4</td>
<td>22.23</td>
</tr>
<tr>
<td>4</td>
<td>23.58</td>
<td>5</td>
<td>23.58</td>
</tr>
<tr>
<td>5</td>
<td>34.65</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>36.69</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>41.97</td>
<td>7</td>
<td>38.24</td>
</tr>
<tr>
<td>8</td>
<td>44.13</td>
<td>8</td>
<td>44.13</td>
</tr>
<tr>
<td>9</td>
<td>53.49</td>
<td>10</td>
<td>52.86</td>
</tr>
<tr>
<td>10</td>
<td>55.55</td>
<td>11</td>
<td>55.55</td>
</tr>
<tr>
<td>11</td>
<td>63.49</td>
<td>12</td>
<td>63.22</td>
</tr>
<tr>
<td>12</td>
<td>84.92</td>
<td>13</td>
<td>84.92</td>
</tr>
<tr>
<td>13</td>
<td>91.37</td>
<td>14</td>
<td>91.37</td>
</tr>
<tr>
<td>14</td>
<td>101.24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>110.14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td>16</td>
<td>126.44</td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix \([F_{\text{Baseline}} - F_{\text{Damaged}}]\)
Pseudoflexibility Loads

Load Case 1

Load Case 2

Load Case 3
Displacement Patterns

![Displacement Profile (Load 1, Girder 1)](image)

![Displacement Profile (Load 1, Girder 2)](image)

![Displacement Profile (Load 2, Girder 1)](image)

![Displacement Profile (Load 2, Girder 2)](image)

![Displacement Profile (Load 3, Girder 1)](image)

![Displacement Profile (Load 3, Girder 2)](image)
Change in Displacement

(Load 1, Girder 1)

(Load 2, Girder 1)

(Load 3, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 2)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3 Girder 2)
JT. 7, 14 RESTRAINED
(numerical)
## Dynamic Properties

### 7_14 Fixed Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.27 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>2</td>
<td>20.78 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>3</td>
<td>25.87 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>27.41 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>5</td>
<td>42.26 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>6</td>
<td>43.97 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>44.94 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>8</td>
<td>46.58 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>9</td>
<td>54.42 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>10</td>
<td>60.87 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>11</td>
<td>64.54 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>12</td>
<td>90.58 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>97.79 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>109.81 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>120.34 Hz</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
### MAC Values

#### 2 Supports Fixed Modes

<table>
<thead>
<tr>
<th>Baseline Modes</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.999</td>
<td>0.046</td>
<td>0.000</td>
<td>0.001</td>
<td>0.012</td>
<td>0.000</td>
<td>0.009</td>
<td>0.000</td>
<td>0.033</td>
<td>0.023</td>
<td>0.008</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>0.045</td>
<td>0.999</td>
<td>0.000</td>
<td>0.000</td>
<td>0.046</td>
<td>0.000</td>
<td>0.029</td>
<td>0.000</td>
<td>0.080</td>
<td>0.065</td>
<td>0.040</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>0.000</td>
<td>0.000</td>
<td>0.922</td>
<td>0.000</td>
<td>0.000</td>
<td>0.367</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.072</td>
<td>0.000</td>
<td>0.097</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.922</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.366</td>
<td>0.006</td>
<td>0.030</td>
<td>0.000</td>
<td>0.000</td>
<td>0.072</td>
<td>0.000</td>
<td>0.097</td>
</tr>
<tr>
<td>5</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.384</td>
<td>0.000</td>
<td>0.000</td>
<td>0.911</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.101</td>
<td>0.000</td>
<td>0.129</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.384</td>
<td>0.001</td>
<td>0.000</td>
<td>0.004</td>
<td>0.912</td>
<td>0.012</td>
<td>0.051</td>
<td>0.000</td>
<td>0.000</td>
<td>0.101</td>
<td>0.000</td>
<td>0.128</td>
</tr>
<tr>
<td>7</td>
<td>0.030</td>
<td>0.010</td>
<td>0.000</td>
<td>0.000</td>
<td>0.211</td>
<td>0.000</td>
<td>0.971</td>
<td>0.005</td>
<td>0.217</td>
<td>0.026</td>
<td>0.012</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.001</td>
<td>0.120</td>
<td>0.000</td>
<td>0.000</td>
<td>0.077</td>
<td>0.000</td>
<td>0.121</td>
<td>0.001</td>
<td>0.749</td>
<td>0.467</td>
<td>0.308</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>0.050</td>
<td>0.008</td>
<td>0.000</td>
<td>0.001</td>
<td>0.17</td>
<td>0.000</td>
<td>0.338</td>
<td>0.008</td>
<td>0.659</td>
<td>0.690</td>
<td>0.302</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>10</td>
<td>0.002</td>
<td>0.060</td>
<td>0.000</td>
<td>0.000</td>
<td>0.337</td>
<td>0.000</td>
<td>0.082</td>
<td>0.001</td>
<td>0.016</td>
<td>0.485</td>
<td>0.914</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.040</td>
<td>0.000</td>
<td>0.162</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.908</td>
<td>0.000</td>
<td>0.376</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.040</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.161</td>
<td>0.005</td>
<td>0.034</td>
<td>0.000</td>
<td>0.000</td>
<td>0.909</td>
<td>0.000</td>
<td>0.376</td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
<td>0.000</td>
<td>0.024</td>
<td>0.000</td>
<td>0.000</td>
<td>0.095</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.400</td>
<td>0.000</td>
<td>0.912</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>0.000</td>
<td>0.000</td>
<td>0.024</td>
<td>0.000</td>
<td>0.000</td>
<td>0.095</td>
<td>0.000</td>
<td>0.003</td>
<td>0.018</td>
<td>0.000</td>
<td>0.000</td>
<td>0.399</td>
<td>0.000</td>
<td>0.912</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.024</td>
<td>0.000</td>
<td>0.000</td>
<td>0.095</td>
<td>0.000</td>
<td>0.003</td>
<td>0.018</td>
<td>0.000</td>
<td>0.000</td>
<td>0.399</td>
<td>0.000</td>
<td>0.912</td>
</tr>
</tbody>
</table>

### Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Frequency [Hz]</th>
<th>2 Supports Fixed</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.17</td>
<td>18.27</td>
<td>0.57%</td>
<td>0.999 Horz</td>
</tr>
<tr>
<td>2</td>
<td>20.65</td>
<td>20.78</td>
<td>0.63%</td>
<td>0.999 Horz</td>
</tr>
<tr>
<td>3</td>
<td>22.23</td>
<td>25.87</td>
<td>16.35%</td>
<td>0.922 Vert</td>
</tr>
<tr>
<td>4</td>
<td>23.58</td>
<td>27.41</td>
<td>16.24%</td>
<td>0.922 Vert</td>
</tr>
<tr>
<td>5</td>
<td>34.65</td>
<td>43.97</td>
<td>26.92%</td>
<td>0.911 Vert</td>
</tr>
<tr>
<td>6</td>
<td>36.69</td>
<td>46.58</td>
<td>26.95%</td>
<td>0.912 Vert</td>
</tr>
<tr>
<td>7</td>
<td>41.97</td>
<td>42.26</td>
<td>0.68%</td>
<td>0.976 Horz</td>
</tr>
<tr>
<td>8</td>
<td>44.13</td>
<td>44.94</td>
<td>1.85%</td>
<td>0.971 Horz</td>
</tr>
<tr>
<td>9</td>
<td>53.49</td>
<td>-</td>
<td>-</td>
<td>-     Horz</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>54.42</td>
<td>-</td>
<td>-     Horz</td>
</tr>
<tr>
<td>10</td>
<td>55.55</td>
<td>-</td>
<td>-</td>
<td>-     Horz</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>60.87</td>
<td>-</td>
<td>-     Horz</td>
</tr>
<tr>
<td>11</td>
<td>63.49</td>
<td>64.54</td>
<td>1.65%</td>
<td>0.914 Horz</td>
</tr>
<tr>
<td>12</td>
<td>84.92</td>
<td>90.58</td>
<td>6.67%</td>
<td>0.908 Vert</td>
</tr>
<tr>
<td>13</td>
<td>91.37</td>
<td>97.79</td>
<td>7.02%</td>
<td>0.909 Vert</td>
</tr>
<tr>
<td>14</td>
<td>101.24</td>
<td>109.81</td>
<td>8.47%</td>
<td>0.912 Vert</td>
</tr>
<tr>
<td>15</td>
<td>110.14</td>
<td>120.34</td>
<td>9.26%</td>
<td>0.912 Vert</td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix $[F_{\text{Baseline}} - F_{\text{Damaged}}]$

![Matrix Plot]

![3D Flexibility Matrix Plot]
Displacement Profiles

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison
JT. 4, 7, 11, 14 RESTRAINED
(numerical)
Dynamic Properties

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.37</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>2</td>
<td>21.22</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>3</td>
<td>34.36</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>36.39</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>5</td>
<td>44.26</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>6</td>
<td>45.57</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>7</td>
<td>49.29</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>52.28</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>9</td>
<td>55.08</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>10</td>
<td>61.98</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>11</td>
<td>67.47</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>12</td>
<td>101.56</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>110.28</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>14</td>
<td>113.70</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>124.78</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
MAC Values

<table>
<thead>
<tr>
<th>Baseline Modes</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Supports Fixed Modes</td>
<td>0.999</td>
<td>0.042</td>
<td>0.000</td>
<td>0.000</td>
<td>0.018</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.032</td>
<td>0.023</td>
<td>0.002</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>5</td>
<td>0.040</td>
<td>0.998</td>
<td>0.000</td>
<td>0.001</td>
<td>0.022</td>
<td>0.003</td>
<td>0.000</td>
<td>0.000</td>
<td>0.052</td>
<td>0.038</td>
<td>0.045</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
<td>0.000</td>
<td>0.705</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.698</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.132</td>
<td>0.000</td>
<td>0.005</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.705</td>
<td>0.002</td>
<td>0.001</td>
<td>0.000</td>
<td>0.698</td>
<td>0.005</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.131</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
<td>0.000</td>
<td>0.698</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.705</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.003</td>
<td>0.000</td>
<td>0.132</td>
</tr>
<tr>
<td>9</td>
<td>0.008</td>
<td>0.063</td>
<td>0.000</td>
<td>0.001</td>
<td>0.691</td>
<td>0.673</td>
<td>0.000</td>
<td>0.000</td>
<td>0.162</td>
<td>0.035</td>
<td>0.182</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>10</td>
<td>0.027</td>
<td>0.011</td>
<td>0.000</td>
<td>0.000</td>
<td>0.712</td>
<td>0.721</td>
<td>0.000</td>
<td>0.000</td>
<td>0.201</td>
<td>0.011</td>
<td>0.009</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>11</td>
<td>0.001</td>
<td>0.134</td>
<td>0.000</td>
<td>0.000</td>
<td>0.074</td>
<td>0.062</td>
<td>0.000</td>
<td>0.000</td>
<td>0.694</td>
<td>0.648</td>
<td>0.011</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>12</td>
<td>0.052</td>
<td>0.008</td>
<td>0.000</td>
<td>0.001</td>
<td>0.186</td>
<td>0.299</td>
<td>0.000</td>
<td>0.001</td>
<td>0.692</td>
<td>0.735</td>
<td>0.103</td>
<td>0.000</td>
<td>0.002</td>
<td>0.000</td>
<td>0.002</td>
</tr>
<tr>
<td>13</td>
<td>0.002</td>
<td>0.063</td>
<td>0.000</td>
<td>0.000</td>
<td>0.297</td>
<td>0.326</td>
<td>0.000</td>
<td>0.000</td>
<td>0.224</td>
<td>0.022</td>
<td>0.980</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>14</td>
<td>0.000</td>
<td>0.000</td>
<td>0.124</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>
## Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Baseline Frequency [Hz]</th>
<th>Mode</th>
<th>4 Supports Fixed Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.17</td>
<td>1</td>
<td>18.37</td>
<td>1.09%</td>
<td>0.999</td>
<td>Horz</td>
</tr>
<tr>
<td>2</td>
<td>20.65</td>
<td>2</td>
<td>21.22</td>
<td>2.77%</td>
<td>0.998</td>
<td>Horz</td>
</tr>
<tr>
<td>3</td>
<td>22.23</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td>4</td>
<td>23.58</td>
<td>3</td>
<td>34.36</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td>5</td>
<td>34.65</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td>6</td>
<td>36.69</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td>7</td>
<td>41.97</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Horz</td>
</tr>
<tr>
<td>8</td>
<td>44.13</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Horz</td>
</tr>
<tr>
<td>9</td>
<td>53.49</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Horz</td>
</tr>
<tr>
<td>10</td>
<td>55.55</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Horz</td>
</tr>
<tr>
<td>11</td>
<td>63.49</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Horz</td>
</tr>
<tr>
<td>12</td>
<td>84.92</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td>13</td>
<td>91.37</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td>14</td>
<td>101.24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td>15</td>
<td>110.14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Vert</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix $[F_{\text{Baseline}} - F_{\text{Damaged}}]$
Displacement Profiles

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
JT. 3, 10 CROSS-MEMBER HINGE
(numerical)
## Dynamic Properties

### Jt. 3, 10 Hinge Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.16</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>2</td>
<td>20.62</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>3</td>
<td>22.31</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>23.65</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>5</td>
<td>34.72</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>36.77</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>41.97</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>8</td>
<td>44.20</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>9</td>
<td>53.45</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>10</td>
<td>55.55</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>11</td>
<td>63.62</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>12</td>
<td>85.18</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>91.66</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>101.68</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>110.65</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
### MAC Values

**Jt. 3, 10 Hinge Modes**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.17</td>
<td>1</td>
<td>18.16</td>
<td>0.04%</td>
<td>1.00 Horz</td>
</tr>
<tr>
<td>2</td>
<td>20.65</td>
<td>2</td>
<td>20.62</td>
<td>0.15%</td>
<td>1.00 Horz</td>
</tr>
<tr>
<td>3</td>
<td>22.23</td>
<td>3</td>
<td>22.31</td>
<td>0.34%</td>
<td>1.00 Vert</td>
</tr>
<tr>
<td>4</td>
<td>23.58</td>
<td>4</td>
<td>23.65</td>
<td>0.30%</td>
<td>1.00 Vert</td>
</tr>
<tr>
<td>5</td>
<td>34.65</td>
<td>5</td>
<td>34.72</td>
<td>0.22%</td>
<td>1.00 Vert</td>
</tr>
<tr>
<td>6</td>
<td>36.69</td>
<td>6</td>
<td>36.77</td>
<td>0.21%</td>
<td>1.00 Vert</td>
</tr>
<tr>
<td>7</td>
<td>41.97</td>
<td>7</td>
<td>41.97</td>
<td>0.02%</td>
<td>1.00 Horz</td>
</tr>
<tr>
<td>8</td>
<td>44.13</td>
<td>8</td>
<td>44.20</td>
<td>0.18%</td>
<td>1.00 Horz</td>
</tr>
<tr>
<td>9</td>
<td>53.49</td>
<td>9</td>
<td>53.45</td>
<td>0.07%</td>
<td>1.00 Horz</td>
</tr>
<tr>
<td>10</td>
<td>55.55</td>
<td>10</td>
<td>55.55</td>
<td>0.00%</td>
<td>1.00 Horz</td>
</tr>
<tr>
<td>11</td>
<td>63.49</td>
<td>11</td>
<td>63.62</td>
<td>0.21%</td>
<td>1.00 Horz</td>
</tr>
<tr>
<td>12</td>
<td>84.92</td>
<td>12</td>
<td>85.18</td>
<td>0.31%</td>
<td>1.00 Vert</td>
</tr>
<tr>
<td>13</td>
<td>91.37</td>
<td>13</td>
<td>91.66</td>
<td>0.31%</td>
<td>1.00 Vert</td>
</tr>
<tr>
<td>14</td>
<td>101.24</td>
<td>14</td>
<td>101.68</td>
<td>0.43%</td>
<td>1.00 Vert</td>
</tr>
<tr>
<td>15</td>
<td>110.14</td>
<td>15</td>
<td>110.65</td>
<td>0.46%</td>
<td>1.00 Vert</td>
</tr>
</tbody>
</table>

### Difference in Modal Frequencies
Static Properties

Change in Flexibility Matrix \([F_{\text{Baseline}} - F_{\text{Damaged}}]\)
Displacement Profiles

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
JT. 3 HINGE, NO PLATES
(numerical)
## Dynamic Properties

### Jt. 3 Hinge Modes

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>18.12 Hz</th>
<th>Horz. Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 2</td>
<td>20.63 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>Mode 3</td>
<td>22.15 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>Mode 4</td>
<td>23.51 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>Mode 5</td>
<td>34.70 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>Mode 6</td>
<td>36.77 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>Mode 7</td>
<td>41.80 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>Mode 8</td>
<td>43.82 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>Mode 9</td>
<td>53.46 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>Mode 10</td>
<td>55.43 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>Mode 11</td>
<td>62.95 Hz</td>
<td>Horz. Bending</td>
</tr>
<tr>
<td>Mode 12</td>
<td>84.29 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>Mode 13</td>
<td>90.81 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>Mode 14</td>
<td>100.54 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>Mode 15</td>
<td>109.50 Hz</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
### Baseline Modes

<table>
<thead>
<tr>
<th>Column</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.000</td>
<td>0.007</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.010</td>
<td>0.028</td>
<td>0.001</td>
<td>0.043</td>
<td>0.006</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>0.017</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.026</td>
<td>0.012</td>
<td>0.112</td>
<td>0.007</td>
<td>0.065</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>0.000</td>
<td>0.998</td>
<td>0.049</td>
<td>0.006</td>
<td>0.007</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>4</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.066</td>
<td>0.999</td>
<td>0.007</td>
<td>0.007</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.999</td>
<td>0.033</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002</td>
<td>0.002</td>
<td>0.030</td>
<td>0.999</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>0.002</td>
<td>0.035</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.993</td>
<td>0.089</td>
<td>0.027</td>
<td>0.002</td>
<td>0.332</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>8</td>
<td>0.028</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.120</td>
<td>0.996</td>
<td>0.002</td>
<td>0.241</td>
<td>0.21</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>9</td>
<td>0.003</td>
<td>0.113</td>
<td>0.000</td>
<td>0.000</td>
<td>0.031</td>
<td>0.004</td>
<td>0.999</td>
<td>0.089</td>
<td>0.027</td>
<td>0.002</td>
<td>0.332</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>0.044</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.042</td>
<td>0.269</td>
<td>0.002</td>
<td>0.999</td>
<td>0.029</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>0.006</td>
<td>0.062</td>
<td>0.000</td>
<td>0.000</td>
<td>0.348</td>
<td>0.012</td>
<td>0.058</td>
<td>0.030</td>
<td>0.999</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>0.000</td>
<td>0.000</td>
<td>0.005</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
<td>0.000</td>
<td>0.005</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.004</td>
<td>0.004</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.000</td>
<td>0.000</td>
<td>0.005</td>
<td>0.004</td>
<td>0.002</td>
<td>0.005</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.038</td>
<td>0.040</td>
</tr>
</tbody>
</table>

### Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Jt. 3 Hinge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>1</td>
<td>18.17</td>
</tr>
<tr>
<td>2</td>
<td>20.65</td>
</tr>
<tr>
<td>3</td>
<td>22.23</td>
</tr>
<tr>
<td>4</td>
<td>23.58</td>
</tr>
<tr>
<td>5</td>
<td>34.65</td>
</tr>
<tr>
<td>6</td>
<td>36.69</td>
</tr>
<tr>
<td>7</td>
<td>41.97</td>
</tr>
<tr>
<td>8</td>
<td>44.13</td>
</tr>
<tr>
<td>9</td>
<td>53.49</td>
</tr>
<tr>
<td>10</td>
<td>55.55</td>
</tr>
<tr>
<td>11</td>
<td>63.49</td>
</tr>
<tr>
<td>12</td>
<td>84.92</td>
</tr>
<tr>
<td>13</td>
<td>91.37</td>
</tr>
<tr>
<td>14</td>
<td>101.24</td>
</tr>
<tr>
<td>15</td>
<td>110.14</td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix $[F_{\text{Baseline}} - F_{\text{Damaged}}]$
Displacement Profiles

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)  
(Load 1, Girder 2)  
(Load 2, Girder 1)  
(Load 2, Girder 2)  
(Load 3, Girder 1)  
(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
APPENDIX G: EXPERIMENTAL TEST RESULTS
### BASELINE GRID PROPERTIES

*(experimental)*

**Dynamic Properties**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Period [sec]</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>140.53</td>
<td>0.04471</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>169.69</td>
<td>0.03703</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>209.73</td>
<td>0.02996</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>257.05</td>
<td>0.02444</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>407.98</td>
<td>0.01540</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>422.66</td>
<td>0.01487</td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>591.91</td>
<td>0.01062</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>606.71</td>
<td>0.01036</td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>650.81</td>
<td>0.00965</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td>758.07</td>
<td>0.00829</td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>794.26</td>
<td>0.00791</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td>862.37</td>
<td>0.00729</td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td>891.84</td>
<td>0.00705</td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td>915.52</td>
<td>0.00686</td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td>930.48</td>
<td>0.00675</td>
</tr>
<tr>
<td>Mode</td>
<td>Frequency</td>
<td>Mode Type</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>----------------------</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>22.37 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>27.00 Hz</td>
<td>Vert. Torsion</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>33.38 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>40.91 Hz</td>
<td>Vert. Torsion</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>64.93 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>67.27 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>94.21 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>96.56 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>103.58 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>120.65 Hz</td>
<td>Vert. Torsion</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>126.41 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>137.25 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>141.94 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>145.71 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>148.09 Hz</td>
<td>Vert. Bending</td>
<td></td>
</tr>
</tbody>
</table>
JT. 4 SETTLEMENT
(experimental)
## Dynamic Properties

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.10 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>26.53 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>3</td>
<td>33.10 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>39.80 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>5</td>
<td>61.37 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>66.59 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>67.80 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>94.63 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>9</td>
<td>96.64 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>10</td>
<td>106.58 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>11</td>
<td>122.66 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>12</td>
<td>128.18 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>140.69 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>142.37 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>144.17 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>16</td>
<td>146.72 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>17</td>
<td>149.23 Hz</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>

- **Mode 1** – 22.10 Hz, Vert. Bending
- **Mode 2** – 26.53 Hz, Vert. Bending
- **Mode 3** – 33.10 Hz, Vert. Bending
- **Mode 4** – 39.80 Hz, Vert. Bending
- **Mode 5** – 61.37 Hz, Vert. Bending
- **Mode 6** – 66.59 Hz, Vert. Bending
- **Mode 7** – 67.80 Hz, Vert. Bending
- **Mode 8** – 94.63 Hz, Vert. Bending
- **Mode 9** – 96.64 Hz, Vert. Bending
- **Mode 10** – 106.58 Hz, Vert. Torsion
- **Mode 11** – 122.66 Hz, Vert. Torsion
- **Mode 12** – 128.18 Hz, Vert. Bending
- **Mode 13** – 140.69 Hz, Vert. Bending
- **Mode 14** – 142.37 Hz, Vert. Bending
- **Mode 15** – 144.17 Hz, Vert. Bending
- **Mode 16** – 146.72 Hz, Vert. Bending
- **Mode 17** – 149.23 Hz, Vert. Bending
### MAC Values

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Jt 4 Settlement</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>22.10</td>
<td>1.21%</td>
<td>0.998</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>26.53</td>
<td>1.78%</td>
<td>0.996</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>33.10</td>
<td>0.83%</td>
<td>0.997</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>39.80</td>
<td>2.71%</td>
<td>0.984</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>66.59</td>
<td>2.55%</td>
<td>0.913</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>67.80</td>
<td>0.79%</td>
<td>0.927</td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>94.63</td>
<td>0.45%</td>
<td>0.981</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>96.64</td>
<td>0.08%</td>
<td>0.999</td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>106.58</td>
<td>2.90%</td>
<td>0.990</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td>122.66</td>
<td>1.67%</td>
<td>0.979</td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>128.18</td>
<td>1.40%</td>
<td>0.993</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td>140.69</td>
<td>2.55%</td>
<td>0.963</td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td>142.37</td>
<td>0.30%</td>
<td>0.956</td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td>146.72</td>
<td>0.69%</td>
<td>0.895</td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td>149.23</td>
<td>0.77%</td>
<td>0.956</td>
</tr>
</tbody>
</table>

### Difference in Modal Frequencies
Static Properties

Change in Flexibility Matrix \([F_{\text{baseline}} - F_{\text{damage}}]\)
Pseudoflexibility Loads

**Load Case 1**

**Load Case 2**

**Load Case 3**
Displacement Patterns

- Displacement Profile (Load 1, Girder 1)
- Displacement Profile (Load 1, Girder 2)
- Displacement Profile (Load 2, Girder 1)
- Displacement Profile (Load 2, Girder 2)
- Displacement Profile (Load 3, Girder 1)
- Displacement Profile (Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison
JT. 4 SETTLEMENT
(experimental)
## Dynamic Properties

### Jt. 7 Settlement Experimental Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.25 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>26.85 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>3</td>
<td>33.10 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>40.38 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>5</td>
<td>64.36 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>67.57 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>68.24 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>76.22 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>9</td>
<td>94.24 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>10</td>
<td>99.88 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>11</td>
<td>118.86 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>12</td>
<td>126.63 Hz</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>13</td>
<td>142.71 Hz</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>151.89 Hz</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>

![Mode 1](image1) ![Mode 2](image2) ![Mode 3](image3)

![Mode 4](image4) ![Mode 5](image5) ![Mode 6](image6)

![Mode 7](image7) ![Mode 8](image8) ![Mode 9](image9)

![Mode 10](image10) ![Mode 11](image11) ![Mode 12](image12)

![Mode 13](image13) ![Mode 14](image14)
### MAC Values

#### Jt 7 Settlement Modes

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline Modes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.00</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>1.00</td>
<td>0.16</td>
<td>0.06</td>
<td>0.02</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>0.03</td>
<td>1.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.07</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>0.03</td>
<td>1.00</td>
<td>0.06</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
<td>0.01</td>
<td>0.47</td>
<td>0.01</td>
<td>0.11</td>
<td>0.14</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>0.02</td>
<td>0.00</td>
<td>0.05</td>
<td>1.00</td>
<td>0.13</td>
<td>0.04</td>
<td>0.14</td>
<td>0.04</td>
<td>0.10</td>
<td>0.14</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.99</td>
<td>0.16</td>
<td>0.17</td>
<td>0.03</td>
<td>0.01</td>
<td>0.08</td>
<td>0.17</td>
<td>0.05</td>
<td>0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>0.00</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.93</td>
<td>0.89</td>
<td>0.07</td>
<td>0.01</td>
<td>0.09</td>
<td>0.09</td>
<td>0.42</td>
<td>0.95</td>
<td>0.94</td>
</tr>
<tr>
<td>7</td>
<td>1.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>1.00</td>
<td>0.15</td>
<td>0.06</td>
<td>0.01</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Baseline Modes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.00</td>
<td>0.05</td>
<td>1.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
<td>0.01</td>
<td>0.50</td>
<td>0.01</td>
<td>0.14</td>
<td>0.15</td>
<td>0.04</td>
</tr>
<tr>
<td>9</td>
<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.06</td>
<td>0.04</td>
<td>0.12</td>
<td>0.04</td>
<td>0.06</td>
<td>0.83</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>10</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.04</td>
<td>0.06</td>
<td>0.26</td>
<td>0.69</td>
<td>0.01</td>
<td>0.15</td>
<td>0.91</td>
<td>0.85</td>
<td>0.06</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.98</td>
<td>0.14</td>
<td>0.18</td>
<td>0.07</td>
<td>0.03</td>
<td>0.09</td>
<td>0.28</td>
<td>0.12</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>12</td>
<td>0.02</td>
<td>0.02</td>
<td>0.09</td>
<td>0.01</td>
<td>0.00</td>
<td>0.94</td>
<td>0.89</td>
<td>0.00</td>
<td>0.01</td>
<td>0.07</td>
<td>0.12</td>
<td>0.39</td>
<td>0.98</td>
<td>0.95</td>
</tr>
<tr>
<td>13</td>
<td>0.04</td>
<td>0.00</td>
<td>0.08</td>
<td>0.02</td>
<td>0.10</td>
<td>0.92</td>
<td>0.92</td>
<td>0.00</td>
<td>0.05</td>
<td>0.07</td>
<td>0.43</td>
<td>0.96</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.95</td>
<td>0.90</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.41</td>
<td>0.97</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.07</td>
<td>0.02</td>
<td>0.06</td>
<td>0.00</td>
<td>0.17</td>
<td>0.90</td>
<td>0.92</td>
<td>0.01</td>
<td>0.06</td>
<td>0.02</td>
<td>0.13</td>
<td>0.40</td>
<td>0.94</td>
<td>0.92</td>
</tr>
</tbody>
</table>

### Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>1</td>
<td>22.25</td>
<td>0.51%</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>2</td>
<td>26.85</td>
<td>0.60%</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>3</td>
<td>33.10</td>
<td>0.84%</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>4</td>
<td>40.38</td>
<td>1.29%</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>5</td>
<td>64.36</td>
<td>0.88%</td>
<td>0.99</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>6</td>
<td>67.57</td>
<td>0.45%</td>
<td>0.927</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
<td>68.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td>76.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>9</td>
<td>94.24</td>
<td>0.03%</td>
<td>0.999</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>10</td>
<td>99.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>11</td>
<td>118.86</td>
<td>1.48%</td>
<td>0.910</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td>12</td>
<td>126.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>13</td>
<td>137.25</td>
<td>12.89%</td>
<td>0.981</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td>14</td>
<td>142.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td>15</td>
<td>145.71</td>
<td>10.67%</td>
<td>0.952</td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix \([F_{\text{baseline}} - F_{\text{damage}}]\)
Pseudoflexibility Loads

**Load Case 1**

**Load Case 2**

**Load Case 3**

100 lb/pt

Girder Line 1

Girder Line 2

Girder Line 1

Girder Line 2

Girder Line 1
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison
PILE LOSS
(experimental)
### Dynamic Properties

#### Pile Loss Experimental Modes

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 4</td>
<td>Mode 5</td>
<td>Mode 6</td>
</tr>
<tr>
<td>36.05 Hz Vert. Bending</td>
<td>52.01 Hz Vert. Torsion</td>
<td>64.92 Hz Vert. Bending</td>
</tr>
<tr>
<td>Mode 7</td>
<td>Mode 8</td>
<td>Mode 9</td>
</tr>
<tr>
<td>70.76 Hz Vert. Torsion</td>
<td>70.86 Hz Vert. Torsion</td>
<td>80.16 Hz Vert. Torsion</td>
</tr>
<tr>
<td>Mode 10</td>
<td>Mode 11</td>
<td>Mode 12</td>
</tr>
<tr>
<td>86.07 Hz Vert. Torsion</td>
<td>94.22 Hz Vert. Bending</td>
<td>97.11 Hz Vert. Bending</td>
</tr>
<tr>
<td>Mode 13</td>
<td>Mode 14</td>
<td>Mode 15</td>
</tr>
<tr>
<td>103.89 Hz Vert. Torsion</td>
<td>126.35 Hz Vert. Bending</td>
<td>130.02 Hz Vert. Torsion</td>
</tr>
<tr>
<td>Mode 16</td>
<td>Mode 17</td>
<td></td>
</tr>
<tr>
<td>143.94 Hz Vert. Bending</td>
<td>146.01 Hz Vert. Bending</td>
<td></td>
</tr>
<tr>
<td>Baseline Modes</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>---------------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>1</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.52</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>0.56</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>6</td>
<td>0.37</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>0.02</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>0.55</td>
<td>0.00</td>
</tr>
<tr>
<td>9</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>0.30</td>
<td>0.01</td>
</tr>
<tr>
<td>11</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>12</td>
<td>0.40</td>
<td>0.01</td>
</tr>
<tr>
<td>13</td>
<td>0.40</td>
<td>0.05</td>
</tr>
<tr>
<td>14</td>
<td>0.33</td>
<td>0.01</td>
</tr>
<tr>
<td>15</td>
<td>0.38</td>
<td>0.06</td>
</tr>
</tbody>
</table>
## Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Baseline Frequency [Hz]</th>
<th>Pile Loss Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>22.35</td>
<td>0.07%</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>26.98</td>
<td>0.10%</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>36.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>64.92</td>
<td>0.02%</td>
<td>0.995</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>94.22</td>
<td>0.01%</td>
<td>0.999</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>97.109</td>
<td>0.57%</td>
<td>0.958</td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>103.89</td>
<td>0.30%</td>
<td>1.000</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>126.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td>143.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix \([F_{\text{baseline}} - F_{\text{damage}}]\)
Pseudoflexibility Loads

Load Case 1

Load Case 2

Load Case 3
Displacement Patterns

- Displacement Profile (Load 1, Girder 1)
- Displacement Profile (Load 1, Girder 2)
- Displacement Profile (Load 2, Girder 1)
- Displacement Profile (Load 2, Girder 2)
- Displacement Profile (Load 3, Girder 1)
- Displacement Profile (Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3 Girder 2)
JT. 7, 14 RESTRAINED
(experimental)
## Dynamic Properties

### 2 Jts Fixed Experimental Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.60</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>29.85</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>3</td>
<td>36.41</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>38.23</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>5</td>
<td>44.45</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>46.70</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>65.44</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>67.84</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>9</td>
<td>94.60</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>10</td>
<td>97.57</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>11</td>
<td>107.06</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>12</td>
<td>112.21</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>123.33</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>14</td>
<td>129.32</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>141.73</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
### MAC Values

#### Jt 7,14 Fixed Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>MAC</th>
<th>Percentage Difference</th>
<th>Frequency [Hz]</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.970</td>
<td>-</td>
<td>22.37</td>
<td>1</td>
<td>24.60</td>
<td>10.00%</td>
</tr>
<tr>
<td>2</td>
<td>0.969</td>
<td>-</td>
<td>27.01</td>
<td>2</td>
<td>29.85</td>
<td>10.54%</td>
</tr>
<tr>
<td>3</td>
<td>0.966</td>
<td>-</td>
<td>33.38</td>
<td>3</td>
<td>36.41</td>
<td>9.07%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>38.23</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.970</td>
<td>-</td>
<td>40.91</td>
<td>5</td>
<td>44.45</td>
<td>8.64%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>6</td>
<td>46.70</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.986</td>
<td>-</td>
<td>64.93</td>
<td>7</td>
<td>65.44</td>
<td>0.78%</td>
</tr>
<tr>
<td>6</td>
<td>0.952</td>
<td>-</td>
<td>67.27</td>
<td>8</td>
<td>67.84</td>
<td>0.85%</td>
</tr>
<tr>
<td>7</td>
<td>0.973</td>
<td>-</td>
<td>94.21</td>
<td>9</td>
<td>94.60</td>
<td>0.42%</td>
</tr>
<tr>
<td>8</td>
<td>0.968</td>
<td>-</td>
<td>96.56</td>
<td>10</td>
<td>97.57</td>
<td>1.04%</td>
</tr>
<tr>
<td>9</td>
<td>0.966</td>
<td>-</td>
<td>103.58</td>
<td>11</td>
<td>107.06</td>
<td>3.36%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>12</td>
<td>112.21</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.955</td>
<td>-</td>
<td>120.65</td>
<td>13</td>
<td>123.33</td>
<td>2.22%</td>
</tr>
<tr>
<td>11</td>
<td>0.957</td>
<td>-</td>
<td>126.41</td>
<td>14</td>
<td>129.32</td>
<td>2.30%</td>
</tr>
<tr>
<td>12</td>
<td>0.978</td>
<td>-</td>
<td>137.25</td>
<td>15</td>
<td>141.73</td>
<td>3.26%</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix \([F_{\text{baseline}} - F_{\text{damage}}]\)
Pseudoflexibility Loads

Load Case 1

Load Case 2

Load Case 3
Displacement Patterns

Displacement Profile (Load 1, Girder 1)

Displacement Profile (Load 1, Girder 2)

Displacement Profile (Load 2, Girder 1)

Displacement Profile (Load 2, Girder 2)

Displacement Profile (Load 3, Girder 1)

Displacement Profile (Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
JT. 4, 7, 11, 14 RESTRAINED
(experimental)
# Dynamic Properties

## 4 Jts Fixed Experimental Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.72</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>34.05</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>3</td>
<td>37.37</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>46.55</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>5</td>
<td>66.17</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>68.64</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>95.28</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>97.95</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>9</td>
<td>111.86</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>10</td>
<td>130.76</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>11</td>
<td>133.16</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>12</td>
<td>140.37</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>144.87</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>147.38</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>154.85</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
### MAC Values

#### 4 Jts. Fixed Modes

<table>
<thead>
<tr>
<th>Baseline Modes</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Jt 4,7,11,14 Fixed</th>
<th>Difference in Modal Frequencies</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>22.37</td>
<td>1</td>
<td>27.72</td>
<td>23.95%</td>
<td>0.947</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>27.01</td>
<td>2</td>
<td>34.05</td>
<td>26.09%</td>
<td>0.961</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>33.38</td>
<td>3</td>
<td>37.37</td>
<td>11.96%</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>40.91</td>
<td>4</td>
<td>46.55</td>
<td>13.77%</td>
<td>0.954</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>64.93</td>
<td>5</td>
<td>66.17</td>
<td>1.91%</td>
<td>0.992</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>67.27</td>
<td>6</td>
<td>68.64</td>
<td>2.04%</td>
<td>0.935</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>94.21</td>
<td>7</td>
<td>95.28</td>
<td>1.14%</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>96.56</td>
<td>8</td>
<td>97.95</td>
<td>1.44%</td>
<td>0.947</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>103.58</td>
<td>9</td>
<td>111.86</td>
<td>7.99%</td>
<td>0.973</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>120.65</td>
<td>10</td>
<td>130.76</td>
<td>8.38%</td>
<td>0.952</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>126.41</td>
<td>11</td>
<td>133.16</td>
<td>5.34%</td>
<td>0.954</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>137.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix \([F_{\text{baseline}} - F_{\text{damage}}]\)
Pseudoflexibility Loads

Load Case 1

Load Case 2

Load Case 3
Displacement Patterns
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

Strain, in/in
Distance Along Girder, in.

Curvature
FEM
100 lb/pt

(Load 1, Girder 2)

Strain, in/in
Distance Along Girder, in.

Curvature
FEM
100 lb/pt

(Load 2, Girder 1)

Strain, in/in
Distance Along Girder, in.

Curvature
FEM
100 lb/pt

(Load 2, Girder 2)

Strain, in/in
Distance Along Girder, in.

Curvature
FEM
100 lb/pt

(Load 3, Girder 1)

Strain, in/in
Distance Along Girder, in.

Curvature
FEM
100 lb/pt

(Load 3, Girder 2)

Strain, in/in
Distance Along Girder, in.

Curvature
FEM
100 lb/pt
JT. 3, 10 CROSS MEMBER HINGES
(experimental)
## Dynamic Properties

### Jt. 3,10 Hinge Experimental Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.38</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>27.02</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>3</td>
<td>33.33</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>40.92</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>5</td>
<td>64.68</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>67.01</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>68.27</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>94.16</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>9</td>
<td>96.52</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>10</td>
<td>103.54</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>11</td>
<td>120.23</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>12</td>
<td>1226.28</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>13</td>
<td>137.22</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>145.20</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>148.04</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>

![Mode 1 - 22.38 Hz Vert. Bending](image1)
![Mode 2 - 27.02 Hz Vert. Torsion](image2)
![Mode 3 - 33.33 Hz Vert. Bending](image3)
![Mode 4 - 40.92 Hz Vert. Bending](image4)
![Mode 5 - 64.68 Hz Vert. Bending](image5)
![Mode 6 - 67.01 Hz Vert. Bending](image6)
![Mode 7 - 68.27 Hz Vert. Bending](image7)
![Mode 8 - 94.16 Hz Vert. Bending](image8)
![Mode 9 - 96.52 Hz Vert. Bending](image9)
![Mode 10 - 103.54 Hz Vert. Torsion](image10)
![Mode 11 - 120.23 Hz Vert. Torsion](image11)
![Mode 12 - 1226.28 Hz Vert. Bending](image12)
![Mode 13 - 137.22 Hz Vert. Bending](image13)
![Mode 14 - 145.20 Hz Vert. Bending](image14)
![Mode 15 - 148.04 Hz Vert. Bending](image15)
### MAC Values

<table>
<thead>
<tr>
<th>Jt 3,10 Hinge Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>13</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>15</td>
</tr>
</tbody>
</table>

### Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>1</td>
<td>22.38</td>
<td>0.04%</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>2</td>
<td>27.02</td>
<td>0.05%</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>3</td>
<td>33.33</td>
<td>0.13%</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>4</td>
<td>40.92</td>
<td>0.02%</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>5</td>
<td>64.68</td>
<td>0.39%</td>
<td>0.99</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>6</td>
<td>67.01</td>
<td>0.38%</td>
<td>0.998</td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>8</td>
<td>94.16</td>
<td>0.05%</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>9</td>
<td>96.52</td>
<td>0.04%</td>
<td>0.999</td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>10</td>
<td>103.54</td>
<td>0.04%</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td>11</td>
<td>120.23</td>
<td>0.35%</td>
<td>0.999</td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>12</td>
<td>126.28</td>
<td>0.10%</td>
<td>0.999</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td>13</td>
<td>137.22</td>
<td>0.02%</td>
<td>0.999</td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td>14</td>
<td>145.2</td>
<td>0.35%</td>
<td>0.983</td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td>15</td>
<td>148.04</td>
<td>0.03%</td>
<td>0.999</td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix \([F_{\text{baseline}} - F_{\text{damage}}]\)
Pseudoflexibility Loads

Load Case 1

Load Case 2

Load Case 3
Displacement Patterns
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Change in Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3 Girder 2)
JT. 3 HINGE, NO PLATES

(experimental)
## Dynamic Properties

### Jt. 3 Hinge Experimental Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.40</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>2</td>
<td>27.12</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>3</td>
<td>33.53</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>4</td>
<td>41.21</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>5</td>
<td>64.37</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>6</td>
<td>64.39</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>7</td>
<td>67.37</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>8</td>
<td>67.51</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>9</td>
<td>94.44</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>10</td>
<td>96.77</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>11</td>
<td>104.00</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>12</td>
<td>121.71</td>
<td>Vert. Torsion</td>
</tr>
<tr>
<td>13</td>
<td>127.22</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>14</td>
<td>137.86</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>15</td>
<td>145.45</td>
<td>Vert. Bending</td>
</tr>
<tr>
<td>16</td>
<td>148.27</td>
<td>Vert. Bending</td>
</tr>
</tbody>
</table>
## MAC Values

<table>
<thead>
<tr>
<th>Mode</th>
<th>Jt 3 Hinge Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
</tr>
</tbody>
</table>

## Difference in Modal Frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Baseline Frequency [Hz]</th>
<th>Jt 3 Hinge Frequency [Hz]</th>
<th>% Freq Difference</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.37</td>
<td>22.40</td>
<td>0.16%</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>27.01</td>
<td>27.12</td>
<td>0.43%</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
<td>33.38</td>
<td>33.53</td>
<td>0.44%</td>
<td>0.999</td>
</tr>
<tr>
<td>4</td>
<td>40.91</td>
<td>41.21</td>
<td>0.74%</td>
<td>0.999</td>
</tr>
<tr>
<td>5</td>
<td>64.93</td>
<td>64.37</td>
<td>0.87%</td>
<td>0.981</td>
</tr>
<tr>
<td>6</td>
<td>67.27</td>
<td>67.37</td>
<td>0.14%</td>
<td>0.997</td>
</tr>
<tr>
<td>7</td>
<td>94.21</td>
<td>94.44</td>
<td>0.25%</td>
<td>0.993</td>
</tr>
<tr>
<td>8</td>
<td>96.56</td>
<td>96.77</td>
<td>0.21%</td>
<td>0.988</td>
</tr>
<tr>
<td>9</td>
<td>103.58</td>
<td>104.00</td>
<td>0.41%</td>
<td>0.996</td>
</tr>
<tr>
<td>10</td>
<td>120.65</td>
<td>121.71</td>
<td>0.88%</td>
<td>0.992</td>
</tr>
<tr>
<td>11</td>
<td>126.41</td>
<td>127.22</td>
<td>0.64%</td>
<td>0.984</td>
</tr>
<tr>
<td>12</td>
<td>137.25</td>
<td>137.86</td>
<td>0.44%</td>
<td>0.986</td>
</tr>
<tr>
<td>13</td>
<td>141.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>145.71</td>
<td>145.45</td>
<td>0.18%</td>
<td>0.975</td>
</tr>
<tr>
<td>15</td>
<td>148.09</td>
<td>148.27</td>
<td>0.12%</td>
<td>0.986</td>
</tr>
</tbody>
</table>
Static Properties

Change in Flexibility Matrix \([F_{\text{baseline}} - F_{\text{damage}}]\)
Pseudoflexibility Loads

**Load Case 1**

**Load Case 2**

**Load Case 3**
Displacement Patterns

Displacement Profile (Load 1, Girder 1)

Displacement Profile (Load 1, Girder 2)

Displacement Profile (Load 2, Girder 1)

Displacement Profile (Load 2, Girder 2)

Displacement Profile (Load 3, Girder 1)

Displacement Profile (Load 3, Girder 2)
Change in Displacement

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Curvature

(Load 1, Girder 1)

(Load 1, Girder 2)

(Load 2, Girder 1)

(Load 2, Girder 2)

(Load 3, Girder 1)

(Load 3, Girder 2)
Strain Comparison
LIST OF REFERENCES


