January 2013

Effect of Bolted Joint Preload on Structural Damping

Weiwei Xu
University of South Florida, weiweixu@mail.usf.edu

Effect of Bolted Joint Preload on Structural Damping

by

Weiwei Xu

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
Department of Mechanical Engineering
College of Engineering
University of South Florida

Major Professor: Daniel P. Hess, Ph.D.
Rasim Guldiken, Ph.D.
Craig Lusk, Ph.D.

Date of Approval:
July 2, 2013

Keywords: Impact testing, Modal parameters, Frequency response function measurement, Natural frequency, Loose bolt detection

ACKNOWLEDGMENTS

I would like to express my great appreciation to Dr. Daniel Hess for all of his valuable and constructive suggestions throughout the planning and development of this thesis. His patient guidance and generous time and support were crucial to the success of this research.

I am also particularly grateful to Dr. Rasim Guldiken and Dr. Craig Lusk, my thesis committee members, for their willingness to give their time and support.

Lastly, I would like to thank the staff working in the machine shop for all of their help in manufacturing the experimental specimens and providing me with all the necessities.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Bolted joints are integral parts of mechanical systems, and bolt preload loss is one of the major failure modes for bolted joint structures. Understanding the damping and frequency response to a varying preload in a single-bolted lap-joint structure can be very helpful in predicting and analyzing more complicated structures connected by these joints.

In this thesis, the relationship between the bolt preload and the natural frequency, and the relationship between the bolt preload and the structural damping, have both been investigated through impact hammer testing on a single-bolted lap-joint structure. The test data revealed that the bolt preload has nonlinear effects on the structural damping and on the natural frequency of the structure. The damping ratios of the test structure were determined to increase with decreasing preload. An increase in structural damping is beneficial in most engineering circumstances, for it will reduce the vibrational response and noise subjected to external excitations. It was also observed that the modal frequency increased with increasing preload, but remained approximately constant for preload larger than 30% in the bolt yield strength. One application for studying the preload effect is the detection for loose bolts in structures. The possibility of using impact testing for estimating preload loss has been confirmed, and the modal damping was determined to be a more sensitive indicator than the natural frequency in a single-bolted lap-joint structure.

CHAPTER 1: INTRODUCTION

All structures exhibit some level of damping due to energy dissipation mechanisms. In many cases, damping is desirable because it limits vibration in structures such as buildings, vehicles, bridges, and aerospace systems. Fasteners are often used to connect or build up structures from numerous components. The resulting joints in a structure often provide a significant portion of the total damping.

There are three different sources of damping related to the structural damping in the assembled structures, based on the definition of structural damping provided by Gual [1]. First is the material damping of individual components, which occurs as a result of material characteristics. Second is the energy loss from micro-slip or macro-slip at the contacting surfaces through friction, as with bolted or welded connections. The last one is damping through the medium at the interfaces in relative motion, as with lubricated bearings.

Bolts and nuts are among the most widely used types of fasteners in mechanical design. Different kinds of structures rely on bolted joints to connect components for easy access and maintenance. In addition, bolted joints can induce a large amount of damping in a structure. According to Beards [2], bolted joints can contribute up to 90% of the structural damping in a bolted joint structure. This is especially true and useful for most conventional structural materials, such as aluminum and steel, since a large damping capacity is desirable for the purpose of minimizing resonant vibration amplitudes and reducing noise.

There are four major factors that affect structural damping of a bolted joint: bolt preload, friction coefficient (surface finish) of the contacting surfaces, clamping boundary conditions, and micro-slip or macro-slip between bolted surfaces [3, 4]. In this thesis, the effect of bolted joint preload on structural damping is investigated. Preload is an important aspect in designing bolted joint structures and the bolt preload loss is one of the major failure modes for mechanical failures [5].

At this time there is no previous research found in the literature on applying the impact hammer testing method to detect loose bolts or estimate preload level in the bolted structures. The ability to detect loose bolts in structures and estimate preload loss by measuring modal parameters through impact testing have been investigated in this thesis. In addition, the sensitivities of using natural frequency and modal damping changes as indicators for bolt loosening were compared.

1.1 Background

Bolted joint connections are commonly used in most engineering mechanical structures. One notable feature of a bolted joint compared to a welded or a riveted joint is that it can be loosened or tightened by adjusting the applied preload. There is a relationship between damping, natural frequency of the structure and the fastener preload. The research for the influence of bolted joint preload on natural frequency and modal damping in structures has been the subject of several papers.

The experimental results of Nanda [6] showed that the first natural frequency of the layered and jointed structure increased when the bolts' tightening preload were increased from 0 to 10 ft-lb. However, the natural frequency stayed constant when tightening torque was larger than 7.5 ft-lb. The values of the first natural frequency in the bolted and layered structure in each preload level tested were smaller than those of its equivalent monolithic solid beam.

Esteban and Rogers [7] studied the energy dissipation through joints in a structure with two bolted beams and this structure was tested under free boundary conditions by using non-destructive piezoceramic actuator-sensors. It was found that the energy dissipation doubled when the bolt was slightly loosened, and thus an increase in damping resulted from an decrease in preload. The results also indicated that, by decreasing preload, the structure's stiffness decreased, and thus, natural frequency decreased.

Butner et al. [8, 9] investigated the effects of the varying preload on a preloaded interface. The preload in the bolts on the fixture were applied at four different levels: hand tight, 50ft-lb, fully tight, and 100ft-lb. Modal impact tests were performed to investigate the dynamic response as the preload changed in the bolted interface. The results show that with the increase in preload level, modal frequencies increase at the first six measured vibration modes with a decrease in modal damping. The study also shows that the magnitude of the acceleration response increases with an increase in preload.

The loss of preload on a bolt can lead to fastener failure and a decrease in structural stiffness, therefore the ability to detect loose bolts is crucial for ensuring the structure's integrity. Over the years, researchers have studied many methods that are effective for detecting loose bolts in structures and in estimating preload loss, such as the investigation done by Janette Jaques and Doug Adams [10]. They explored a new approach for diagnosing the loose bolts within a structure using the Impact Modulation method. This method is one kind of nondestructive evaluation technique called the

Nonlinear Elastic Wave Spectroscopy method and is applied by exciting a structure with both an impact hammer and a high frequency actuator at the same time. It was proved to be effective in identifying the presence of loose bolts by quantifying the difference in response amplitudes at the natural frequencies. It can also be used to estimate changes in bolt preload by comparing the area under the response spectra in the modulation range to a baseline data.

A recent paper on effective frequency domain measurement method for detecting loose bolts was presented by Vincent Caccese, et al.[11] in 2004. The authors used frequency domain techniques to investigate a square composite plate excited by a piezoelectric actuator bolted with 16 bolts for loose bolts detection purposes by quantifying changes in bolt preload of composite/metal hybrid connection. They found out that if one of 16 bolts was loosened, a small decrease in natural frequency was detected. While when all of the 16 bolts were loosened, a large decrease in natural frequency was detected. This method was proved to be useful in identifying the presence of loose bolts by assessing the change of natural frequency with respect to different preloads.

1.2 Objective

This thesis presents results from well-controlled experiments on a simple bolted lap joint structure subjected to impact force excitation. During the experiments, the relationship between different preload levels in the bolt and natural frequencies in the structure as well as the relationship between different preload levels and damping ratios were studied. The impact hammer testing method for investigating the relationship between bolted joint preload and the structure's modal properties is useful for several reasons. It provides a nondestructive and efficient method for detecting loose bolts in bolted structures and verifies the structural integrity by checking the structure's natural frequencies and damping ratios. The objectives of this research are to:

- Quantify the relationship between the applied preload and the structure's fundamental modal properties (damping and natural frequency) for different bolt strengths and mating materials through experimental studies
- Assess fastener loosening by measuring modal parameters in a bolted joint structure through impact hammer testing

1.3 Overview

This thesis describes the effect of varying levels of preload on different plate materials and different strength bolts for a simple lap-joint structure.

Chapter 2 presents the experimental setup for impact hammer testing and the setup for the dynamic signal analyzer. It also provides the geometric dimensions and tolerances for the test plates, the details for the different strength bolts and the different bolt preload levels used in the experiments, and an adequate test plan for the experimental procedure and the signal analysis procedure.

Chapter 3 presents a structural analysis showing Von Mises stress and bearing pressure calculation prior to the experiments for the purpose of ensuring that all the bolts and the test plates were in their elastic deformation ranges. It also displays the first three vibrational mode shapes from the finite element analysis for better understanding of the test data.

Chapter 4 presents all the test data from modal impact testing in both table and graph forms, and includes the data discussion sections for the performed experiments.

Chapter 5 combines the findings from the experiments in the monolithic solid plate testing with the experimental results from the two plates bolted with a single bolt structure.

Finally, Chapter 6 summarizes all the findings.

CHAPTER 2: EXPERIMENTAL SETUP AND TEST PROCEDURE

2.1 Overview

A single-bolted lap-joint structure is adopted in order to determine the relationship between applied preload and structure's natural frequencies and the relationship between applied preload and modal damping in a bolted joint structure. A three dimensional drawing of the test components is shown in Figure 2.1. The bolted lap joint structure tested consists of four different parts: plates, bolt, nut and washers. This structure was assembled in the following order: bolt, washer 1, plate 1, plate 2, washer 2, nut, as shown in Figure 2.1.

Impact hammer testing was performed in this thesis to study the response of the bolted joint structure when subject to low-level impact. These tests were to investigate the preload effect on structure's modal properties and to demonstrate the effectiveness of the proposed impact testing method for loose bolt detection and preload level estimation in a single-bolted structure. The experimental setup with detailed instrumentation is shown in Figure 2.2. The weight for the different test components is presented in Appendix A. The measuring instruments will be specified in detail in the next section. The test setup consists of:

- Structural components: Test bolts, Test plates, Nuts and Washers
- Data acquisition equipment: DSP Technology SigLab Model 50-21 Signal Analyzer

- PC-Windows computer loaded with VNA dynamic signal analysis SigLab software
- PC Card to SCSI Adapter: ADAPTEC Slim SCSI 1460D
- A miniature accelerometer: ICP Accelerometer 309A
- Impact Hammer: PCB Impulse Force Hammer 086C03
- Experimental tools: torque wrenches and sockets

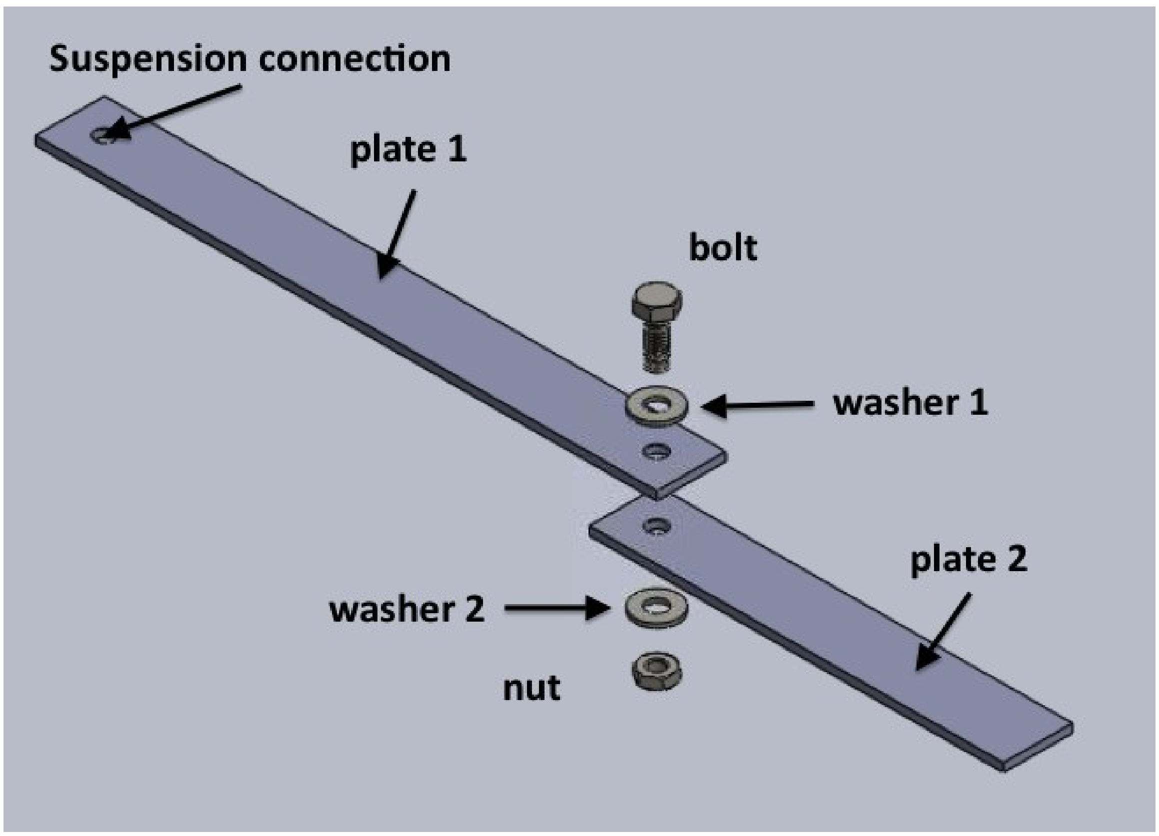


Figure 2.1 Bolted lap joint structure

2.2 Apparatus

2.2.1 Test Bolts

Two different strengths bolts, Grade 5 and Grade 8 bolts were used in performing impact tests. All of the bolts used to fasten the plate were ¼ inch in diameter with 20 threads per inch. Table 2.1 shows the detail information of the bolt configurations in the experiments, where tensile strength presents the maximum load in tension (pulling apart) that a bolt can withstand before breaking or fracturing, and yield strength presents the maximum load at which a bolt exhibits permanent deformation.

Table 2.1 Test bolts information

Head Markings	Grade	Size	Material	Proof Load (psi)	Minimum Yield Strength (psi)	Minimum Tensile Strength (psi)	Application
3 Radial Line	Grade 5	UNC ¼-20	Medium Carbon Steel, Quenched and Tempered	85,000	92,000	120,000	Commonly used in automobiles manufacturing
6 Radial Line	Grade 8		Medium Carbon Alloy Steel, Quenched and Tempered	120,000	130,000	150,000	Commonly used in heavy manufacturing

2.2.2 Preload Levels Calculation

Modal impact tests of seven different preload levels were carried out to find out the preload effect on modal frequencies and damping ratios in a simple bolted lap joint structure. The seven different applied torque values for Grade 5 bolts are 5, 10, 30, 50, 80, 110, 140 in-lbs., while the seven different applied torque values for Grade 8 bolts are 5, 10, 30, 55, 80, 110, 140 in-lbs.

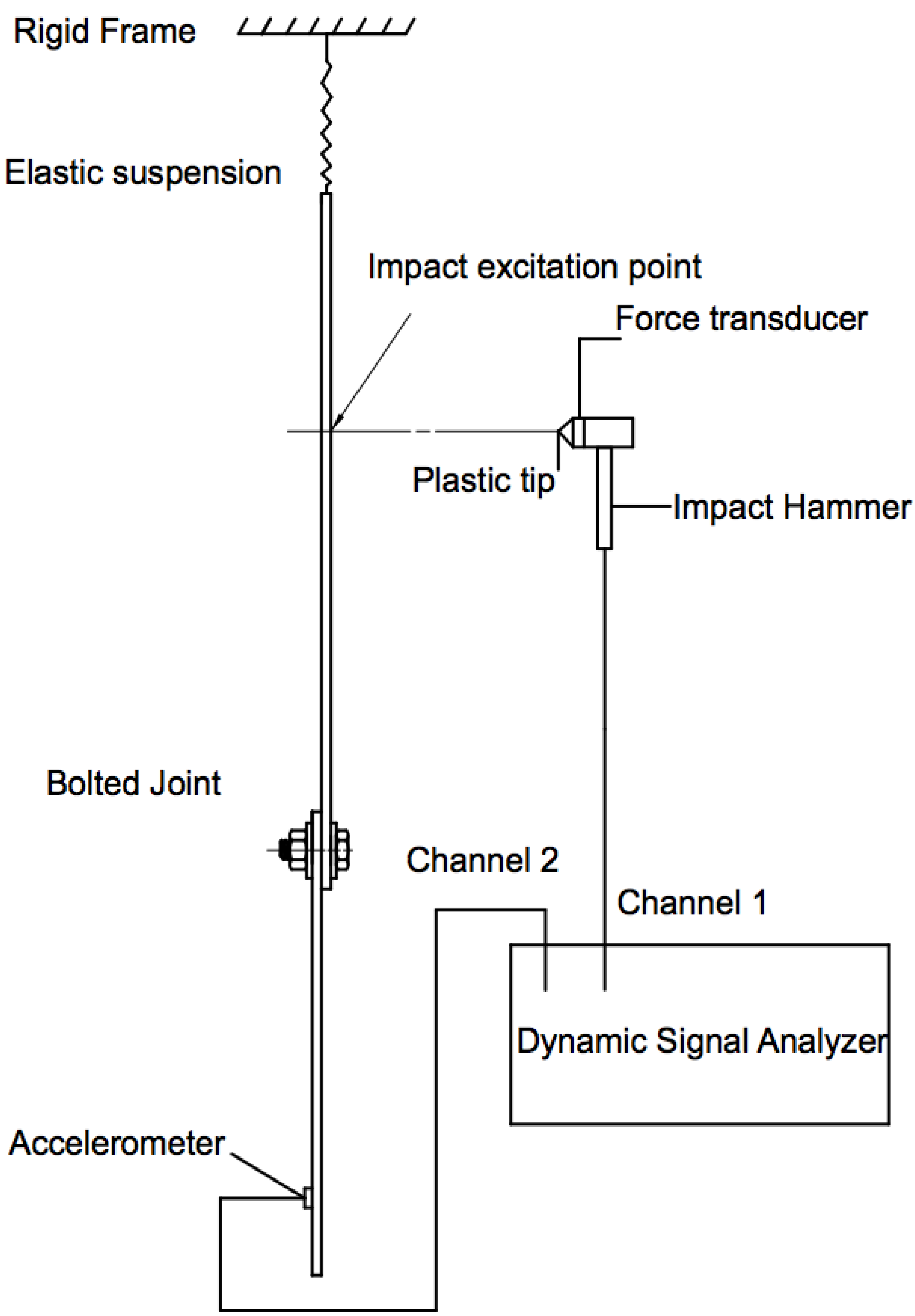


Figure 2.2 Schematic of test set-up

Bolt preload is often specified in terms of "n" percentage (n%) of the bolt's yield strength. The relationship of preload value and n% in bolt yield strength can be expressed as:

$$\text{Preload (n\%)} = \text{n\%} * \sigma_y * A_s \tag{2-1}$$

where σ_y presents bolt's minimum yield strength and A_s presents bolt's tensile stress area[1].

Torque-Preload relationship [12] can be expressed as:

$$T = K * D * P \tag{2-2}$$

where T represents the applied tightening torque (in-lbs.), K is a nut factor related to friction (dimensionless constant), D designates the nominal diameter of the bolt (in.) and P represents the bolt preload. For most small to medium size bolts, K is between 0.15 and 0.3. As a rough approximation for the lubricated bolts, K≈0.20 was used in the following calculations. The bolt preload can also be expressed by rearranging equation (2-2):

$$\text{Preload (n\%)} = \frac{T}{K*D} \tag{2-3}$$

By substituting equation (2-3) into equation (2-1), the bolt preload percentage in yield strength (n%) can be calculated as:

$$\text{n\%} = \frac{T}{K*D*\sigma_y*A_s} \tag{2-4}$$

The minimum yield strength of the Grade 5 bolts used is 92 ksi, and the minimum yield strength of the Grade 8 bolts used is 130 ksi as listed in the Table 2.1. For UNC (Unified National Coarse) ¼-20 bolts used in the experiments, D = 1/4 inch and the

[1] http://www.fastenal.com/content/feds/pdf/Article%20-%20Bolted%20Joint%20Design.pdf

tensile stress area $A_s = 0.0318\ in.^2$

$$\sigma_{y\ (Grade\ 5)} = 92{,}000 \text{ psi}$$

$$\sigma_{y\ (Grade\ 8)} = 130{,}000 \text{ psi}$$

where Grade 5 and Grade 8 designates Grade 5 and Grade 8 bolts, respectively.

As an example, consider Grade 5 ¼-20 bolt with applied torque values of 5 in-lbs., thus T = 5 in-lbs. During the tightening process, the torque applied produces an axial preload tension on the bolt and washers. The preload on the bolts and washers can be calculated using equation (2-3):

$$\text{P} = \frac{T}{K\times D} = \frac{T}{0.2\times 0.25} = \frac{5}{0.05} = 100 \text{ (lbs.)}$$

The bolt preload percentage in yield strength (n%) can be calculated using equation (2-4):

$$n\% = \frac{5}{0.2 * 0.25 * \sigma_{y\ (Grade\ 5)} * 0.0318} = 3.41\% \approx 3\%$$

Repeating this calculation procedure for Grade 5 bolt with the rest applied preload values of 10, 30, 50, 80, 110, 140 in-lbs. and for Grade 8 bolt with 5, 10, 30, 55, 80, 110, 140 in-lbs. torque, yields the results shown in Table 2.2 and Table 2.3.

Table 2.2 Grade 5 bolt percent preload and torque

Preload level	Torque (in-lb.)	Preload (lb.)	Percent (%) Preload in Bolt Yield Strength
1	5	100	3%
2	10	200	7%
3	30	600	21%
4	50	1000	34%
5	80	1600	55%
6	110	2200	75%
7	140	2800	96%

Table 2.3 Grade 8 bolt percent preload and torque

Preload level	Torque (in-lb.)	Preload (lb.)	Percent (%) Preload in Bolt Yield Strength
1	5	100	2%
2	10	200	5%
3	30	600	15%
4	55	1100	27%
5	80	1600	39%
6	110	2200	53%
7	140	2800	68%

2.2.3 Test Plates

A single lap-joint structure with two plates connected with one bolt was adopted when impact testing was performed (Figure 2.1). The test configurations investigated in this thesis consist of a 9 x 1 x 0.125 inches steel or aluminum plate bolted to a 6 x 1 x 0.125 inches steel or aluminum plate with one ¼-inch diameter Grade 5 or Grade 8 bolt. Two Grade 5 washers were placed under the bolt head and the nut, respectively. In addition, the aluminum and steel monolithic plates with identical geometric dimension and tolerance in the assembled bolted two plates configurations were used for baseline testing. The baseline tests were conducted by performing impact tests on bolted monolithic plates made from the same aluminum and steel materials. There are six different plates manufactured during the experiments: aluminum plate 1, aluminum plate 2, steel plate 1, steel plate 2, aluminum monolithic plate, and steel monolithic plate as shown in Figure 2.3 and Figure 2.4.

For the 9 x 1 x 0.125 inches plate 1 (Figure 2.3 (a)), two ¼-inch holes were drilled ½-inch away from the short edge symmetrically, one hole for bolted connection and the other hole for elastic suspension support from the ceiling. For 6 x 1 x 0.125 inches plate 2

(Figure 2.3 (b)), one ¼-inch hole was drilled ½-inch away from the short edge for bolted connection. The monolithic plate (Figure 2.4) is 14 inches in length, and has 1 inch x 0.125 inch cross section on its edges with a 1 x 1 x 0.25 inch overlap region bolted with one ¼-inch diameter Grade 5 or Grade 8 bolt with two washers. The details of the geometric dimensions and tolerances for three test plates are shown in Appendix C.

Aluminum 6061-T6511 (ASTM B221) was used in fabricating the aluminum plates. This aluminum material has 45,000 psi in maximum tensile strength and 40,000 psi in maximum yield strength. The steel plates were fabricated from cold rolled 1018 material, which have 70,000 psi in maximum yield strength and approximately 85,000 psi in maximum tensile strength. The test plates' materials information is listed in Table 2.4.

Table 2.4 Test plates materials information

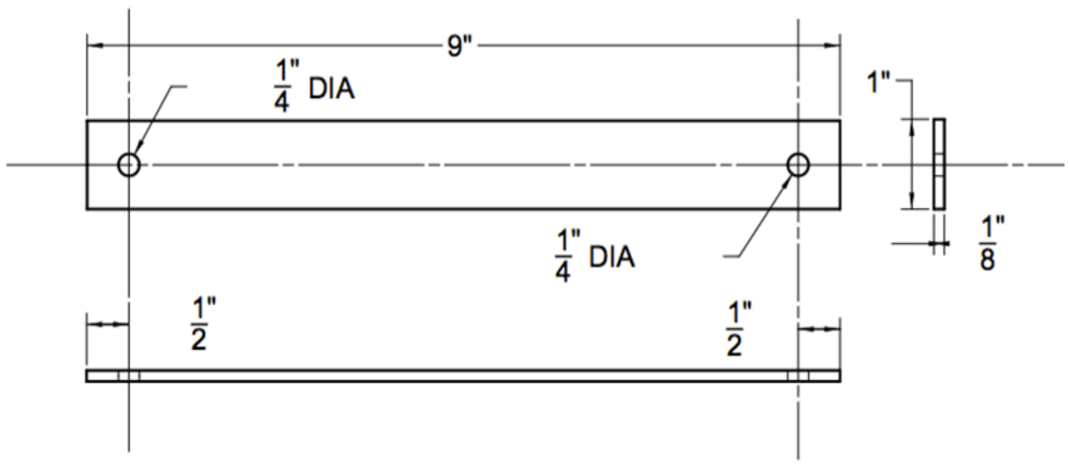
Material	Grade	Maximum tensile strength (psi)	Maximum yield strength (psi)	Note
Aluminum	6061-T6511 (ASTM B221)[2]	45,000	40,000	N/A
Steel	Cold rolled 1018[3]	85,000	70,000	Carbon content: 0.15-0.2

2.2.4 Boundary Condition

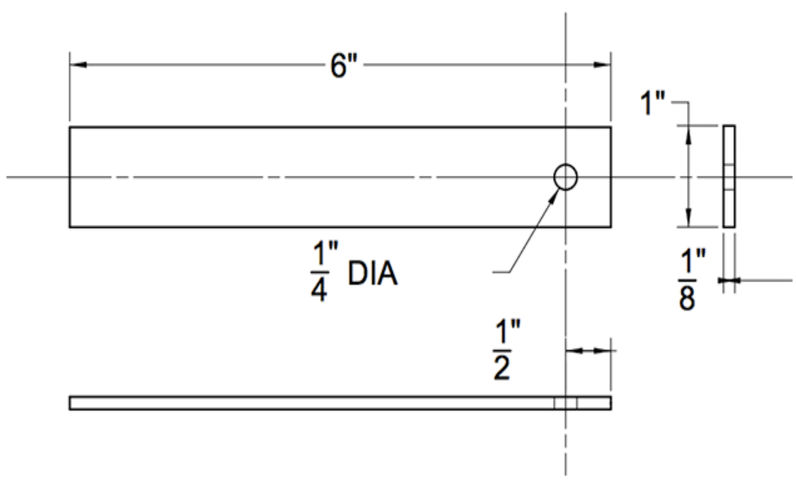
The first step in the experimental setup for frequency analysis is to consider the supporting system, which is the necessary fixture mechanism to constrain the test structure[13]. The test structure was suspended with a Nylon cord and a rubber band. The Nylon Cord was attached to the ceiling first, and then connected to the test structure

[2] http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6
[3] http://www.speedymetals.com/information/Material26.html

through a rubber band. As long as the suspension frequency of the structure is less than 10% of the natural frequency of the first vibration mode of the structure, the low suspension mode can be ignored [13].



(a) Plate 1



(b) Plate 2

Figure 2.3 Test plates configurations

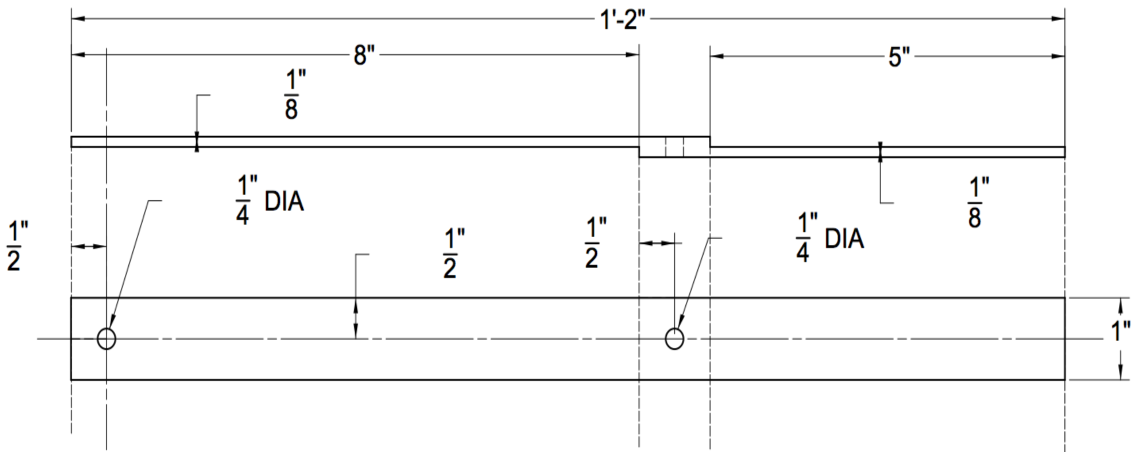


Figure 2.4 Monolithic plate configurations

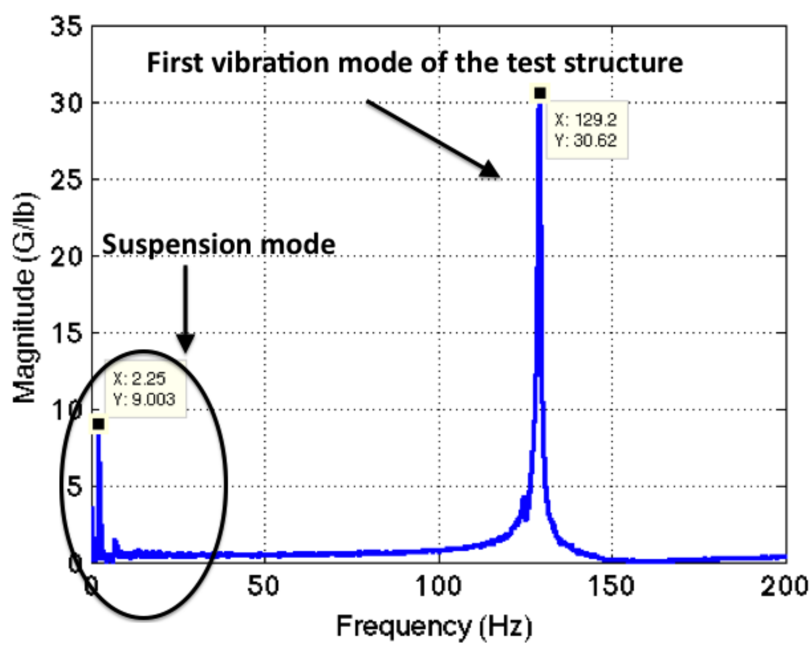


Figure 2.5 Frequency response of the suspended structure

Figure 2.5 shows the transfer function magnitude of acceleration over impact force with focused frequency range of 0-200Hz extracted from Grade 5 bolt connecting two steel plates data. The resonance frequency of the suspension system was around

2.25Hz and the natural frequency of the first vibration mode is 127.9Hz. Since the suspension frequency is much less than 10% of the first mode of the test structure, the suspension mode had a negligible effect during the experiments.

2.3 Measurement Instrumentation

2.3.1 Torque Wrenches

In this experiment, two pre-calibrated dial torque wrenches and a hand wrench were used to apply seven different torque values for precisely preloading the bolts.

The PROTO torque wrench used in the experiments has a dial indicator that, when applying torque to the handle, rotates clockwise or counterclockwise while showing the exact amount of torque value applied to the nuts and bolts. Once the force is removed from the handle, the pointer will return to zero automatically. There are two pointers in the dial: the yellow one rotates only with the force applied, and the blue pointer can be adjusted by hand or moves along with the yellow pointer. The detailed information of the dial torque wrench used is shown in Table 2.5.

Table 2.5 Proto brand dial torque wrench

Model	Length (in)	Torque Range	Increment	Drive size
J6168F	10	0-30 in-lb.	0.5 in-lb.	1/4”
6177A	10	0-250 in-lb.	5 in-lb.	3/8”

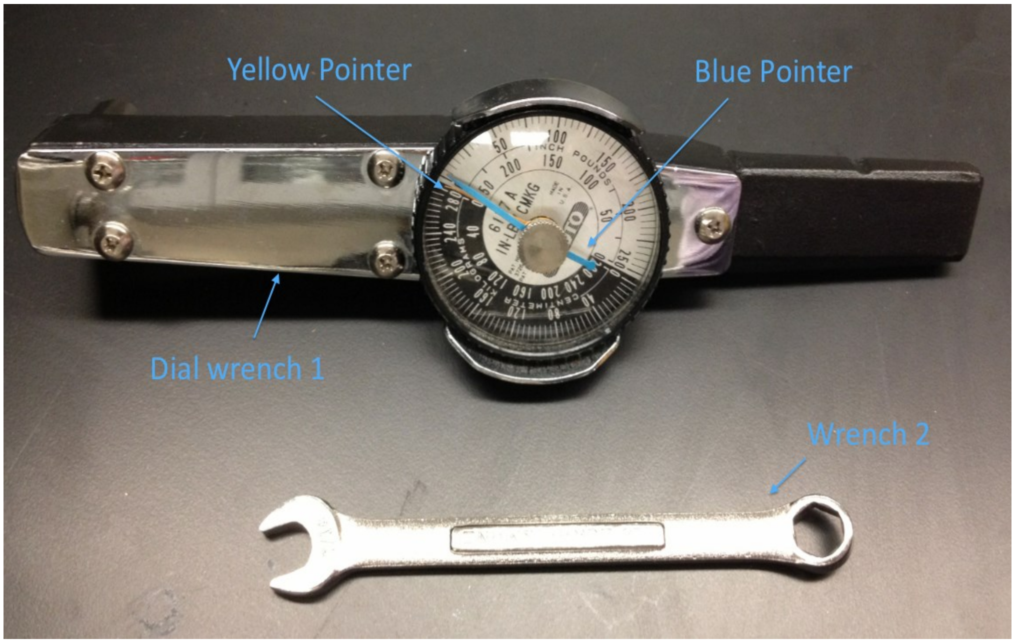


Figure 2.6 Two types of torque wrench used in the experiment

2.3.2 Impact Hammer

The bolted lap-joint structure is excited using an impact hammer to induce the dynamic response. In this thesis, a PCB 086C03 impulse force hammer was used to excite the first three frequency modes investigated. The hammer excitation point was chosen to be three inches away from the top edge on the suspension side of plate 1 along the symmetry line. The impact location is noted in Figure 2.7. Specifications for the impact hammer used in this study are shown in Table 2.6.

2.3.3 Accelerometer

The ICP accelerometer was used for its small size and built-in signal conditioning circuitry. This kind of accelerometer has a low noise regulated constant and can improve sensor accuracy[4]. The specifications of the accelerometer used are shown in Table 2.7. The accelerometer was attached to the 6" x 1" plate 2 surface using wax, and was 1 inch away from the bottom along the symmetry line. Wax was chosen for attaching accelerometers because it is quick, convenient, lightweight, clean and safe on the test surface. For more detailed information on accelerometer location, refer to Figure 2.7 below.

2.3.4 Dynamic Signal Analyzer

A DSP Technology SigLab Model 50-21 Signal Analyzer was used in this study to measure and record all desired time domain or frequency domain signals. The PC-Windows based computer was interfaced with a PC Card to SCSI Adapter, which was used to connect the analyzer and the computer (with SigLab software installed). The Dynamic Signal Analyzer had two channels: Channel 1 for the impact hammer force measurement and Channel 2 for the accelerometer response measurement.

This computing system was used to post-process the measured data and to extract modal parameters from FRF measurements. In this thesis, the SigLab Virtual Network Analyzer (VNA) was used to perform:

- Time domain response of the impact hammer (Figure 2.8)
- Autospectrum of the impact hit (Figure 2.9)
- Time domain response of the accelerometer (Figure 2.10)
- Coherence (Figure 2.11)
- Magnitude of the transfer function (Figure 2.12)

[4] http://www.ueidaq.com/media/static/apps/appnote-030_cessna.pdf

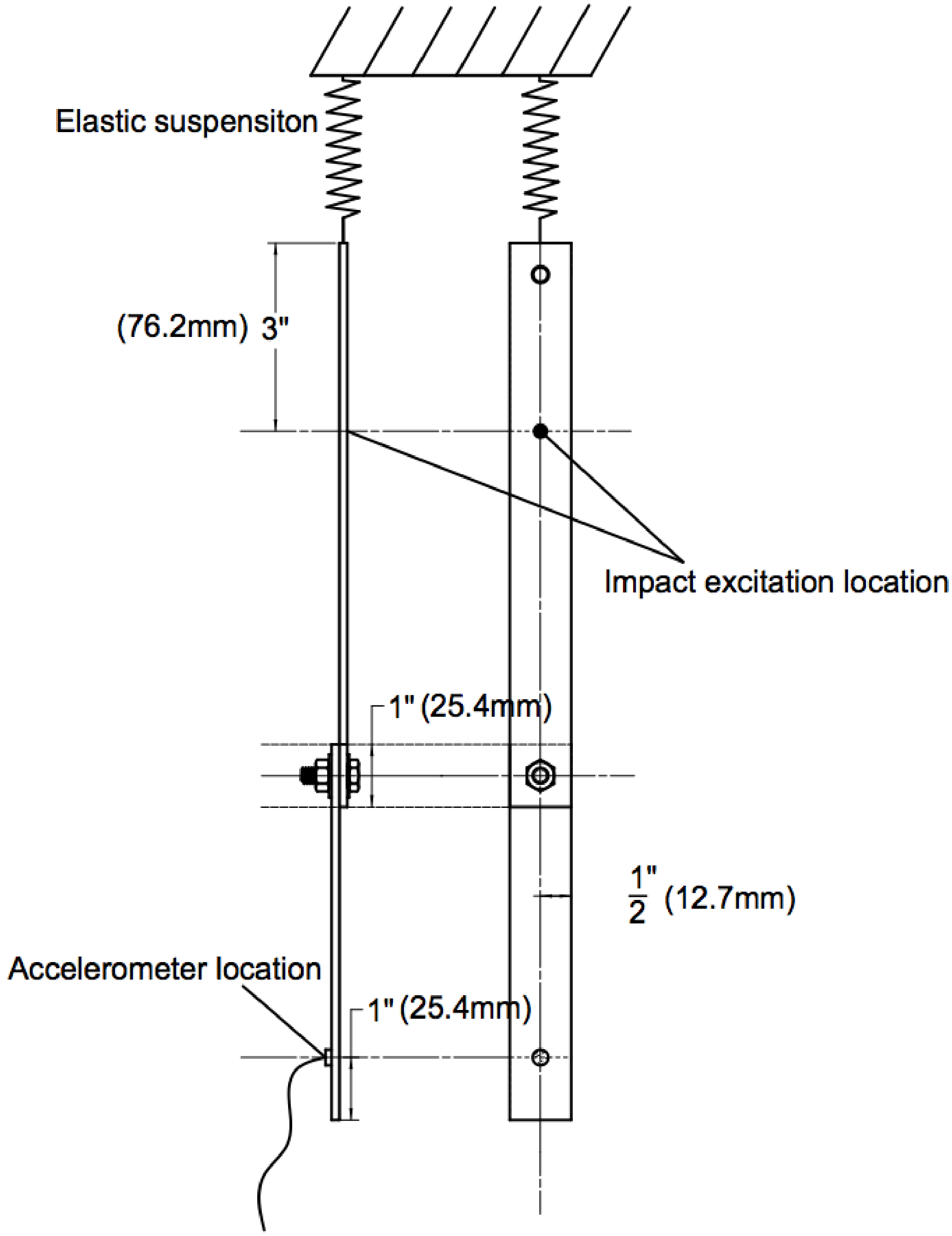
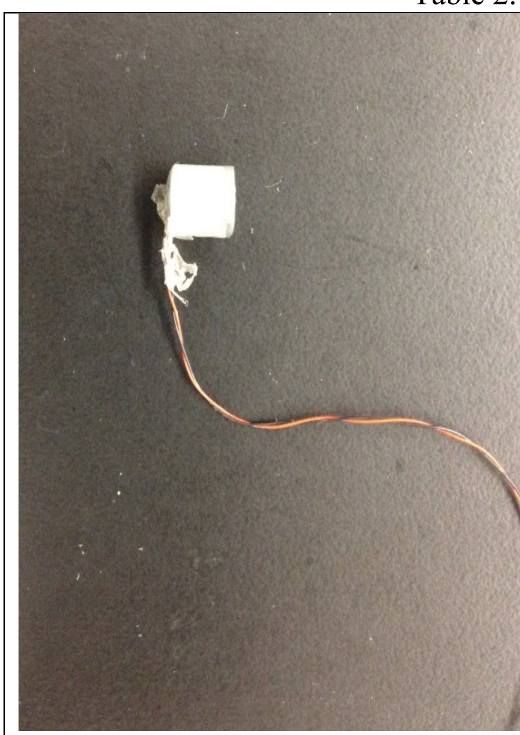


Figure 2.7 Impact hammer striking area and accelerometer attached location

Table 2.6 PCB impact hammer

PCB Impulse Force Hammer	
Model No.	086C03
Serial No.	14415
Measurement Range	0-500lb.
Tip Plastic / Extender none / Hammer Sensitivity (± 15 %)	8.57 mV/ lb.

Table 2.7 ICP accelerometer



ICP Accelerometer	
Model No.	309A
Serial No.	5435
Measurement Range	0-500lb.
Voltage Sensitivity	5.10mV/g

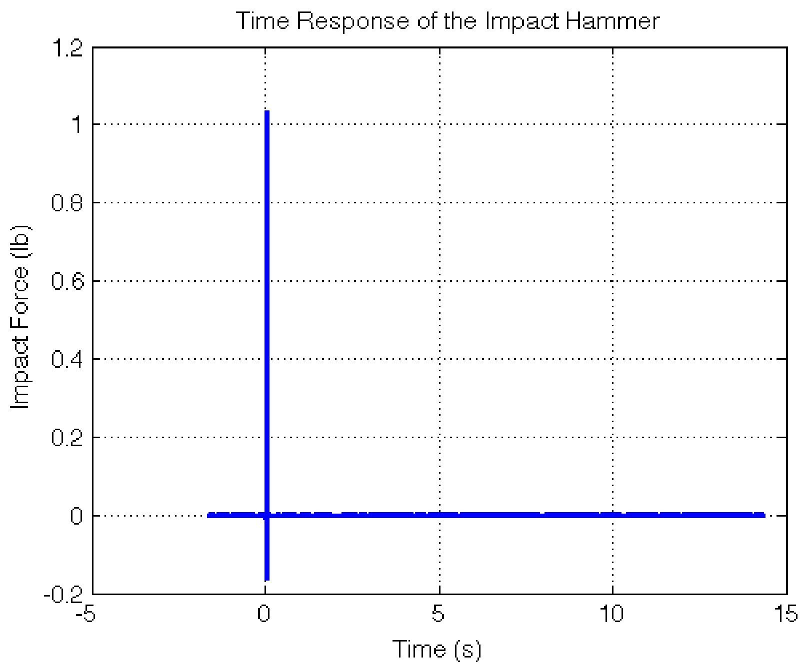


Figure 2.8 Time domain response of the impact hammer

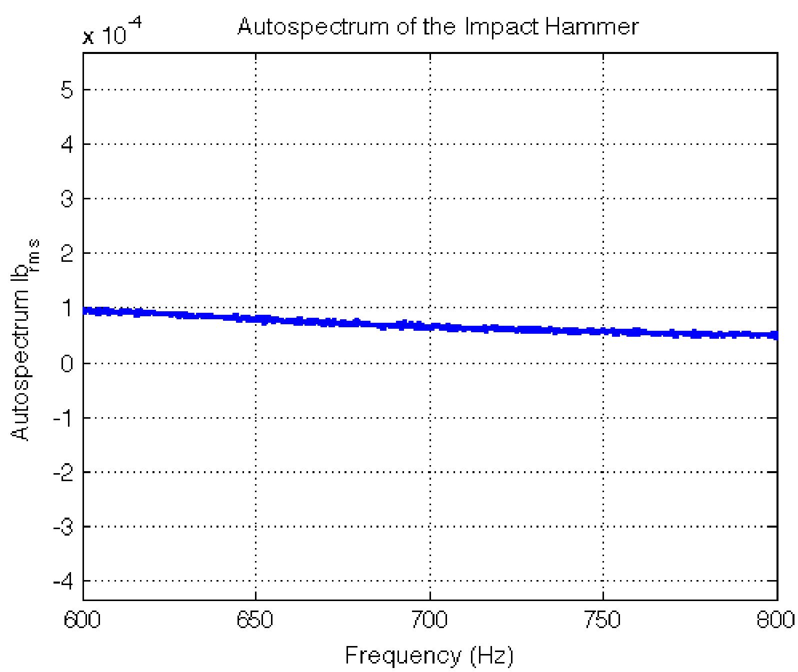


Figure 2.9 Autospectrum of the impact hit

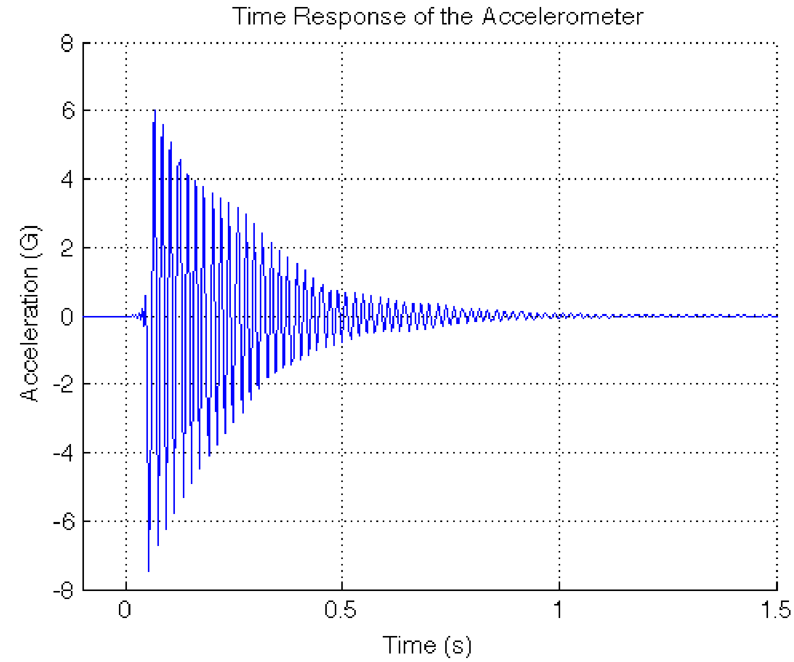


Figure 2.10 Time domain response of the accelerometer

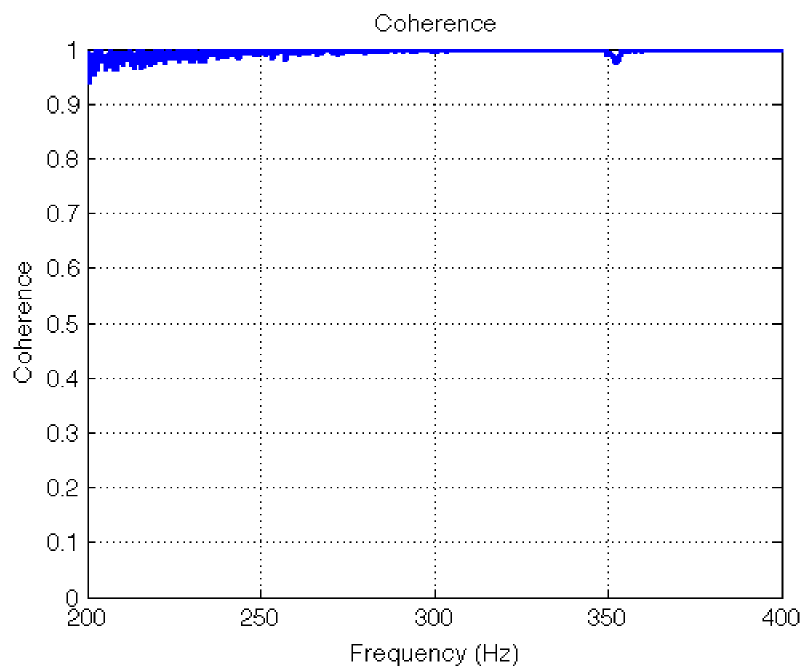


Figure 2.11 Frequency response for transfer function's coherence

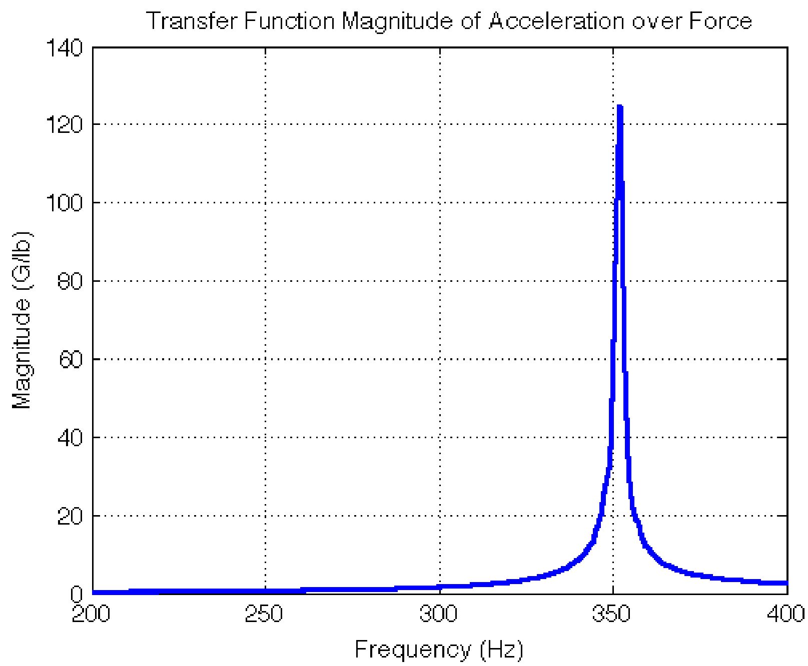


Figure 2.12 Magnitude of the transfer function of acceleration over force

Figure 2.13 Channel 1 and channel 2 settings for Impact hammer testing

2.4 Test Procedure

The step-by-step procedure to perform impact testing of different bolt preload levels to the bolted lap joint structure is outlined in the following three stages. The final dynamic signal analyzer setting is shown in Figure 2.13.

2.4.1 Dynamic Signal Analyzer Parameter Setting

1. Turn on SigLab Analyzer.
2. Turn on PC-windows computer.
3. Open SigLab Dynamic Signal Analyzer (VNA).
4. Select Channel 1 for impact hammer and Channel 2 for accelerometer.
5. Select appropriate sensitivities for input channels, bandwidth and data length[5].
6. Select F20_Exp.01[6].
7. Select overload/double hit rejection.
8. Set to Every frame[7].
9. Set the channel 1 of the impact hammer to 27%.
10. Set the delay to -10.0.

---

[5] Note that these parameters were varied in different tests and will be specified in detail in data discussion sections. The sensitivity for the impact hammer used was 117 lb./V and the sensitivity for the accelerometer used was 196 G/V throughout all different tests. The ultimate frequency resolution of the analysis was determined by the selection of bandwidth and data record length: Frequency Resolution = 2.56 x Bandwidth / Record length.

[6] Note: This option meant that Force 20%, Exponential 0.01. The Force 20% had a weight of unity for the first 20% of the measurement record, and zero thereafter. The exponential window was applied to channel 2. The 0.01 indicates that the exponential has decayed to 0.01 at the end of the frame.

[7] Data is recorded only if the conditions are met in the frame.

2.4.2 Impact Hammer Testing

1. Check the threads of Grade 5/Grade 8 bolts that will be tested in the experiments[8].
2. Lubricate the bolt, nut and washers by dropping two or three drops of 3-in-one multi-purpose oil[9].
3. Assemble the lap joint structure by carefully joining bolt, washer 1, test plate 1, test plate 2, washer 2 and nut together as shown in Figure 2.1.
4. Install the 7/16" socket onto the square drive end of the dial torque wrench by pressing the socket firmly onto the drive anvil.
5. Turn the dial reading to zero by rotating the dial and make sure that the yellow pointer on the gauge registers at zero along with the blue one.
6. Put bolted test plates on the 5 1/2" reversible mechanical jaw (see Figure 2.14), and hold the nut with hand wrench and put the socket of the dial wrench onto the hex bolt head to be preloaded.
7. Apply Preload to the test bolts: Turn the handle of Dial wrench clockwise and pay attention to the yellow and blue pointers' moving in the dial. Keep applying the rotational force until the blue pointer reaches the desired torque value and hold that value for at least three seconds before removing two wrenches. For example, when applying 110 in-lbs. to a Grade 5 Bolt that connecting two aluminum plates, keep applying force to the dial wrench until the blue pointer reaches 110 in-lbs. on the gauge and keep that value for at least 3-5 seconds.

---

[8] Note that any damaged or dirty threads will increase the uncertainty in torque reading, use as received.

[9] The lubrication was made by WD-40 Company, San Diego, CA. The reason for choosing lubrication was to decrease the uncertainty in torque measurement, for uncertainty of lubricated bolts is $\pm 25\%$, while the uncertainty of un-lubricated bolts is $\pm 35\%$. [14] Criteria for preloaded bolts. National Aeronautics and Space Administration.

8. Click the Avg button on SigLab VNA Plot window.

9. Attach the accelerometer 1 inch away from the bottom of the plate 2 along the symmetry line. (See Figure 2.9).

10. Strike the test structure with the impact hammer plastic tip at three inches away from the top edge of plate 1 at noted location shown in Figure 2.9. Hit the lap joint structure with the impact hammer horizontally, and check the real time history of the impact signal. The impact force signal should be a single clear pulse. Make sure that the hammer only strikes the structure once, and avoid "double hit". Take average of four impact hits when performing these tests, and make sure the test structure is hit in the same location for all tests.

11. Check the coherence function, and make sure that the coherence of the interest frequency range is all above 0.95 (except for the coherence of the antinode).

12. Stop the count at 4 and then click the Save button.

13. Apply different torque values to the test bolts[10].

14. Repeat impact testing procedures for each torque value to all different sets of experiments.

15. Post-processing the modal properties data through transfer function plots.

[10] For Grade 5 Bolts, the preload torque is 5, 10, 30, 50, 80, 110, 140 and for Grade 8 Bolt, the preload torque value is 5, 10, 30, 55, 80, 110, 140. The units are all in in-lbs.

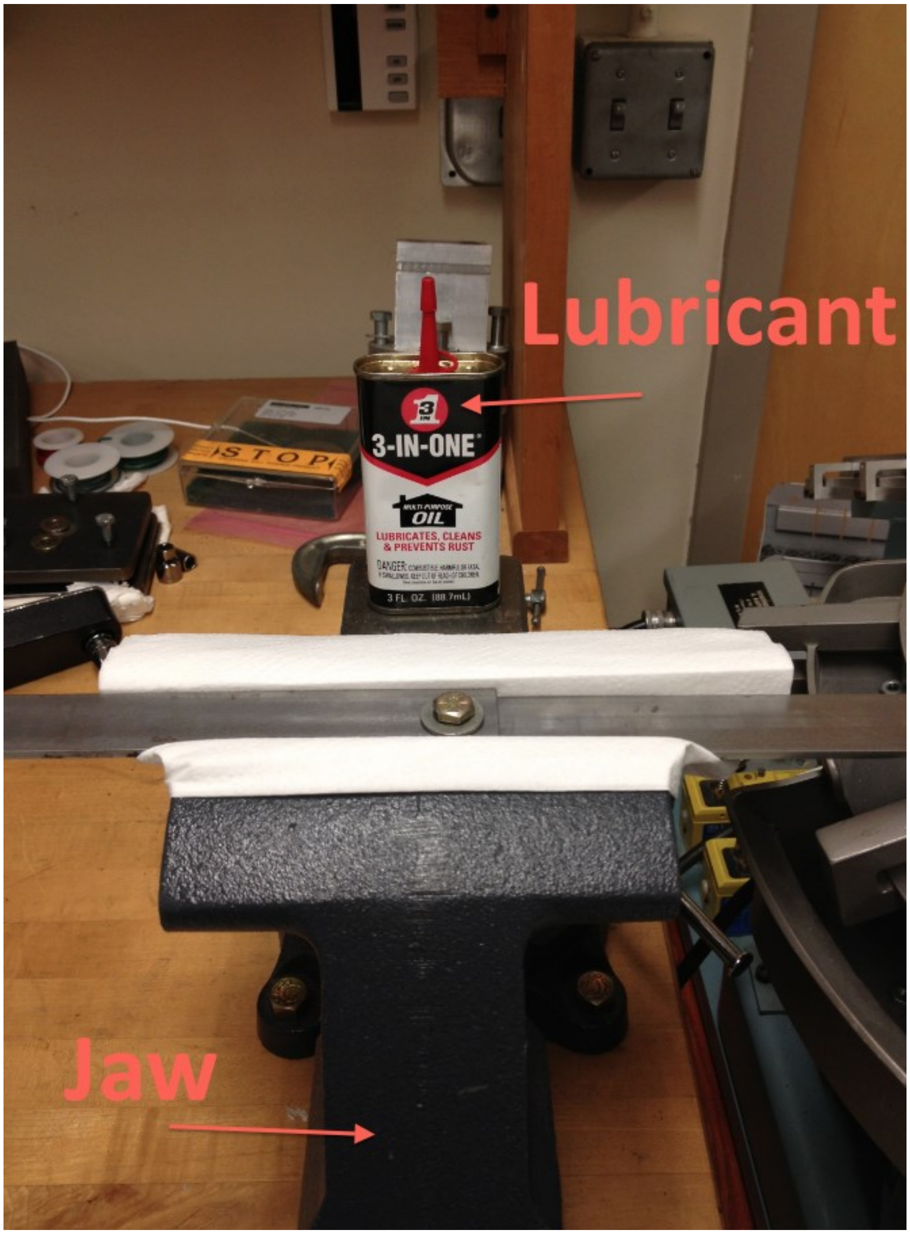


Figure 2.14 5-1/2" reversible mechanical jaw

CHAPTER 3: STRUCTURAL ANALYSIS

3.1 Introduction

This chapter presents the structural analysis for the preloaded bolted lap joint structure prior to experiment. The purpose of doing the structural analysis is to assess stresses due to preload applied on the bolt and the structure to ensure that all the bolts and test plates are in their elastic deformation ranges. It can also help to predict the modal response of the experimental structure under the designed excitation.

3.2 Maximum Stresses on the Bolt during Preloading

Table 3.1 presents the information about the bolt geometry for UNC ¼ inch bolts [15]. The following calculations verify that the shank for all bolts are in their elastic deformation ranges by calculating maximum stresses in the bolted joint under the largest preload applied during impact hammer tests.

Table 3.1 UNC ¼ inch - 20 bolt geometry

UNC Bolts	Major Diameter	Minor Diameter	Number of threads per inch	Distance between nut flats for hex nuts	Tensile stress area
1/4” -20	1/4”	0.189”	20	7/16”	0.0318in^2

The maximum tensile stress on the bolt can be calculated as:

$$\text{Tensile Stress} = \frac{F_{preload}}{A_s} = \frac{2800lb.}{0.0318in^2} = 8.8 \text{ ksi}$$

The largest preload applied and its corresponding torque during the tests is:

$$F_{preload} = 2800\ lb \text{ And Torque} = 140 \text{ in-lbs.}$$

For a ¼ inch - 20 UNC bolt:

$$d_{major} = 0.25"$$

$$d_{nut} = 7/16" = 0.4375"$$

$$A_s = 0.0318\ inch^2$$

where d_{major} is the major diameter of the bolts, d_{nut} is the distance between nut flats for hex nuts, and A_s is the bolts' tensile stress area.

$$d_{nut\_joint} = \frac{d_{major} + d_{nut}}{2} = \frac{0.25" + 0.4375"}{2} = 0.34"$$

$$d_s = \sqrt{\frac{4 \times A_s}{\pi}} = \sqrt{\frac{4 \times 0.0318}{3.14159}} = 0.201in$$

$$\text{Thread Torque} = \text{Torque} - \frac{\mu \times d_{nut_{joint}} \times F_{preload}}{2}$$

$$\text{Thread Torque} = 140 - \frac{0.15 \times 0.34 \times 2800}{2} = 69\ in - lb.$$

$$\text{Shear Stress} = \frac{16 \times Thread\ Torque}{\pi \times d_s^3} = \frac{16 \times 69}{3.14159 \times 0.201^3} = \frac{11 \times 10^2}{0.0255} = 43ksi$$

$$\text{Von Mises Stress} = \sqrt{(\text{Tensile Stress})^2 + 3(\text{Shear Stress})^2}$$

$$\text{Von Mises Stress} = \sqrt{(8800)^2 + 3(43000)^2} = 75ksi$$

where d_{nut_joint} represents the effective contact diameter between the nut and joint surface and is the average of major diameter and the distance between parallel nut flats for a hex nut. μ represents the friction coefficient for bolts, and with general machine oil lubrication, $\mu = 0.15$.

The minimum yield strength for a Grade 5 bolt is 92 ksi, and the minimum yield strength for a Grade 8 bolt is 130 ksi. It can be seen that those two values are larger than the maximum Von Mises Stress calculated under the largest preload applied during experiments.

3.3 Bearing Pressure Calculation

Grade 5 UNC ¼ - 20 Flat Washers were used during all the experiments. The inside diameter (I.D) is 5/16", and the outside diameter (O.D) is 0.734". The bearing pressure area is the area of the washer, as marked in Figure 3.1 as the blue ring below. So the bearing pressure area can be calculated as:

$$A_{washer} = \pi \left(\left(\frac{0.734}{2}\right)^2 - \left(\frac{0.3125}{2}\right)^2 \right) = 0.3464 \ (in^2)$$

The formula for bearing pressure is defined as load over area, so the bearing pressure on the test plates through washers is:

$$\text{Bearing Pressure} = \frac{F_{preload}}{A_{washer}}$$

The largest preload applied was 2800lb., so the maximum bearing pressure is:

$$\text{Bearing Pressure} = \frac{2800}{0.3464} = 8.1 \text{ ksi}$$

The maximum bearing pressure calculated is smaller than the yield strength of aluminum material (40ksi), and it is much smaller than the yield strength of the steel material (70ksi).

3.4 Finite Element Analysis

The third part of the structural analysis section presents the simulation analysis performed on a preloaded bolted joint structure. The first three vibrational mode shapes and their nodal line locations are computed using the Finite Element Method with SolidWorks simulation software for a better understanding of vibrational characteristics. The first three vibrational mode shapes for aluminum and steel test plates are investigated here.

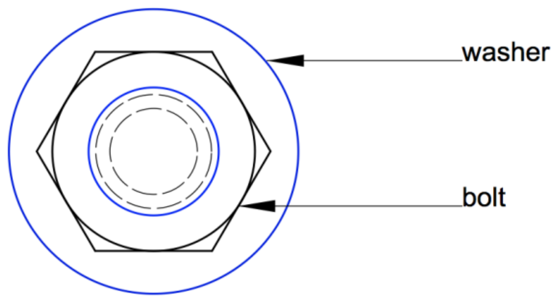


Figure 3.1 Washer bearing pressure area

3.4.1 Description of the Finite Element Model

The FE model consists of four parts: plate 1, plate 2, washer 1, and washer 2 as shown in Figure 3.2. Figure 3.3 shows part of the three-dimensional Finite Element mesh with applied preload force for this simplified lap joint model. Both test plates and washers in the Finite Element analysis were modeled with controlled dimensions. The SolidWorks simulation is used for both meshing and analyzing the model.

Three different kinds of materials are used in this FE model: 6061-T6 (SS) and AISI cold rolled 1018 Steel for both Plate 1 and Plate 2; Alloy steel for washers. Table 3.2 shows the material properties needed for the following simulation analysis.

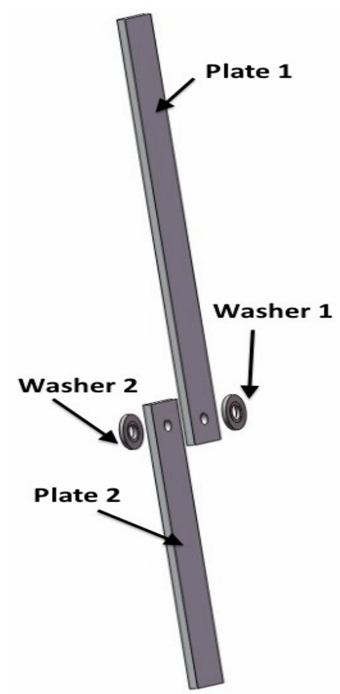


Figure 3.2 Simplified lap joint Finite Element model

Table 3.2 Material properties of FE Model

Materials	6061-T6	1018 Steel, Cold Rolled	Alloy Steel
Elastic Modulus	1,000 ksi	29,732 ksi	30,458 ksi
Poisson's Ratio	0.33	0.29	0.28
Shear Modulus	3,771 ksi	11,603 ksi	11458 ksi
Mass Density	0.097544 lb./in^3	0.284322 lb./in^3	0.27818 lb./in^3
Tensile Strength	45 ksi	61 ksi	105 ksi
Yield Strength	40 ksi	51 ksi	90 ksi

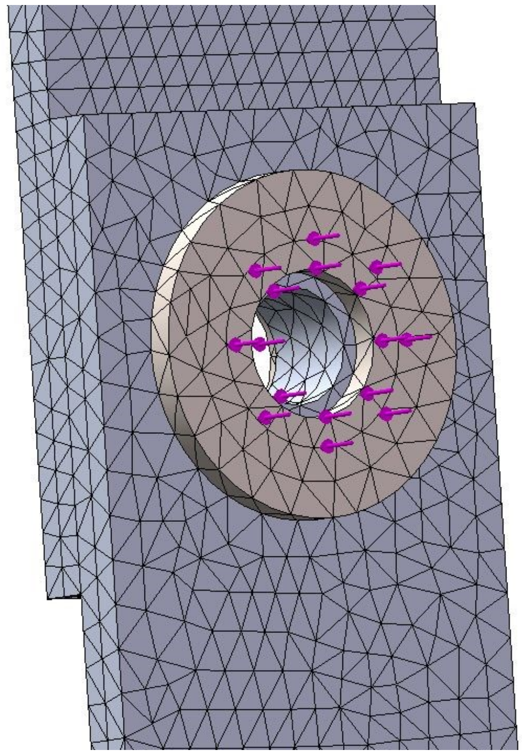


Figure 3.3 Finite Element zoom in mesh with applied preload

3.4.2 Elastic Support, Contact, and Element Mesh

Elastic upper support to the top face of Plate 1 was applied as shown in the Table 3.3, with a normal and shear stiffness value of 1 (lb./in)/in^2 to simulate the elastic suspension of the test plates presented in Chapter 2.

As for contact information, the global contact with bonded type and compatible mesh options were chosen. All the parts were treated as solid body, and their volumetric properties are shown in Table 3.4. For all different parts in this model, the curvature based mesh was used and had four Jacobian points. The mesh quality was high with maximum element size of 0.1 inch and minimum element size of 0.03 inch. This Finite Element mode mesh has 36732 total nodes and 21287 total elements.

Table 3.3 Elastic support in the simulation process

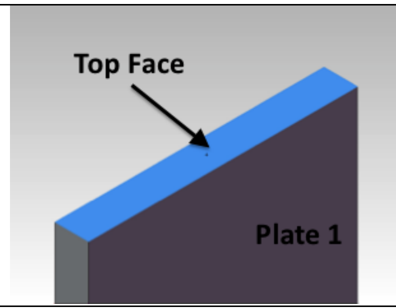
Fixture type	Upper support on Plate 1
Elastic Support	

Table 3.4 Volumetric properties for Plate 1 and Plate 2 made from different materials

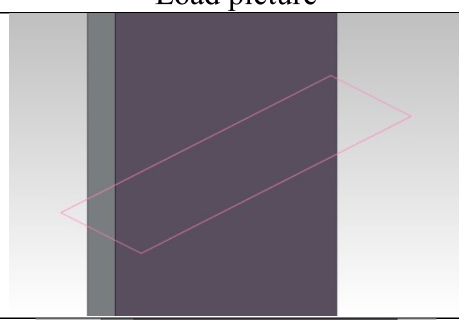
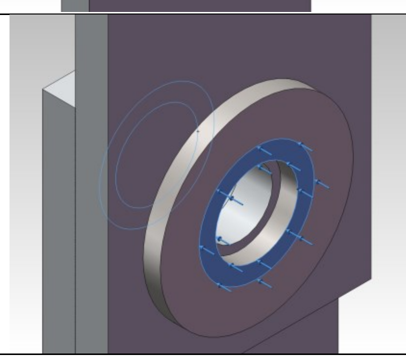
Part	Volumetric Properties
Plate 1 of Aluminum 6061-T6	Mass:0.109138 lb Volume:1.11886 in^3 Density:0.0975437 lb/ in^3 Weight:0.109064 lbf
Plate 2 of Aluminum 6061-T6	Mass:0.0725592 lb Volume:0.743864 in^3 Density:0.0975437 lb/ in^3 Weight:0.07251 lbf
Plate 1 of cold rolled 1018	Mass:0.318117 lb Volume:1.11886 in^3 Density:0.284322 lb/ in^3 Weight:0.317902 lbf
Plate 2 of cold rolled 1018	Mass:0.211497 lb Volume:0.743864 in^3 Density:0.284322 lb/ in^3 Weight:0.211353 lbf

3.4.3 Applied Load

Two different types of load (see Table 3.5) were applied to this finite elements model:

1. Gravitational force with top frame as its reference and this force vector value is (0,0, -386.22) in/s^2.
2. The second one is the preload applied normal to both washer surfaces. The bolted preload in the experiments is simplified in the FEM as normal compressive forces applied to the washers for the purpose of easily obtaining a quick and good mesh. The applied force value is 100 lb, which is the value of the smallest applied preload level during experiments resulting from tightening torque of 5 in-lbs.

Table 3.5 Force in the simulation process

Load	Load picture	Value
Gravity		(0,0, -386.22) in/s^2 English (IPS)
Preload		100lb

3.4.4 Mode Shapes

Vibrational modes are inherent properties of the structure and depend on mass, damping, stiffness and boundary conditions. Each mode has its own natural frequency, modal damping ratio and mode shape. The first three mode shapes for the simplified lap joint Finite Element model with two washers subjected to 100lb preload are shown in Figure 3.4. Due to the identical geometry conditions except for the different mass densities property, the mode shapes for steel and aluminum test plates are very similar. The difference is resulted from the different mass and elastic properties.

Table 3.6 Nodal line locations for aluminum and steel test plates

		Aluminum test plates nodal line locations (inch)		Steel test plates nodal line locations (inch)	
Mode	Node	Plate 1	Plate 2	Plate 1	Plate 2
1	1	3.22	2.59	3.18	2.69
2	1	1.80	4.07	1.85	4.11
	2	7.20	N/A	7.11	N/A
3	1	1.31	0.87	1.31	0.906
	2	5.02	4.68	5.00	4.69
	3	8.86	N/A	8.91	N/A

The distances between the top of each plate and each nodal line location marked in the Figure 3.4 for vibrational mode shape 1, 2 and 3 of both cold rolled 1018 Steel and Aluminum 6061-T6 test plates are listed in Table 3.6. Figure 3.5, Figure 3.6 and Figure 3.7 show the nodal line locations for the first, second and third vibration modes, respectively with impact excitation point and the accelerometer position. The test structure was excited at each mode with an impact hammer and the dynamic responses were captured by the accelerometer attached. Note that Node 1 of the first mode is unintentionally near the impact excitation point, which affects the results collected from impact hammer testing.

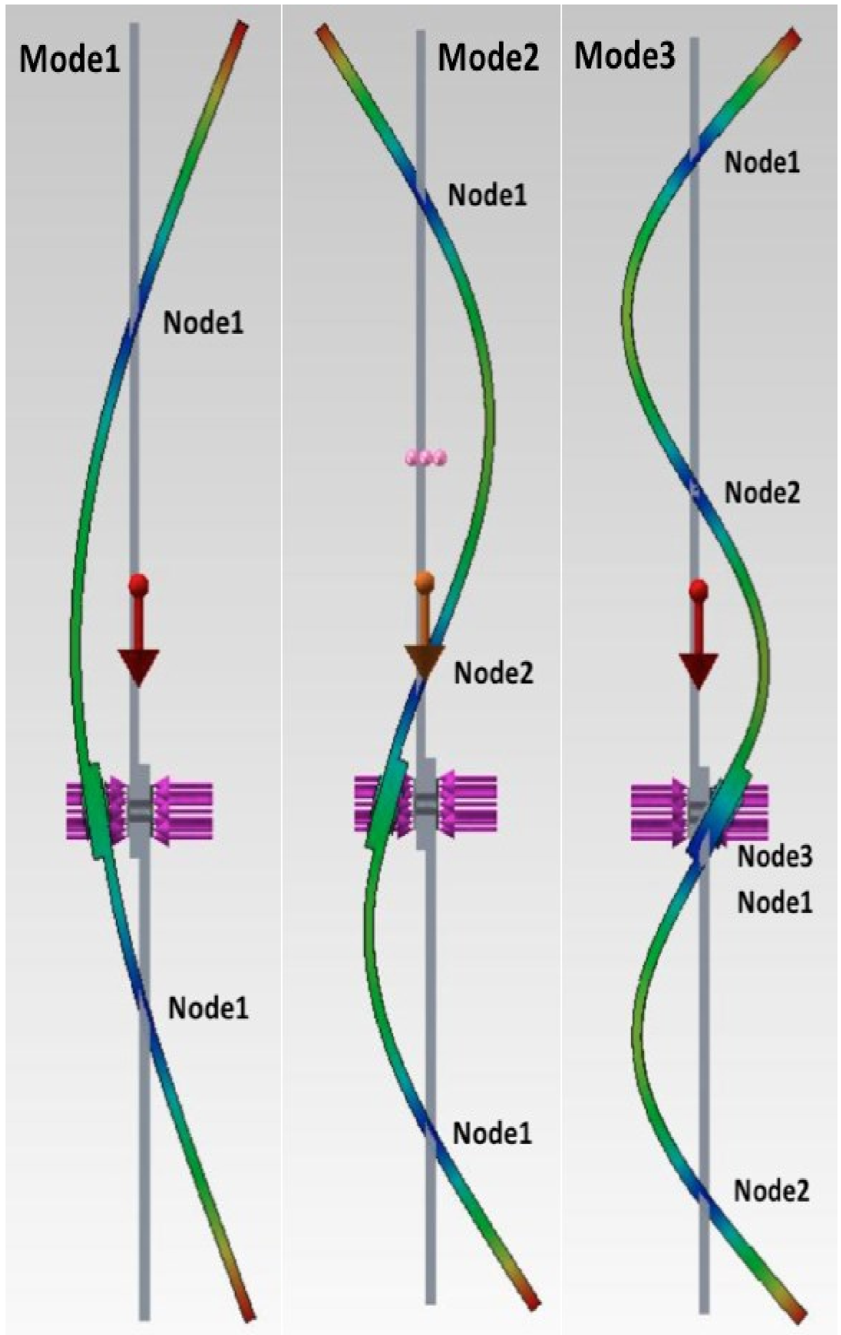


Figure 3.4 First three vibrational mode shapes for aluminum and steel test plates

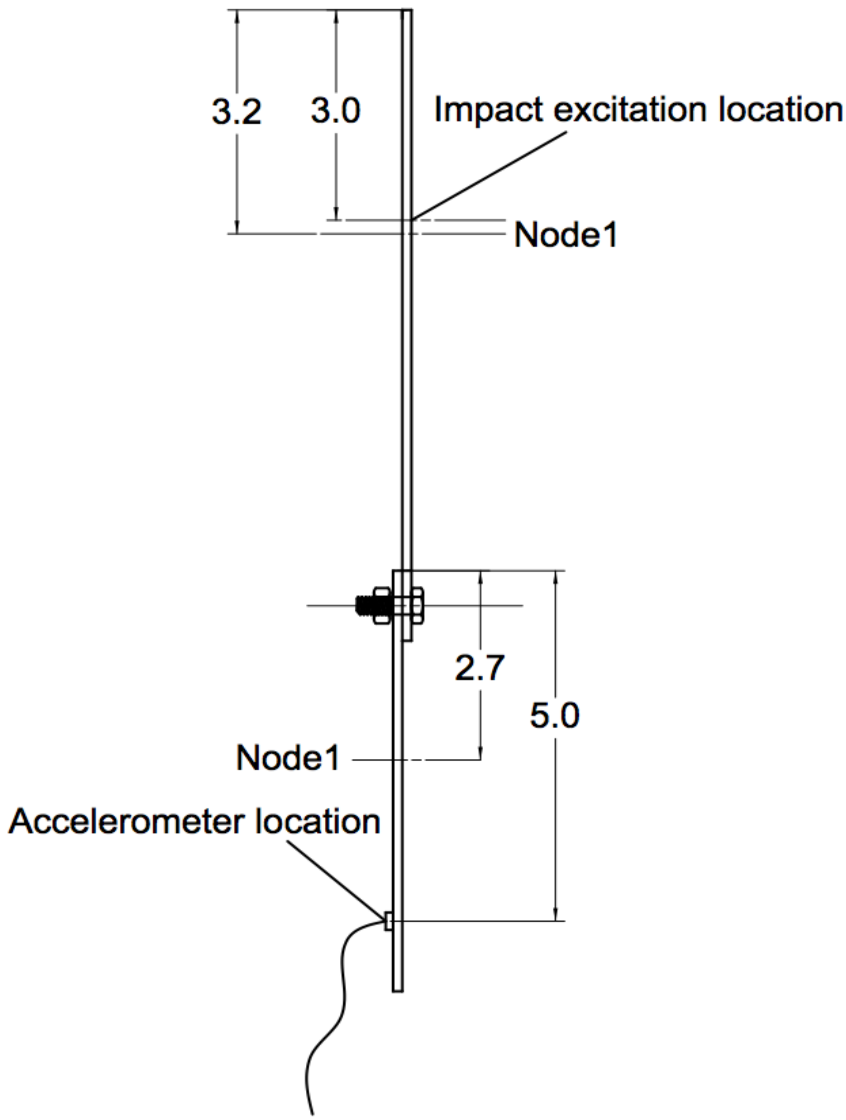


Figure 3.5 Nodal line locations for vibration mode 1 with impact excitation point and the accelerometer location

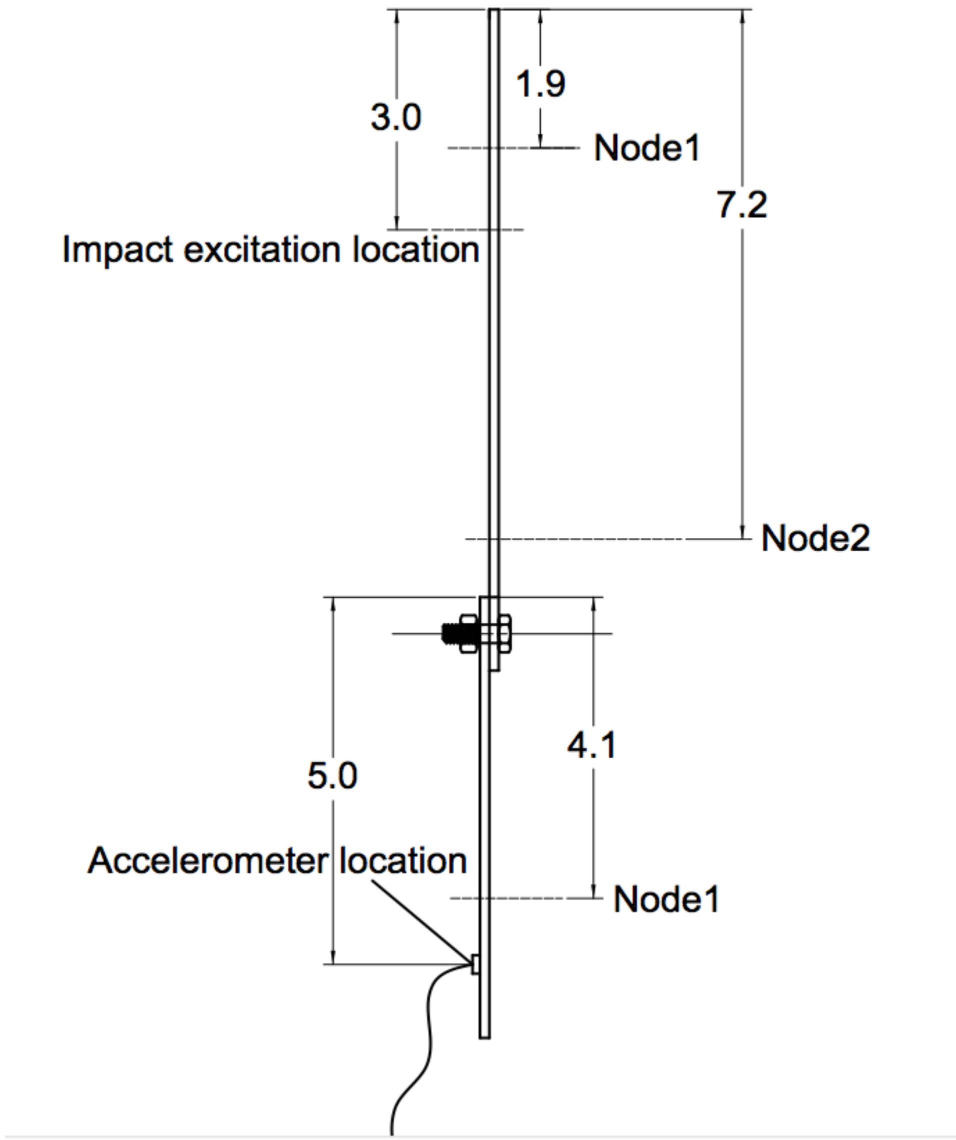


Figure 3.6 Nodal line locations for vibration mode 2 with impact excitation point and the accelerometer location

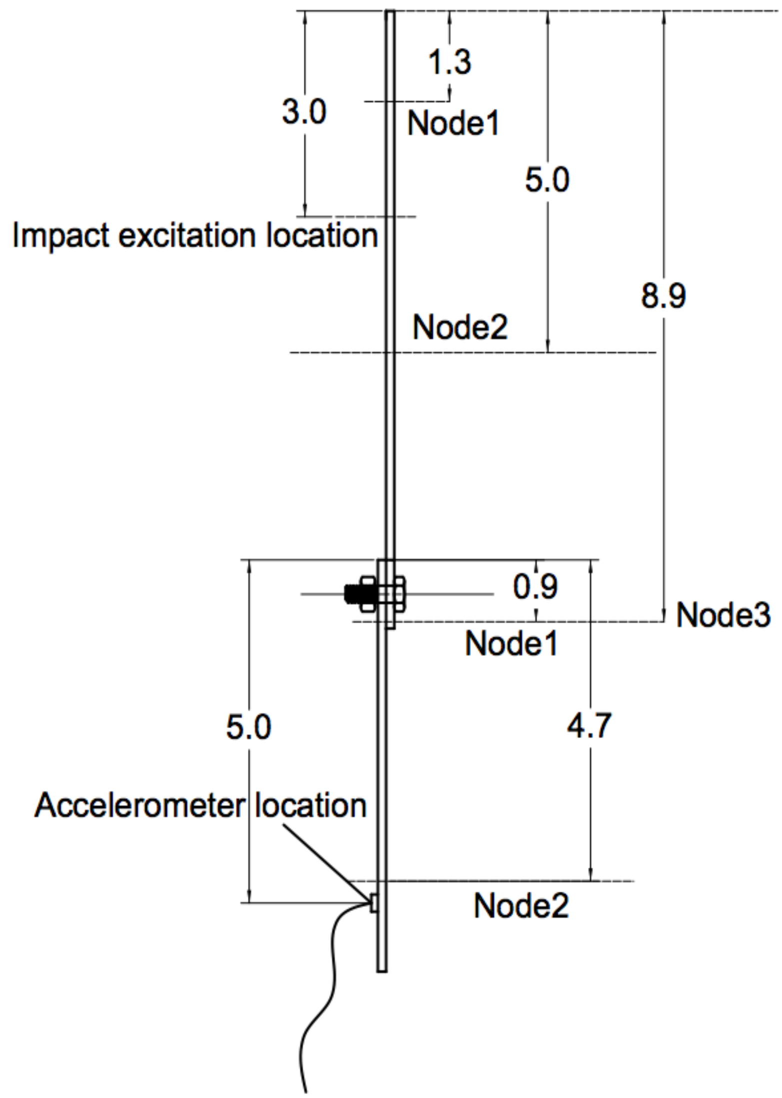


Figure 3.7 Nodal line locations for vibration mode 3 with impact excitation point and the accelerometer location

CHAPTER 4: EXPERIMENTAL DATA ANALYSIS

4.1 Frequency Response Function Measurement

The frequency response measurement is an important aspect of experimental modal analysis. Frequency Response Function and Transfer Function are commonly used in systems for presenting the output-input relationship. Mathematically speaking, the transfer function is defined as the result of the division between the Laplace transform of the output and the Laplace transform of the input. The frequency response function is defined as the result of the division between the Fourier transform of the output and the Fourier transform of the input [13]. In this thesis, the frequency response is the measurement between the acceleration response of the test structure and the hammer impact force input.

The coherence function is the measurement of how much of the acceleration response comes from the impact force input. If all the acceleration response were from the impact force input, then the coherence would be 1. If none of the acceleration response were from the impact force input, then the coherence value would be 0, which indicates that the measured frequency response were full of noise [16]. Figure 4.1 and Figure 4.2 show the coherence function plotted with the transfer function in log scale for the first three vibrational modes tested during the experiments. The coherence function noted in the black box corresponded to a frequency where the test structure did not respond, so the noise level at this particular frequency is very high, thus the coherence was nearly zero at that frequency. In this thesis, the coherence function was used as a measurement indication for data accuracy in the relevant frequency range. According to *Engineering Vibration* [16], ‘‘data with a coherence of less than 0.75 are not used and indicate that the test should be done over’’ (p.509).

4.2 Modal Parameters Extraction

This section explains how to extract the modal frequencies and damping ratios from the measured frequency response plots. The single degree of freedom (SDOF) curve fit method was used for modal frequencies extraction with the assumption that there is sufficient separation between modes [16]. The modal frequencies can be extracted by taking the frequency values of each peak presented in the relevant frequency range as shown in Figure 4.3. In this thesis, the first three modal frequencies are investigated.

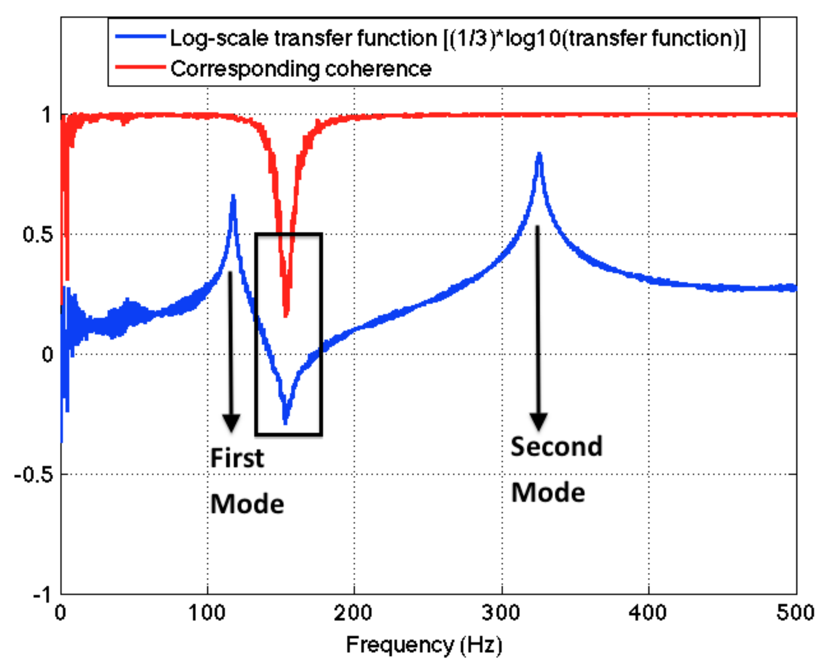


Figure 4.1 Coherence function for the first and second mode

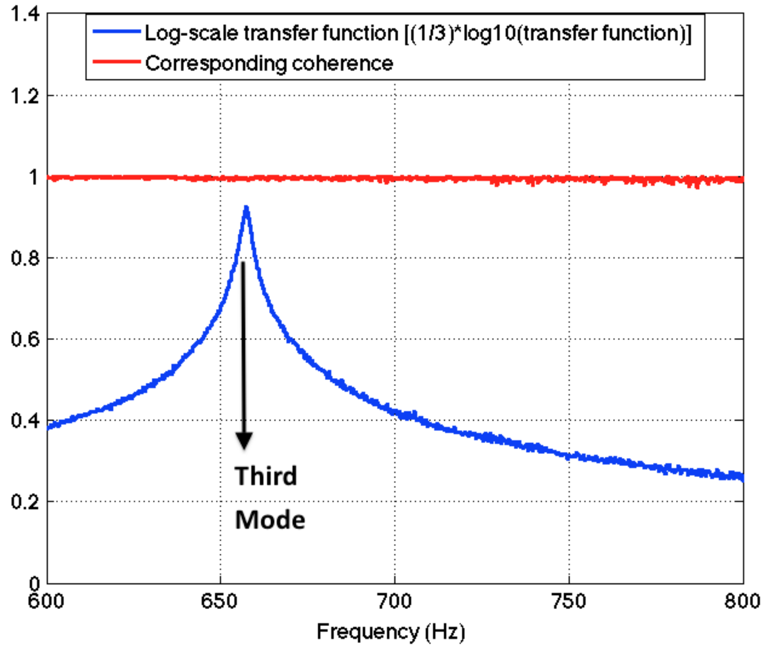


Figure 4.2 Coherence function for the third mode

The damping ratio associated with each modal frequency is assumed to be modal damping ratio ζ, and it can be extracted from the transfer functions magnitude plot of the acceleration over force measured from experiments. In this thesis, the half-power bandwidth method is used to estimate the damping ratio ζ by using three points on the frequency domain plot. The equation for calculating the damping ratio is provided below:

$$\zeta \cong \frac{\omega_a - \omega_b}{2\omega_n} \tag{4-1}$$

where ω_n presents the modal frequency of the interest peak and it has a peak magnitude of $H_{(\omega)max}$ as shown in the Figure 4.4, and ω_a and ω_b correspond to the two frequency values which has a magnitude of $\frac{1}{\sqrt{2}} H_{(\omega)max}$. The equation is an approximate estimation of the damping ratio and it is only valid for a small ζ, when $\zeta < 0.2$.

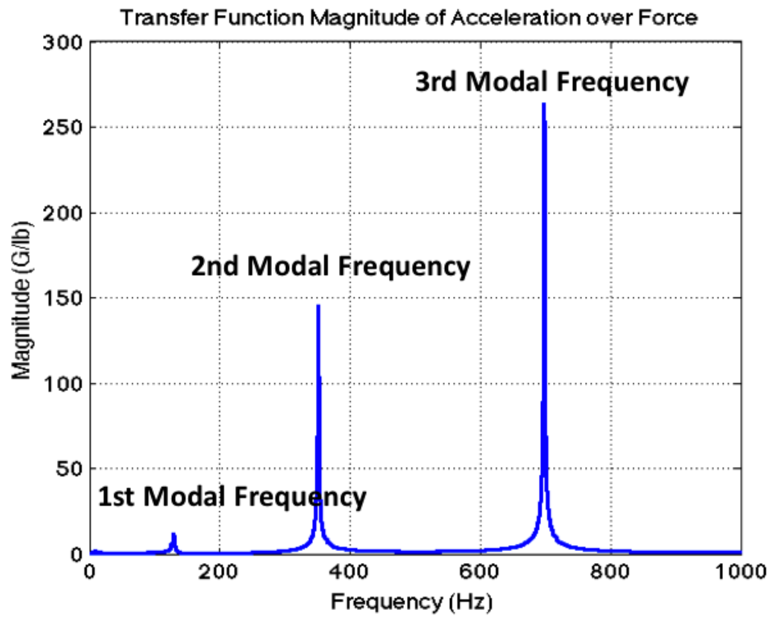


Figure 4.3 First three modal frequencies measured

The step-by-step procedure for modal data extraction is outlined below, take Figure 4.5 as an example [17]:

1. Individual peak on the frequency domain transfer function magnitude plot was found and zoomed in, the frequency value of the maximum magnitude were taken as the modal frequency, for example the modal frequency ω_n=350.7Hz;

2. Note that the maximum value of the transfer function $|H\ (\omega)|_{max}$ = 109.2G/lb. and take the frequencies of two points that have the magnitude of $|H\ (\omega)|_{max}/\sqrt{2}$ = 77.22G/lb., those frequencies are ω_a = 351.3Hz and ω_b=349.8Hz;

3. The damping ratio of this particular peak can be estimated using (4-1):

$$\zeta \cong \frac{\omega_a - \omega_b}{2\omega_n} = \frac{351.3 - 349.8}{2 \times 350.7} = 21.39 \times 10^{-4}$$

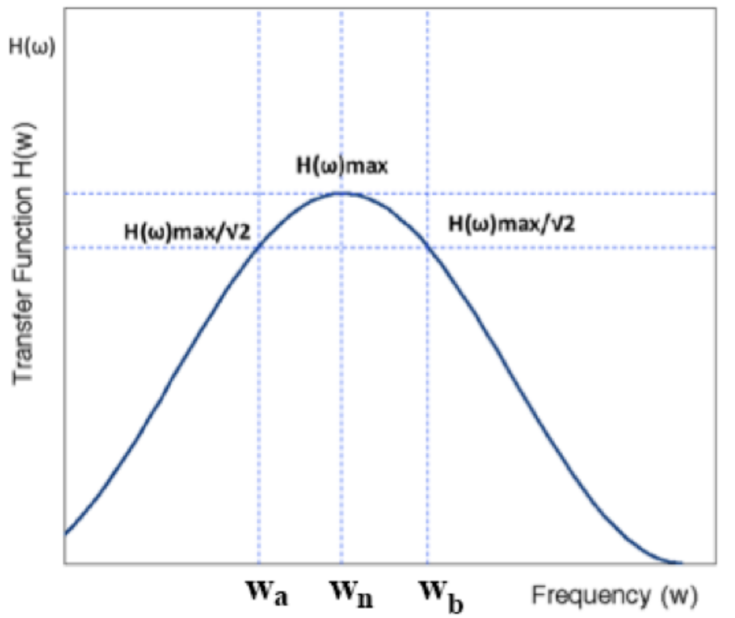


Figure 4.4 Magnitude of the frequency response function measurement

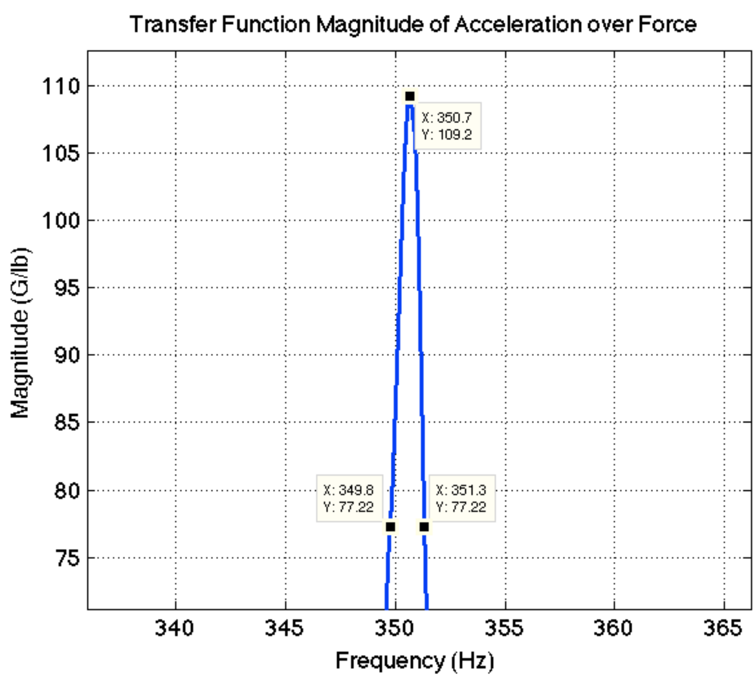


Figure 4.5 Experimental data extraction example

Three requirements need to be taken into consideration before using the half power bandwidth method. First, this method can only be applied to a frequency range where the modal frequencies are widely spread. As shown in Figure 4.3, it can be observed that the first three modal frequencies taken from this thesis are widely spaced in the 0-1000 Hz frequency range. The second requirement is that the frequency resolution should be high enough for determining both the peak and the half power bandwidth points in the transfer function magnitude plots. In this thesis, two different frequency resolutions were used: 0.156Hz and 0.063Hz. The number of the data points in the vicinity of the measured peak should be large enough to form a smooth curve for more exact measurements. The two frequency resolutions were determined to be sufficient enough after examining that the number of the data points when taking the peak and bandwidth points. Lastly this method requires taking multiple input and output signals and averaging them in order to form a high quality frequency response measurement. During all the experiments, four impact tests were performed on each measurement and the dynamic responses were averaged in those four hits. The number of the hits and the accuracy of the test were determined to be acceptable in the data after observing the coherence value of the relevant frequency range to be larger than 0.95 (most of them are above 0.98)[18].

4.3 Experiments Overview

Seven bolt preload levels of two different strength bolts were impact tested using aluminum or steel test plates producing four modal data sets on the bolted lap-joint structure. The data from those four sets of experiments (data presented in Table 4.2 and in Appendix B) were plotted as modal frequency versus different levels of preload and modal damping versus different levels of preload for better analyzing the system vibrational response to different bolt preload levels and jointing materials. The impact tests were performed in the following four cases:

- Two aluminum plates bolted with a Grade 5 bolt
- Two aluminum plates bolted with a Grade 8 bolt
- Two steel plates bolted with a Grade 5 bolt
- Two steel plates bolted with a Grade 8 bolt

In addition, three bolt preload levels of identical size monolithic aluminum and steel solid plates with an identical Grade 5 or a Grade 8 bolt were also tested as baseline for the purpose of comparison. There are four different baseline test sets preformed in this thesis.

- Monolithic aluminum plate bolted with a Grade 5 bolt
- Monolithic aluminum plate bolted with a Grade 8 bolt
- Monolithic steel plate bolted with a Grade 5 bolt
- Monolithic steel plate bolted with a Grade 8 bolt

4.4 Experimental Data for Bolted Lap Joint Structure

Modal impact tests of the bolted aluminum or steel test plates with a Grade 5 or a Grade 8 bolt were carried out to find out the preload effect on modal frequencies and damping ratios. An average of four impact measurements was taken in each impact test, and there are about ten impact hammer tests performed at each preload level. For Grade 5 bolts, the applied torque values are 5, 10, 30, 50, 80, 110, 140 in-lbs., while for Grade 8 bolts, the applied torque values are 5, 10, 30, 55, 80, 110, 140 in-lbs. The test data box plots were used for comparing the effect of different preload levels visually in the graph form. The box plots for the following four cases are presented in Appendix F. The information of the mean value, the 75% quartile value, the 25% quartile value, the highest data point, the lowest data point and the outlier data points is presented in a box plot[19]. The test data plots helped to improve the interpretation of the test data in a table form presented in Appendix B. The one-way ANOVA was used to test for the natural frequencies difference and the modal damping ratio difference among seven different preload levels. The results showed that both the natural frequencies for the different preloads and the modal damping ratios for the different preloads differed significantly among those seven preload levels, for the p-values are all less than 0.01[11]. This indicated that the effects of different preload levels on natural frequency and modal damping were significant.

4.4.1 Aluminum Plates Bolted With a Grade 5 Bolt

The effect of bolted joint preload on aluminum test plates was investigated by performing impact hammer tests with a Grade 5 bolt. Ten impact tests were performed on Grade 5 bolt on aluminum test plates, and for each impact test, the data was averaged

[11] The p-value states the probability value under the null hypothesis that all samples from the groups have an equal mean. If the p-value is almost zero, the null hypothesis is false, and at least one group's mean is different from the others. The common significance levels are 0.05 or 0.01. In this thesis, the significance level of 0.01 is chosen. Thus, if the p-value of this analysis is found less than 0.01, the means from those preload levels are significantly different from each other. If the p-value of this analysis if found larger than 0.01, the means from these two preload levels are equal.

from four hits. The torque values applied were: 5, 10, 30, 50, 80, 110, 140 in inch pounds and the corresponding percentage in bolt's yield strength are: 3%, 7%, 21%, 34%, 55%, 75%, 96%. The test results of varying the bolt preloads are presented in Table 4.2. The test data from Table 4.2 was plotted in Figure 4.6, Figure 4.7, Figure 4.8 and Figure 4.9 as modal frequency versus different levels of preload in yield strength percentages and modal damping versus different levels of preload in yield strength percentages. This was done to allow for better interpreting and analyzing the structure's dynamic responses to different preload levels. While there were ten impact tests performed, there were overlapping results in the test data plots as indicated by the appearance of less markers on those plots.

Table 4.3 reports the mean and standard deviation (SD) for the natural frequencies and the estimated damping ratios on vibrational mode 2 and 3 presented in Table 4.2. The test data from vibration mode 1 is excluded in this case. This was done because the impact excitation location was unintentionally near a node of the first mode and the excitation point at a node yields different results than an impact at other locations.

The procedure to investigate this effect is presented in Chapter 2.4. The testing parameters for bandwidth was 100Hz, frequencies were centered at 300Hz for the second mode and 700Hz for the third mode. The record length was 4096. Details with respect to the frequency resolution settings are shown in the Table 4.1 below.

Table 4.1 Bandwidth and frequency resolution for Grade 5 bolts experiments

Mode	Frequency Range	Bandwidth	Frequency Resolution
2	200-400 Hz	100 Hz	0.063 Hz
3	600-800 Hz	100 Hz	0.063 Hz

Figure 4.6 and Figure 4.8 map the data of a Grade 5 bolt on aluminum plates for the second and third modes as modal frequency versus varying preload in yield strength. It can be observed that the frequencies increased as the preload was increased from 3% to 30% of the bolt's yield strength, but the averages stayed within 1Hz when preload was increased from 30% to 75%.

Interestingly, note that the natural frequencies decreased as the preload was continually increased from 75% to 96% of preload in bolt yield strength. A one-way ANOVA was conducted to compare the effect of 75% and 96% of preload in bolt yield strength for aluminum test plates bolted with a Grade 5 bolt. The test results indicated that there is a 99.99% chance the second modal frequencies for preloads of 75% and 96% in bolt yield strength were significantly different, and there is a 99.97% chance that the third modal frequencies for preloads of 75% and 96% in bolt yield strength were significantly different due to the applied preload. The detail information is provided in Appendix E.

This phenomenon may indicate that there was plastic deformation within the bolt or interface of the aluminum components. In this section "loose bolt" is defined as the bolt with preload of 3% in bolt yield strength, while "tightened bolt" is defined as the bolt with preload of 75% in bolt yield strength. The following analysis will use these definitions of loose bolt and tightened bolt as the basis of comparison.

From Table 4.3, the smallest natural frequencies in this set of experiments are 323.1Hz at 3% of preload on the second mode and 654.4Hz at 3% of preload on the third mode, while the largest natural frequencies are 327.6Hz and 658.4Hz at 75% of preload in bolts' yield strength on Mode 2 and 3 respectively. The natural frequencies increased by 4.5Hz on Mode 2 and 4Hz on Mode 3, thus 1.4% increased and 0.6% increased from a loose bolt to a tightened bolt respectively.

Figure 4.7 and Figure 4.9 show the changes in modal damping with respect to Grade 5 bolt preload levels on the two aluminum plates configuration. Differing from the frequency plots discussed earlier, the damping ratios decreased as the preload was increased from 3% to 75% of the bolt's yield strength.

A one-way ANOVA was again conducted to compare the effect of 75% and 96% of preload on modal damping. This was done because the mean damping ratios increased as the preload was continually increased from 75% to 96% of the bolt's yield strength. The test results indicated that there is 0.3846 chance that the second modal damping ratios for preloads of 75% and 96% in bolt yield strength were not significantly different due to the applied preload. The p-value is larger than 0.01, so the means of damping ratios from these two preload levels are considered to be equal. In other words, the damping ratios of the second mode did not increase as the preload was continually increased from 75% to 96% in bolt yield strength. However, there is a 99.82% chance that the third modal damping ratios for preloads of 75% and 96% in bolt yield strength in aluminum test plates bolted with a Grade 5 bolt case were significantly different due to the applied preload. In other words, the damping ratios of the third mode did increase as the preload was continually increased from 75% to 96% in bolt yield strength. The detail information is provided in Appendix E.

Note that the damping ratios stayed relatively constant in the preload range from 21% to 75%. From Table 3.2, the largest damping ratios in this set of experiments happened when the bolt was loosened, 0.0052 at 3% of preload on the second mode and

0.0026 at 3% of preload on the third mode, while the bolt was tightened to 75% of preload in bolts' yield strength, the damping ratios are 0.0037 and 0.0018 on Mode 2 and 3 respectively. When comparing a loose bolt to a tightened one, the damping ratios increased by 0.0015 on Mode 2 and 0.0008 on Mode 3, and thus, the damping ratios show 42% increased on the second mode and 45.6% increased on the third mode.

4.4.2 Aluminum Plates Bolted With a Grade 8 Bolt

The effect of bolted joint preload on aluminum plates was also investigated by performing impact hammer tests with a Grade 8 bolt. The dynamic response of the structure was analyzed for the first three vibrational modes. The test procedure was identical as the one discussed before, except for the frequency range investigated. For the first and second modes, the frequency range was chosen to be 500Hz, and the record length was set to be 8192. For the third mode, the frequency was centered at 700Hz and the record length was set to be 4096. Details were shown in the Table 4.4.

The test results of varying the preload on a Grade 8 bolt are presented in Table B.1 in Appendix B. The torque values applied are: 5, 10, 30, 55, 80, 110, 140 in inch pounds and the corresponding percentage in bolt's yield strength are: 2%, 5%, 15%, 27%, 39%, 53%, 68%. Seven to ten impact tests were performed on a Grade 8 bolt on aluminum plates, and again the data was averaged for four hits in each trial. For comparing and interpreting the test results, Figures 4.10 to 4.15 were plotted from Table B.1 as modal frequency verse different levels of preload in yield strength percentage and modal damping verse different levels of preload in yield strength percentage. There are overlapping results in the test data plots as indicated by the appearance of less data points presented on those figures. Table 4.5 reports the averages and standard deviation (SD) for the natural frequencies and the estimated damping ratios on the first three vibrational modes.

Figure 4.10, Figure 4.12 and Figure 4.14 show the natural frequencies plotted against Grade 8 bolt preload levels on two aluminum plates. It was observed that the frequencies increased as the preload was increased from 2% to 27% of the bolt's yield strength for the first mode and 2% to 39% for the second and third modes, but the average frequencies stayed within 1Hz in the 27% to 68% preload range.

From Table 4.5, the smallest natural frequencies in this set of experiments are 116.8Hz, 323.7Hz and 656.6Hz at preload at 2% in the bolt yield strength for the first three vibrational modes, while the largest natural frequencies are 118.8Hz, 328.3Hz and 659.3Hz at 68% of preload in bolt yield strength. The natural frequencies increased by 2Hz on Mode 1, 4.6Hz on Mode 2 and 2.7Hz on Mode 3, thus 1.7% increased, 1.4% increased and 0.4% increased from loose bolt, respectively.

Figure 4.11, Figure 4.13 and Figure 4.15 show the changes in modal damping with respect to preload levels on Grade 8 bolt with the two aluminum plates configuration. Similar to the damping plots discussed before, the damping ratios from vibrational mode 2 and 3 decreased as the preload was increased from 2% to 27% of the bolt's yield strength, but stayed rather constant as the preload was continually increased from 27% to 68% of the bolt's yield strength. Note that the damping ratios from the first mode scattered and did not behavior like the other two modes. This phenomenon was credited to the fact that the striking location was close to a node of the first mode on the

Table 4.2 Test results of Al plates bolted with a Grade 5 bolt

Preload in Yield Strength	No.	2nd Mode Frequency (Hz)	2nd Mode Damping (%)	3rd Mode Frequency (Hz)	3rd Mode Damping (%)
3%	1	323.1	0.57	654.1	0.35
	2	323.3	0.59	652.9	0.33
	3	321.7	0.58	652.8	0.29
	4	321.8	0.53	655.4	0.22
	5	321.4	0.56	655.4	0.22
	6	324.4	0.48	655.6	0.22
	7	323.4	0.53	653.8	0.25
	8	324	0.46	653.8	0.23
	9	324.1	0.48	653.7	0.24
	10	324.2	0.45	656.9	0.22
7%	1	326.4	0.38	657.8	0.21
	2	326.6	0.37	657.8	0.21
	3	326.9	0.43	658.4	0.18
	4	326.2	0.48	658.2	0.19
	5	326.2	0.52	657.9	0.2
	6	326.3	0.49	657.8	0.21
	7	326.4	0.44	657.2	0.21
	8	326.5	0.4	657.7	0.18
	9	326.6	0.46	657.4	0.2
	10	326.9	0.46	656.7	0.19
21%	1	327.2	0.37	658.2	0.2
	2	327.2	0.37	657.8	0.17
	3	327.2	0.35	657.9	0.17
	4	327.2	0.37	658.5	0.18
	5	326.6	0.43	658.4	0.17
	6	326.9	0.4	658.2	0.21
	7	326.9	0.41	658	0.16
	8	327.1	0.38	658.4	0.16
	9	327.2	0.41	658.2	0.14
	10	327.3	0.4	658.2	0.16

Table 4.2 (Continued)

Preload in Yield Strength	No.	2nd Mode Frequency (Hz)	2nd Mode Damping (%)	3rd Mode Frequency (Hz)	3rd Mode Damping (%)
34%	1	327.9	0.38	657.5	0.2
	2	327.8	0.38	657.7	0.18
	3	327.6	0.37	658	0.17
	4	327.9	0.41	658.1	0.18
	5	327.6	0.44	657.9	0.17
	6	327.6	0.35	658.4	0.16
	7	327.6	0.35	658.4	0.16
	8	326.6	0.34	657	0.2
	9	326.7	0.34	656.7	0.21
	10	326.7	0.35	657.7	0.17
55%	1	327.8	0.35	658.2	0.18
	2	327.6	0.35	658	0.2
	3	327.3	0.34	658	0.18
	4	327.2	0.31	658.1	0.19
	5	327.5	0.35	657.8	0.19
	6	326.8	0.4	657.9	0.18
	7	326.9	0.4	657.9	0.17
	8	327	0.37	657.7	0.18
	9	328.2	0.37	657.8	0.19
	10	325.6	0.41	657.8	0.18
75%	1	327.6	0.4	657.6	0.17
	2	327.8	0.38	657.6	0.17
	3	327.8	0.38	657.6	0.19
	4	327.8	0.38	657.8	0.18
	5	327.1	0.37	658.8	0.15
	6	327.3	0.37	658.8	0.16
	7	327.4	0.4	658.7	0.17
	8	327.5	0.37	658.9	0.17
	9	327.9	0.34	659.1	0.2
	10	327.6	0.31	659.1	0.2

Table 4.2 (Continued)

Preload in Yield Strength	No.	2nd Mode Frequency (Hz)	2nd Mode Damping (%)	3rd Mode Frequency (Hz)	3rd Mode Damping (%)
96%	1	327.4	0.35	657.9	0.21
	2	327.2	0.37	656.8	0.21
	3	327.1	0.35	656.9	0.21
	4	326.4	0.37	657.1	0.22
	5	326.5	0.35	657.2	0.18
	6	326.4	0.43	657.8	0.17
	7	326.2	0.46	657.7	0.18
	8	326.7	0.35	657.2	0.22
	9	326.9	0.38	657.4	0.24
	10	326.5	0.4	657.3	0.23

Table 4.3 Modal frequencies and damping for aluminum plates with a Grade 5 bolt

Preload in % Yield Strength	Second Mode				Third Mode			
	Modal Frequency (Hz)		Modal Damping (%)		Modal Frequency (Hz)		Modal Damping (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
3	323.1	1.1	0.52	0.052	654.4	1.3	0.26	0.049
7	326.5	0.25	0.44	0.049	657.7	0.49	0.2	0.011
21	327.1	0.21	0.39	0.025	658.2	0.23	0.17	0.019
34	327.4	0.52	0.37	0.034	657.9	0.61	0.18	0.016
55	327.2	0.7	0.36	0.033	657.9	0.15	0.18	0.008
75	327.6	0.26	0.37	0.028	658.4	0.66	0.18	0.015
96	326.7	0.4	0.38	0.037	657.3	0.37	0.21	0.021

Table 4.4 Bandwidth and frequency resolution for Grade 8 bolts experiments

Mode	Frequency Range	Bandwidth	Frequency Resolution
1 and 2	0-500 Hz	500 Hz	0.156 Hz
3	600-800 Hz	100 Hz	0.063 Hz

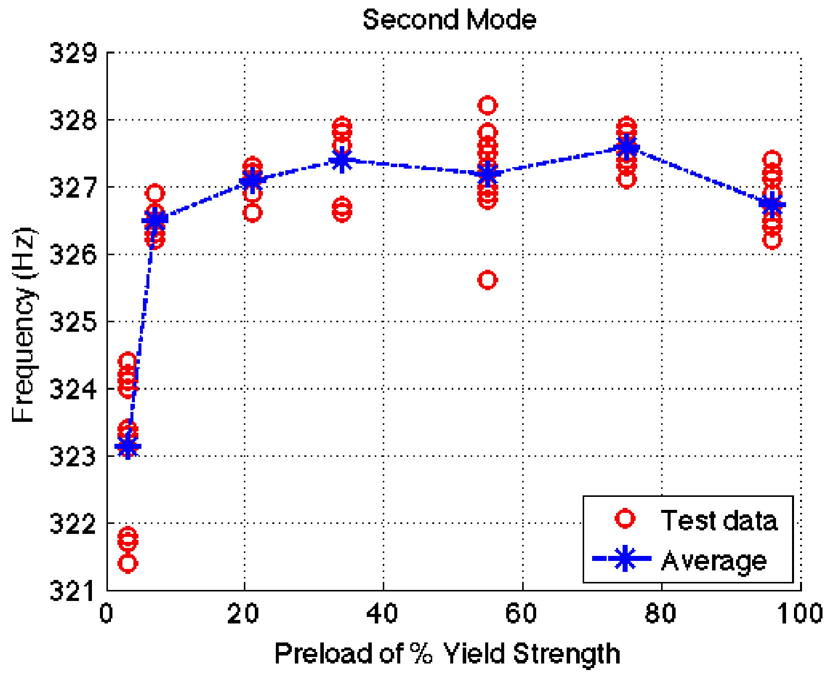


Figure 4.6 Grade 5 bolt connecting two aluminum test plates – modal frequency versus preload on Vibration Mode 2

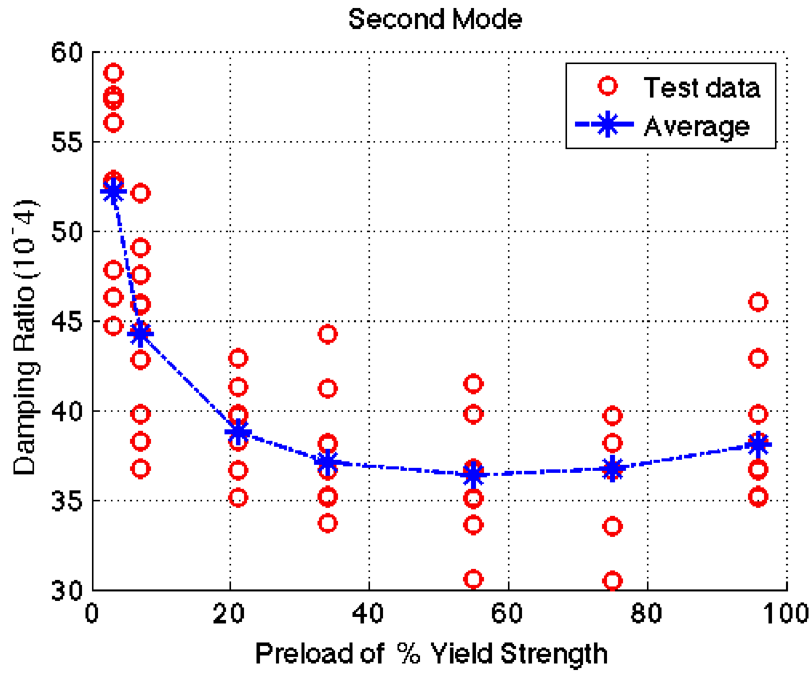


Figure 4.7 Grade 5 bolt connecting two aluminum test plates - modal damping versus preload on Vibration Mode 2

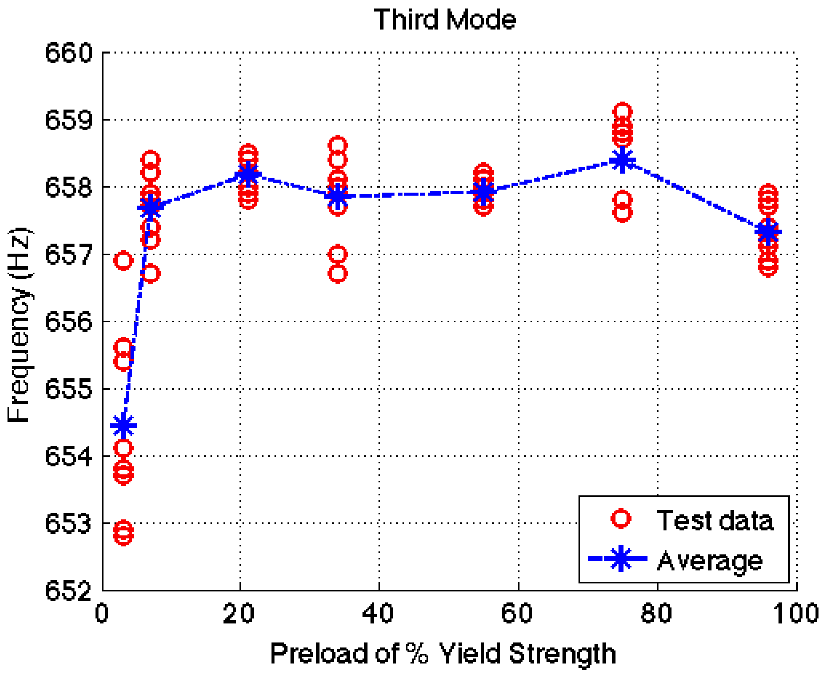


Figure 4.8 Grade 5 bolt connecting two aluminum test plates - modal frequency versus preload on Vibration Mode 3

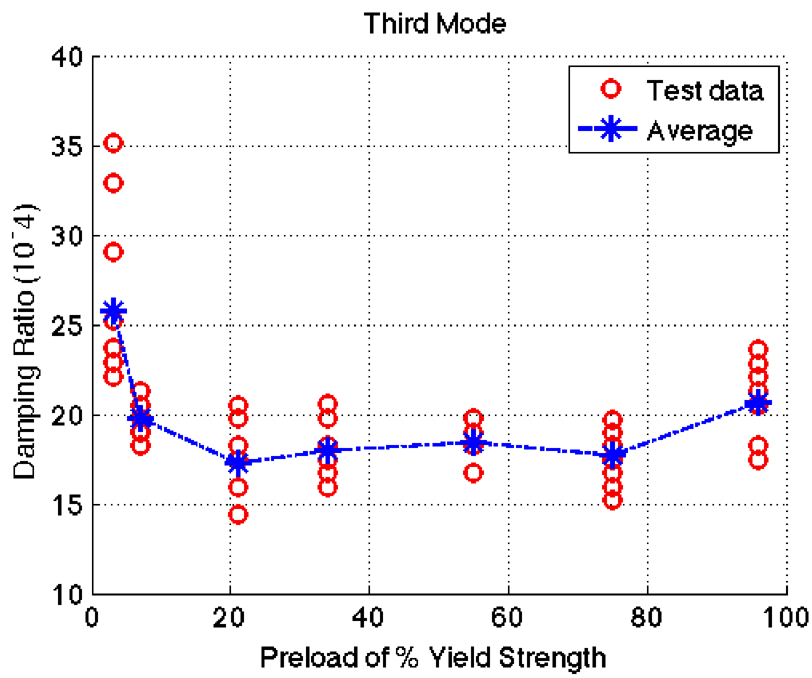


Figure 4.9 Grade 5 bolt connecting two aluminum test plates - modal damping versus preload on Vibration Mode 3

bolted plates. As a result, in the following part of analysis, only the vibrational mode 2 and 3 are discussed.

From Table 4.5, the largest damping ratios in this set of experiments happened when the bolt was loosened, 0.0052 at 2% of preload on the second mode and 0.0023 at 2% of preload on the third mode, while the bolt was tightened to 68% of preload in bolts' yield strength, the damping ratios are 0.0037 and 0.0016 on Mode 2 and 3, respectively. When comparing a loose bolt to a tightened one, the damping ratios increased by 0.0015 on Mode 2 and 0.0007 on Mode 3, and thus, the damping ratios show a 41% decrease on the second mode and 44% decreased on the third mode.

Table 4.5 Modal Frequencies and damping for aluminum Plates with Grade 8 bolt

Preload in % Yield Strength		First Mode		Second Mode		Third Mode	
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
Mean	2	116.8	0.75	323.7	0.52	656.6	0.23
	5	117	0.67	325.5	0.48	656.8	0.21
	15	118.6	0.72	327.8	0.37	658.5	0.16
	27	118.8	0.7	328	0.38	658.9	0.17
	39	118.8	0.48	328.4	0.32	659.3	0.15
	53	118.9	0.52	328.3	0.38	659.3	0.15
	68	118.8	0.69	328.3	0.37	659.3	0.16
SD	2	0.21	0.093	1	0.069	0.8	0.018
	5	0.31	0.061	0.19	0.042	0.4	0.02
	15	0.21	0.064	0.57	0.018	0.4	0.03
	27	0.15	0.04	0.75	0.058	0.098	0.04
	39	0.14	0.12	0.17	0.047	0.46	0.02
	53	0.053	0.02	0	0.012	0.35	0.012
	68	0.2	0.16	0.4	0.03	0.69	0.018

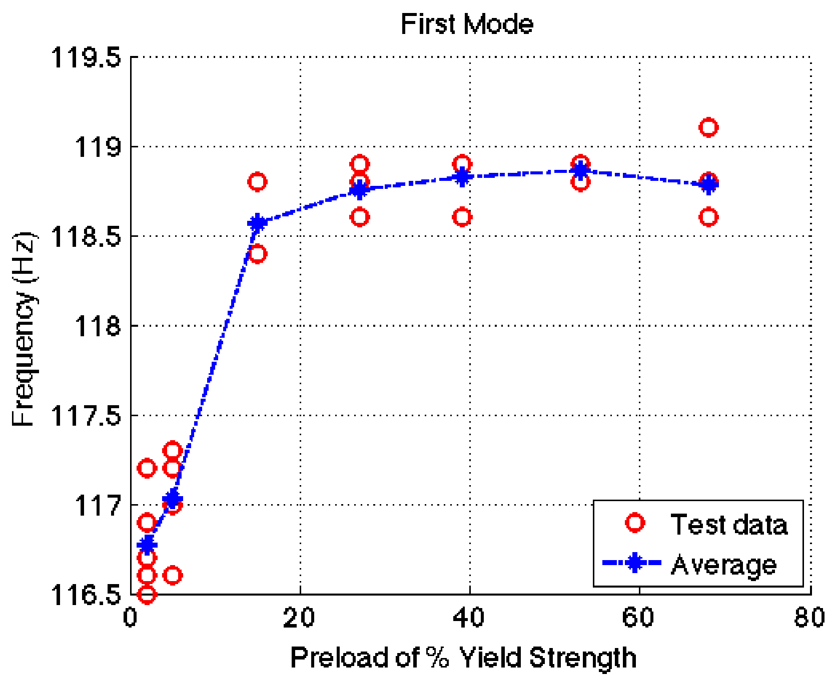


Figure 4.10 Grade 8 bolt connecting two aluminum test plates – modal frequency versus preload on Vibration Mode 1

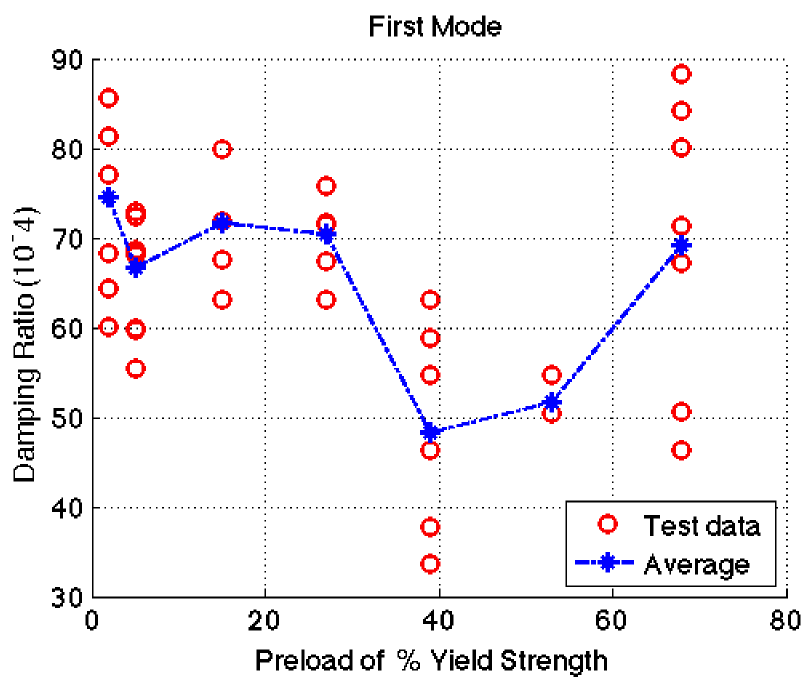


Figure 4.11 Grade 8 bolt connecting two aluminum test plates - modal damping versus preload on Vibration Mode 1

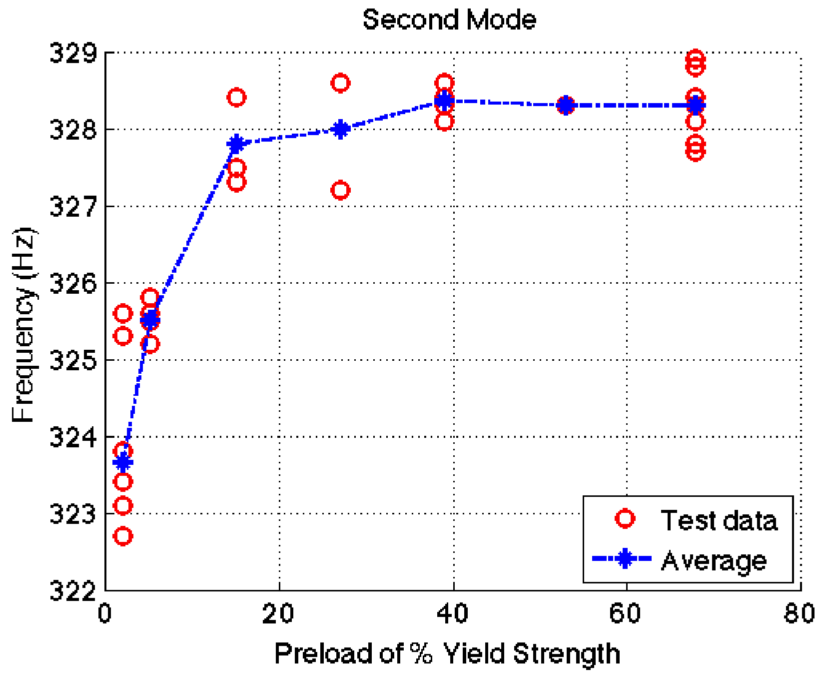


Figure 4.12 Grade 8 bolt connecting two aluminum test plates – modal frequency versus preload on Vibration Mode 2

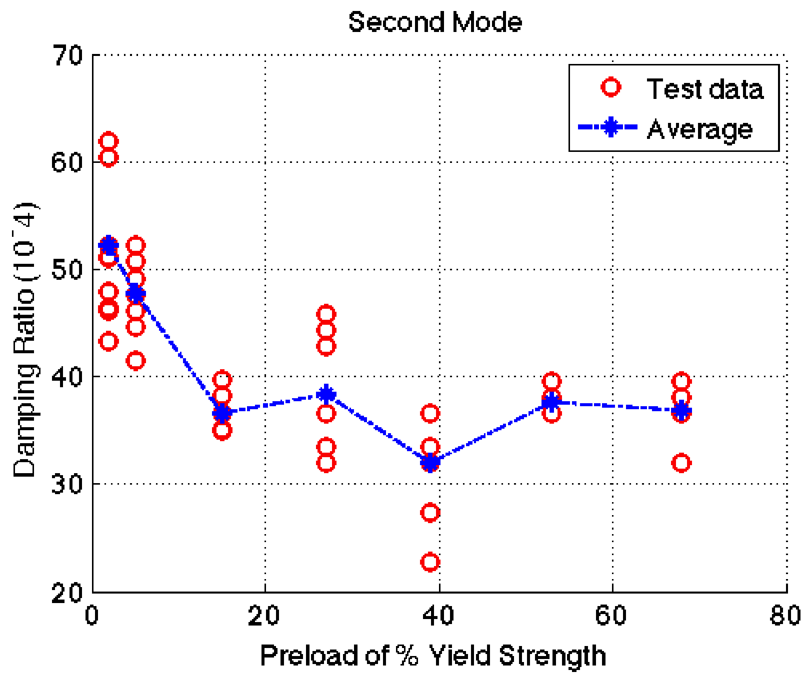


Figure 4.13 Grade 8 bolt connecting two aluminum test plates - modal damping versus preload on Vibration Mode 2

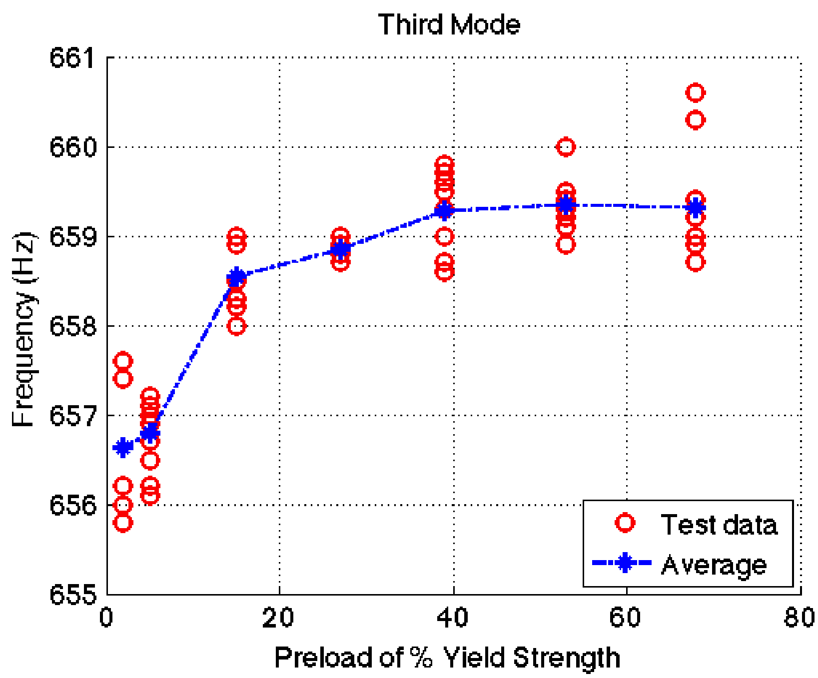


Figure 4.14 Grade 8 bolt connecting two aluminum test plates – modal frequency versus preload on Vibration Mode 3

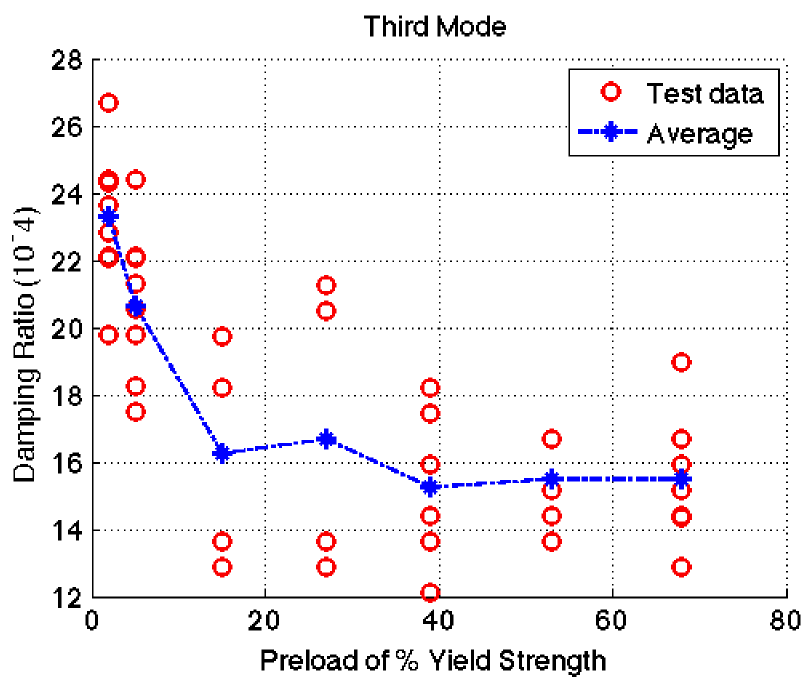


Figure 4.15 Grade 8 bolt connecting two aluminum test plates - modal damping versus preload on Vibration Mode 3

4.4.3 Steel Plates Bolted With a Grade 5 Bolt

The effect of varying the bolt preloads on steel plates was investigated by performing impact hammer tests with a Grade 5 bolt. The test results are presented in Table B.2 in Appendix B and the mean and standard deviation (SD) for the test data are presented in Table 4.6.

Frequencies were centered at 300 Hz for the second mode and 700Hz for the third mode, and the test setting for bandwidth was chosen to be 100Hz for both modes. The record length was set to be 4096. These are the same bandwidth and frequency resolution settings as aluminum plates bolted with a Grade 5 bolt in section 4.5.1. The test data for the first mode was excluded, because the impact point is unintentionally near a node in this mode, which might yield a different result than an impact at other points.

The experiment was performed under seven torque values of 5, 10, 30, 50, 80, 110, 140 in inch pounds and the corresponding percentage in a Grade 5 bolt's yield strength are: 3%, 7%, 21%, 34%, 55%, 75%, 96%, respectively. Figure 4.16, Figure 4.17, Figure 4.18, and Figure 4.19 were plotted from the data taken from Table B.2 and Table 4.6, and show the trends in the graph form associated with increasing preload in percent yield strength. Note that there were overlapping results in the test data plots as indicated by the appearance of fewer data points presented on those figures. The following section will use two definitions, a loose bolt and a tightened bolt. The loose bolt is categorized as a bolt with the preload of only 3% in bolt yield strength. Similarly, the tightened bolt is categorized as a bolt with the preload of 75% in bolt yield strength. In total, ten impact tests were performed and the data from these tests were averaged by four different hits in each trial.

It can be seen from the Table 4.6 that the mean modal frequencies for both the second and third modes increase as the preload in percent yield strength increases from 3% to 96%. Conversely, the percentage of modal damping decreases as the preload increases from 3% to 96%. Figure 4.16 and Figure 4.17 exhibit the trends of different preload levels on modal frequency and modal damping in the second mode. As the preload increases from 3% yield strength to 96% yield strength, there is a gain of 4Hz for mean modal frequency for the second mode, and a 0.0017 decrease in mean modal damping ratios. The 4 Hz increase in mean modal frequency corresponds to a 1.149% increase from the 348 Hz frequency for a test structure with a loose bolt. The 0.0017 decrease in mean modal damping percentage corresponds to a 46% decrease from the 0.0037 mean modal damping for preload in 3 percent yield strength.

Table 4.6 Modal frequencies and damping for steel plates with a Grade 5 bolt

Preload of % Yield Strength	Second Mode				Third Mode			
	Modal Frequency (Hz)		Modal Damping (%)		Modal Frequency (Hz)		Modal Damping (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
3	348	0.84	0.37	0.031	695.9	0.59	0.16	0.013
7	349	0.92	0.27	0.033	696.6	0.4	0.12	0.027
21	350.8	0.25	0.23	0.034	698.1	0.51	0.099	0.01
34	351.3	0.68	0.22	0.037	698.1	0.19	0.09	0.0091
55	351.4	0.54	0.21	0.028	698.3	0.19	0.091	0.0068
75	351.8	0.43	0.25	0.024	698.5	0.27	0.099	0.0088
96	352	0.66	0.2	0.025	698.5	0.33	0.092	0.0094

Figure 4.18 and Figure 4.19 show the trends of varying preload on modal frequency and modal damping in the third mode. From a loose bolt with preload of 3% yield strength to a tightened bolt with preload of 96%, there is a 2.6 Hz increase in mean

modal frequency and a 0.068 decrease in mean modal damping percentage. A 2.6 Hz increase from 695.9 Hz to 698.5 Hz corresponds to a 0.37% increase in modal frequency. A 0.068 decrease from 0.16 to 0.092 corresponds to a 42.5% decrease in mean modal frequency.

4.4.4 Steel Plates Bolted With a Grade 8 Bolt

The effect of varying preload on bolted steel plates was also investigated by replacing the Grade 5 bolt with a Grade 8 bolt. The experiments were performed under seven torque values of 5, 10, 30, 55, 80, 110, 140 in inch pounds and the corresponding percentage in bolt's yield strength are: 2%, 5%, 15%, 27%, 39%, 53%, 68%, respectively. The torque and preload values, the test procedure and the frequency resolution settings are all identical as the aluminum plate bolted with a Grade 8 bolt case discussed in the previous section 4.4.3[12].

The test results of modal frequencies and modal damping ratios for the first three vibrational modes are presented in Table B.3 in Appendix B and the mean and standard deviation (SD) for those test results are presented in Table 4.7. It can be observed from the Table 4.7 that the mean modal frequencies for both the second and third modes increase as the preload of percent yield strength increases from 2% to 68%. Conversely, modal damping decreases as the preload in percent yield strength increases from 2% to 68%.

[12] For the first and second modes, the frequency range was chosen to be 0-500Hz, and the record length was set to be 8192. For the third mode, the frequency was centered at 700Hz, bandwidth was 100Hz and the record length was set to be 4096.

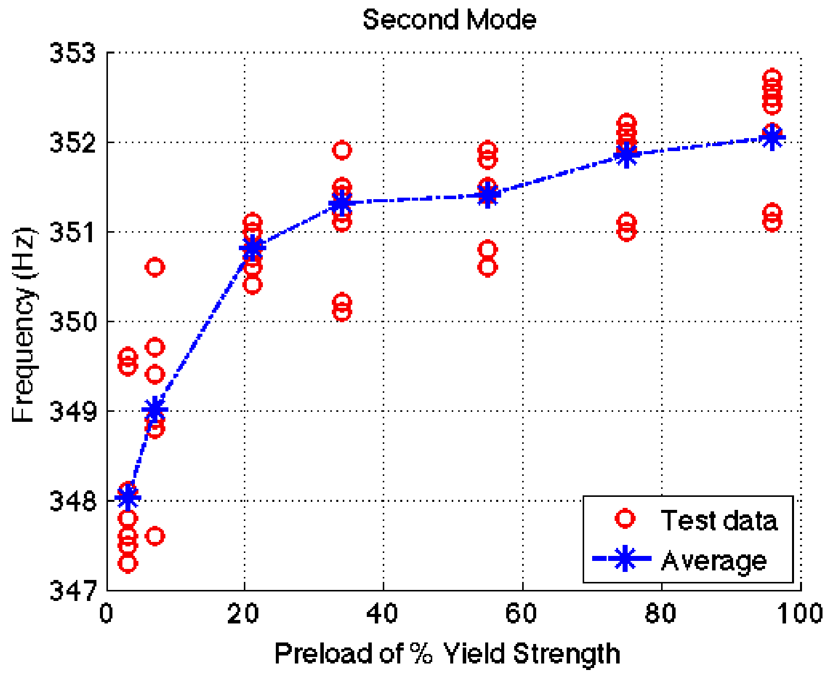


Figure 4.16 Grade 5 bolt connecting two steel test plates – modal frequency versus preload on Vibration Mode 2

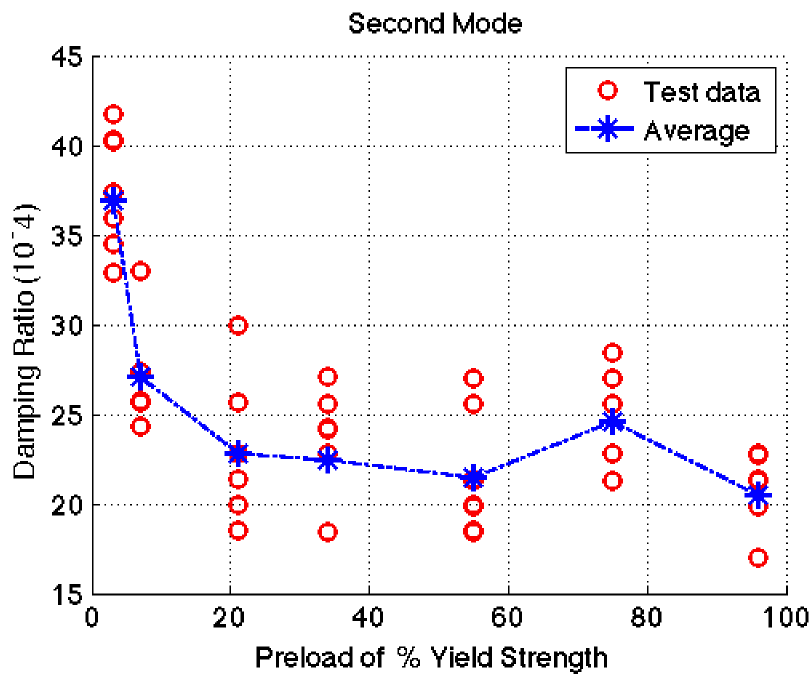


Figure 4.17 Grade 5 bolt connecting two steel test plates - modal damping versus preload on Vibration Mode 2

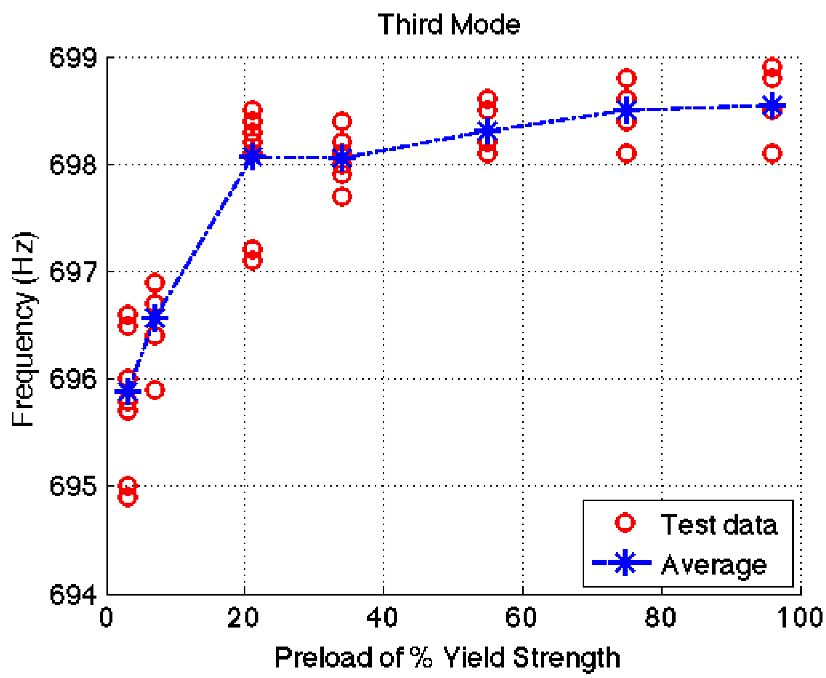


Figure 4.18 Grade 5 bolt connecting two steel test plates - modal frequency versus preload on Vibration Mode 3

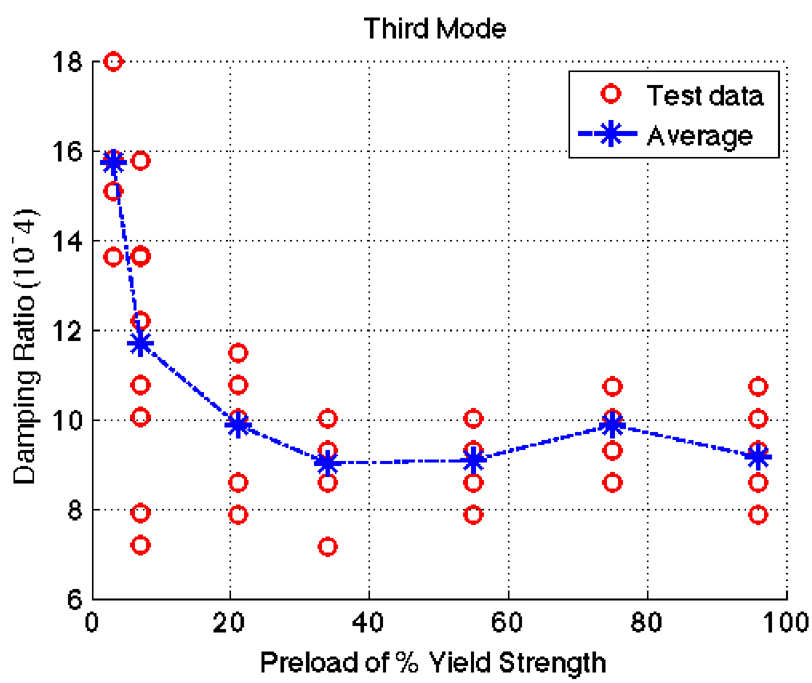


Figure 4.19 Grade 5 bolt connecting two steel test plates - modal damping versus preload on Vibration Mode 3

Figure 4.20 through Figure 4.25 were plotted from the data taken from Table B.3 and Table 4.7, and show the trends associated with increasing preload in percent yield strength. The following section will use two definitions, a loose bolt and a tightened bolt. The "loose bolt" is defined as a bolt with the preload of 2% in bolt yield strength (5 in-lbs.). Similarly, the "tightened bolt" is defined as a bolt with the preload of 68% in bolt yield strength (140 in-lbs.). In total, ten impact tests were performed and the data from these tests were averaged by four different hits in each trial. There were overlapping results in the test data plots as indicated by the appearance of fewer data points presented on those plots.

Figure 4.20 and Figure 4.21 exhibit the trends of different preload levels on modal frequency and modal damping in the first mode. As the preload increases from 2% yield strength to 68% yield strength, there is a gain of 3.2Hz for mean modal frequency and a 0.0021 decrease in mean modal damping. The 3.2Hz increase leads to a 2.55% increase from the first modal frequency for a test structure with a loose bolt. Likewise, the 0.0021 decrease in mean modal damping corresponds to a 32.3% decrease from the first modal damping for a test structure with a loose bolt.

Similarly, Figure 4.22 and Figure 4.23 exhibit the trends of preload effect on modal frequency and modal damping in the second mode. When comparing a test structure with a loose bolt to with a tightened bolt, there is a growth of 4.1Hz for mean modal frequency for the second mode and a 0.0007 decrease in mean modal damping. The increase in mean modal frequency corresponds to a 1.18% increase from the 348.2Hz frequency for a test structure with a loose bolt. The 0.0007 decrease in mean

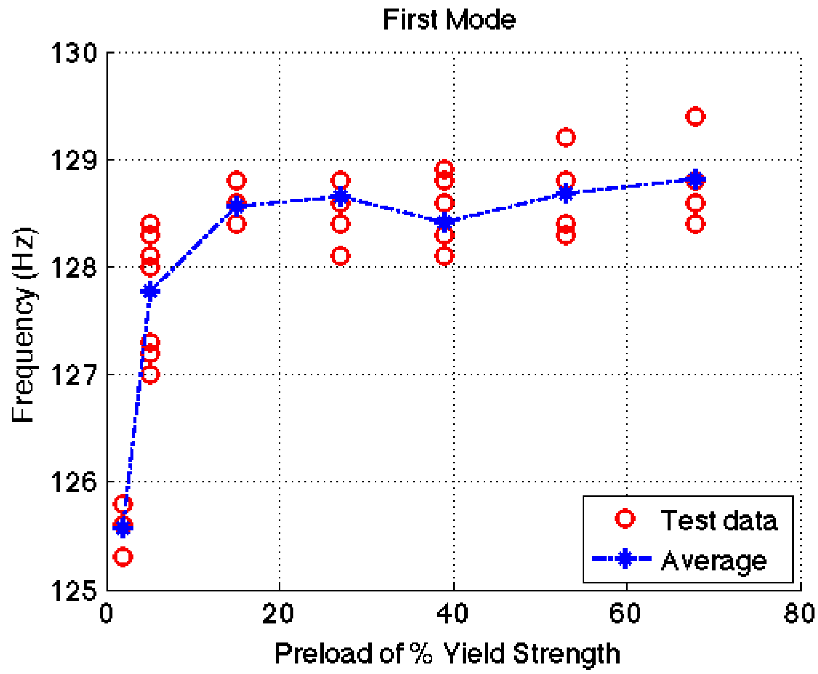


Figure 4.20 Grade 8 bolt connecting two steel test plates – modal frequency versus preload on Vibration Mode 1

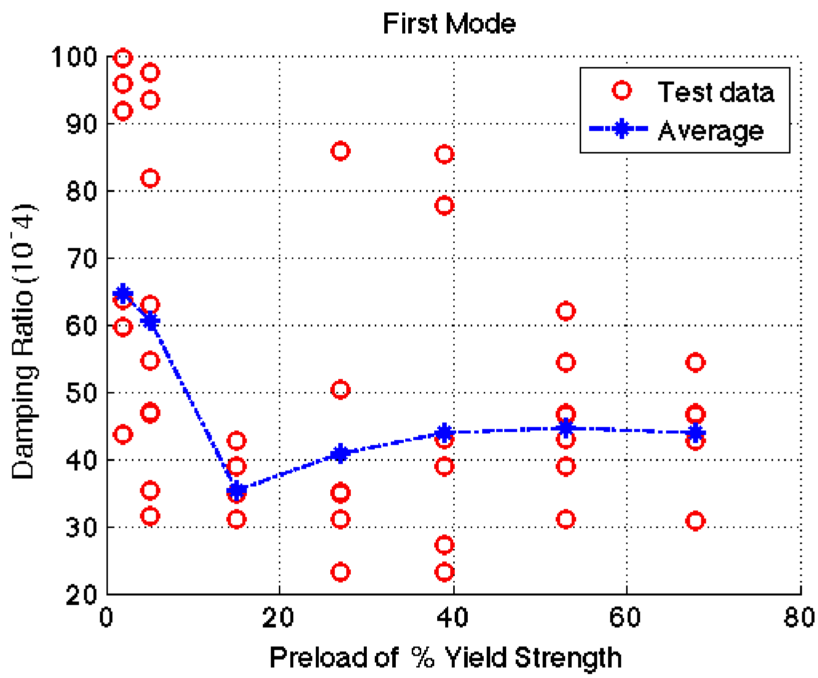


Figure 4.21 Grade 8 bolt connecting two steel test plates - modal damping versus preload on Vibration Mode 1

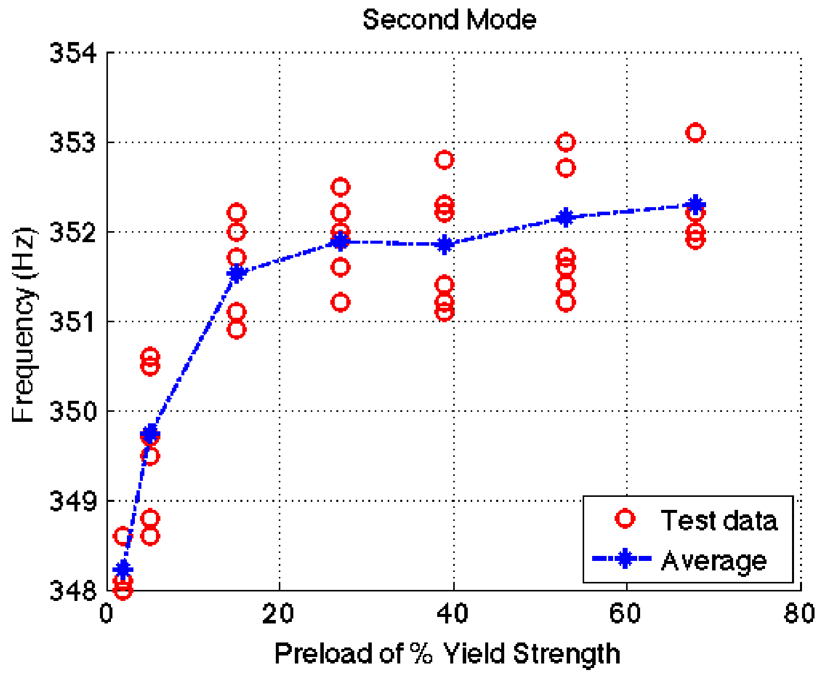


Figure 4.22 Grade 8 bolt connecting two steel test plates – modal frequency versus preload on Vibration Mode 2

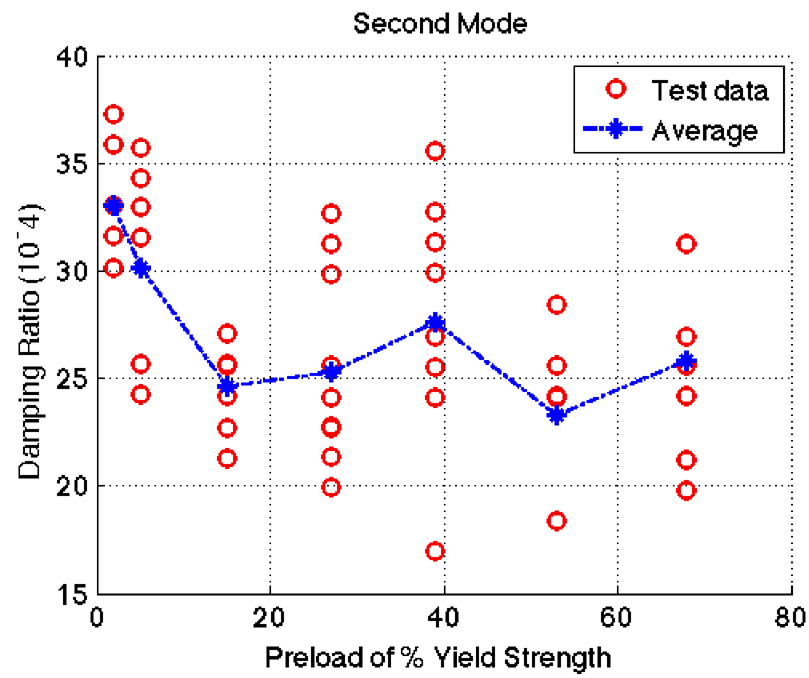


Figure 4.23 Grade 8 bolt connecting two steel test plates - modal damping versus preload on Vibration Mode 2

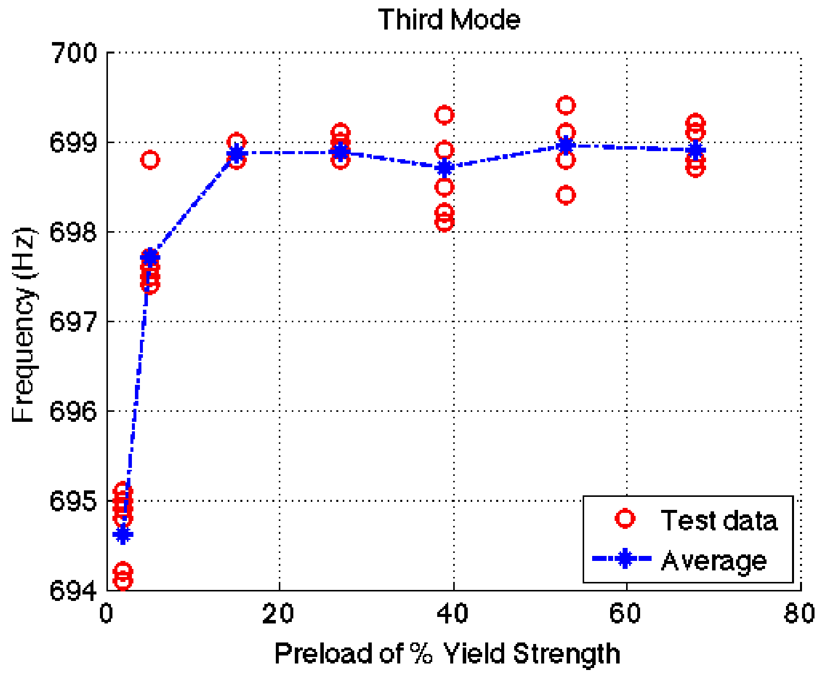


Figure 4.24 Grade 8 bolt connecting two steel test plates – modal frequency versus preload on Vibration Mode 3

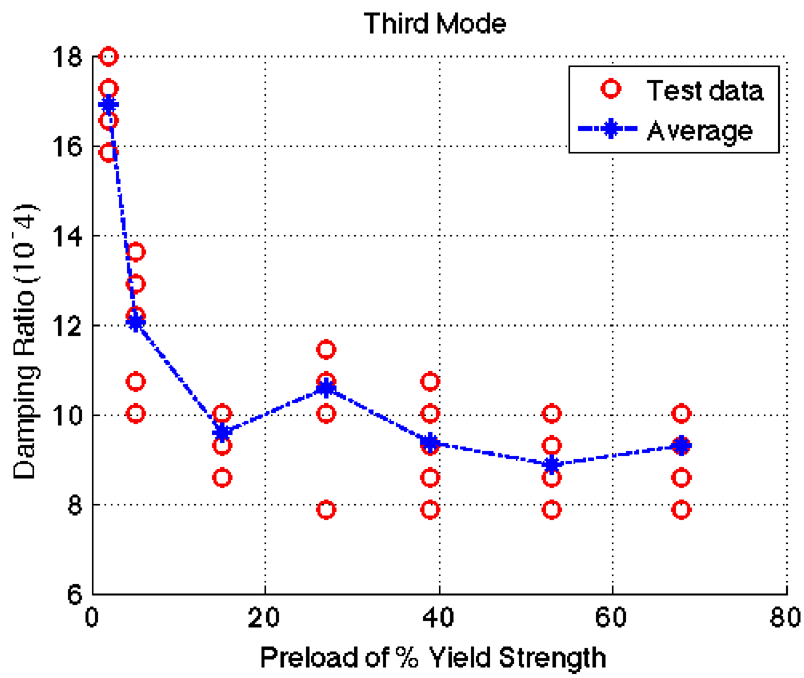


Figure 4.25 Grade 8 bolt connecting two steel test plates - modal damping versus preload on Vibration Mode 3

Table 4.7 Modal frequencies and damping for steel plates with a Grade 8 bolt

	Preload in % Yield Strength	First Mode		Second Mode		Third Mode	
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
Mean	2	125.6	0.65	348.2	0.33	694.6	0.17
	5	127.8	0.61	349.7	0.3	697.7	0.12
	15	128.6	0.35	351.5	0.25	698.9	0.096
	27	128.7	0.41	351.9	0.25	698.9	0.11
	39	128.4	0.44	351.8	0.28	698.7	0.094
	53	128.7	0.45	352.2	0.23	699	0.089
	68	128.8	0.44	352.3	0.26	698.9	0.093
SD	2	0.21	0.23	0.27	0.024	0.43	0.0069
	5	0.57	0.23	0.81	0.046	0.39	0.017
	15	0.13	0.039	0.49	0.018	0.097	0.006
	27	0.24	0.19	0.55	0.044	0.11	0.011
	39	0.32	0.21	0.71	0.068	0.42	0.0099
	53	0.41	0.095	0.79	0.036	0.38	0.0091
	68	0.43	0.098	0.56	0.044	0.19	0.0089

modal damping resulted in a 21.2% decrease from the mean modal damping for a test structure with a loose bolt.

In addition, Figure 4.24 and Figure 4.25 show the trends of varying preload on modal frequency and modal damping in the third mode. From a loose bolt with preload of 2% yield strength to a tightened bolt with preload of 68%, there is a 4.3Hz increase in modal frequency and a 0.077 decrease in modal damping. Again, the increase in third modal frequency corresponds to 0.62% increase from the 694.6Hz frequency for a test structure with a loose bolt. The 0.00077 decrease in third modal damping lead to a 45.3% decrease from the test structure with a loose bolt.

4.5 Experimental Data for Monolithic Test Plate

In order to investigate the effects of bolt preload on the dynamic response of the single bolted lap-joint structure, as a comparison, four sets of baseline tests with monolithic plates were performed. The monolithic plate structure (Figure 2.4) had identical geometry and materials to the bolted lap joint two-plates structure and it was tested under identical impact testing setting.

4.5.1 Monolithic Aluminum Plate Bolted With a Grade 5 Bolt

The monolithic aluminum plate bolted with a Grade 5 bolt was tested for three different torque values. The torque applied was 5 in-lbs., 50 in-lbs. and 140 in-lbs. The tightening preload on the bolt shank caused by these torques is 100lb, 1000lb and 2800lb respectively. The corresponding preload in percent yield strength is 3%, 34% and 96% respectively. The average values of axial tensile stress on the bolt shank caused by these preloads are 3.14ksi, 31.4ksi and 88ksi respectively. These stresses are below the yield strength of 92ksi of the Grade 5 bolt, so there was no yielding or damage to the bolt thread.

The test procedure for performing the monolithic test plate impact testing is outlined in chapter 2.4. An instrumental impact hammer was used to excite the structure and the accelerometer was used to capture the dynamic acceleration response of the monolithic plate. The impact and attached accelerometer locations are shown in Figure 4.5.

The dynamic response of the monolithic plate was analyzed for the first three vibrational modes in the frequency range 0-1000Hz. For the first and second modes, the frequency range was chosen to be 500Hz, and the record length was set to be 8192. For the third mode, the frequency was centered at 700Hz and the record length was set to be 4096. Details are shown in Table 4.1.

Six impact tests were performed on each torque value (5 in-lbs., 50 in-lbs. and 140 in-lbs.) for monolithic aluminum plate testing and there were four hits per single test for averaging one measurement. The resulting modal frequencies and modal damping ratios for the first three vibrational modes are shown in Table 4.8 and the mean and standard deviation (SD) of the test results for monolithic aluminum plate with a Grade 5 bolt are presented in Table 4.9.

Figure 4.27 and Figure 4.28 were plotted from the data taken from Table 4.8 and Table 4.9, and show the trends associated with increasing preload in percent yield strength (3%, 34% and 96% in this case). Figure 4.27 maps the data of a Grade 5 bolt on aluminum monolithic plate in the first three vibration modes as frequency versus varying preloads. It shows that the modal frequencies slightly increase as bolt preload increases from 3% to 96% in bolt yield strength. The influence of the bolt preload on frequency for the monolithic plate was rather small as indicated in the small frequency variations between the three preload levels shown in the plot. Note that the third modal frequency stays relatively constant in terms of increasing preload on the bolt. The difference between the largest average frequency and the smallest average frequency for the first three modal frequencies are 0.5Hz for the first mode, 0.8Hz for the second mode and 0.1Hz for the third mode.

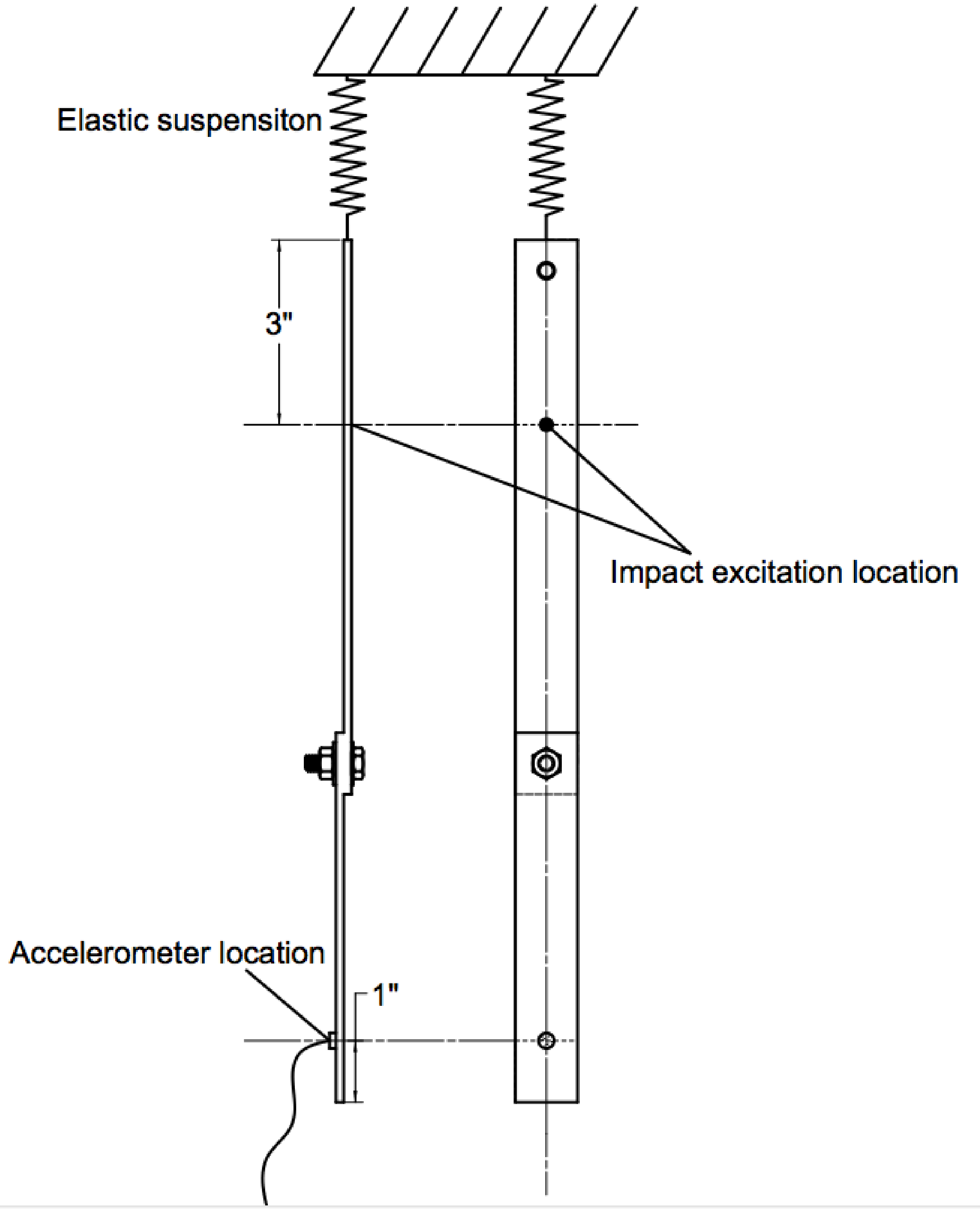


Figure 4.26 Impact and accelerometer attached locations for monolithic test plate

The second graph, Figure 4.28, similarly maps Grade 5 bolt on aluminum monolithic plate but as modal damping ratios versus varying preloads for the first three modes. It can be seen from the plot that modal damping ratios changes slightly as the preload increases from 3% to 96% in bolt yield strength. The damping ratio slightly increases for the first mode, slightly decreases for the second mode and stays relatively constant for the third mode in terms of increasing preload on the bolt. The difference between the trends of the first and second mode might be caused by the fact that the impact excitation point is unintentionally near a node in the first mode. An impact at a node of a mode shape will yield a different result than an impact at other locations. The bolt preload effect on damping in a monolithic plate structure was small as exhibited in the small damping variations between the three preload levels, especially in the third modal damping case.

4.5.2 Monolithic Aluminum Plate Bolted With a Grade 8 Bolt

The Grade 5 bolt used in the monolithic aluminum plate bolted with a Grade 5 bolt case, which is presented in the previous section, was replaced with a Grade 8 bolt. This new combination was also tested for three different torque values. The torques applied were 10 in-lbs., 80 in-lbs. and 140 in-lbs., which were different from the previous case. The tightening preloads on the bolt shank caused by these torques are 200lb, 1600lb and 2800lb respectively. The corresponding preloads in percent yield strength are 5%, 39% and 68% respectively. The average axial tensile stresses on the bolt shank caused by these preloads are 6289psi, 50314psi and 88050psi respectively. These stresses are also below the yield strength (130ksi) of the replaced Grade 8 bolt, and there was no yielding

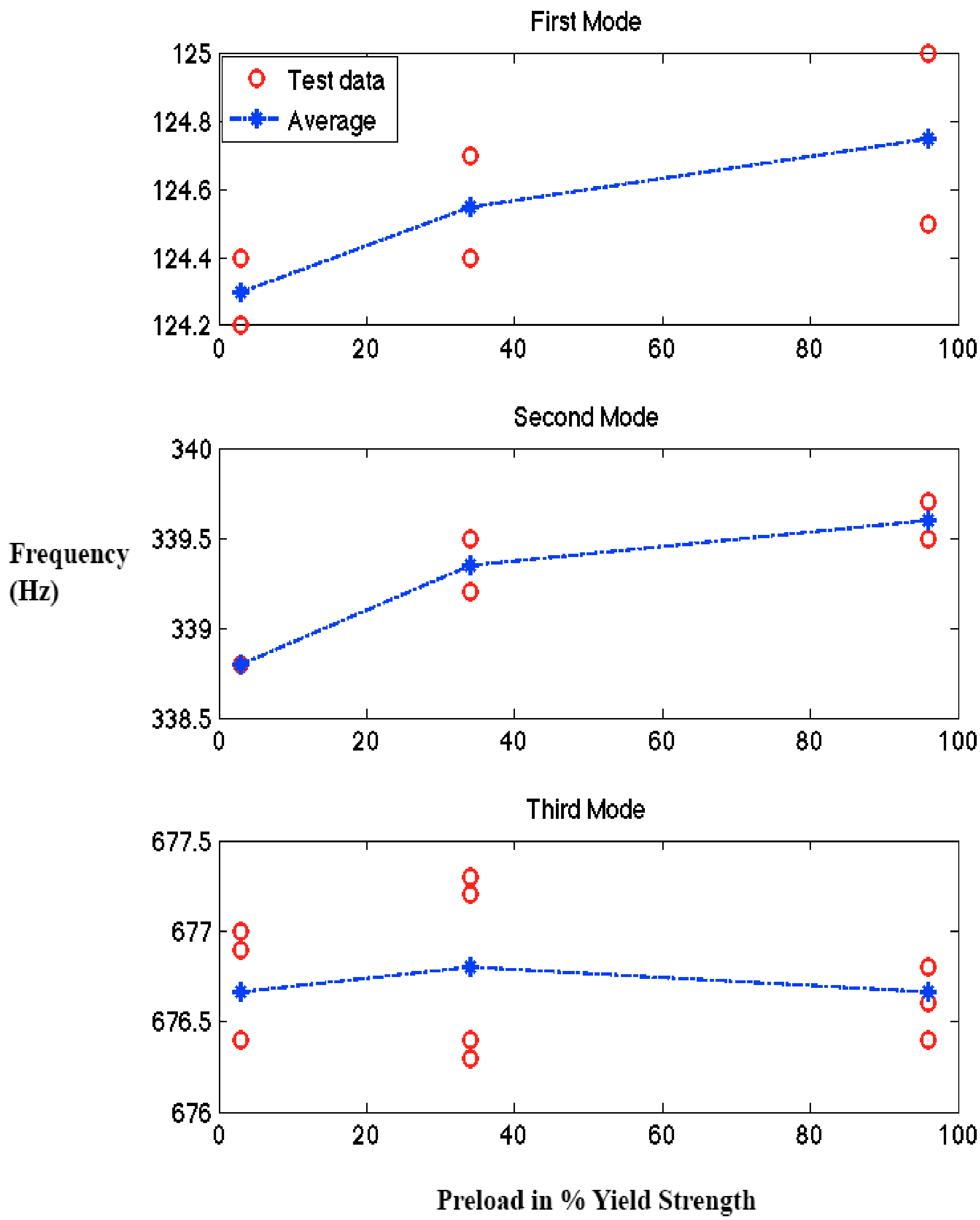


Figure 4.27 The first three modal frequencies versus preload in % yield strength for monolithic aluminum plate with Grade 5 bolt

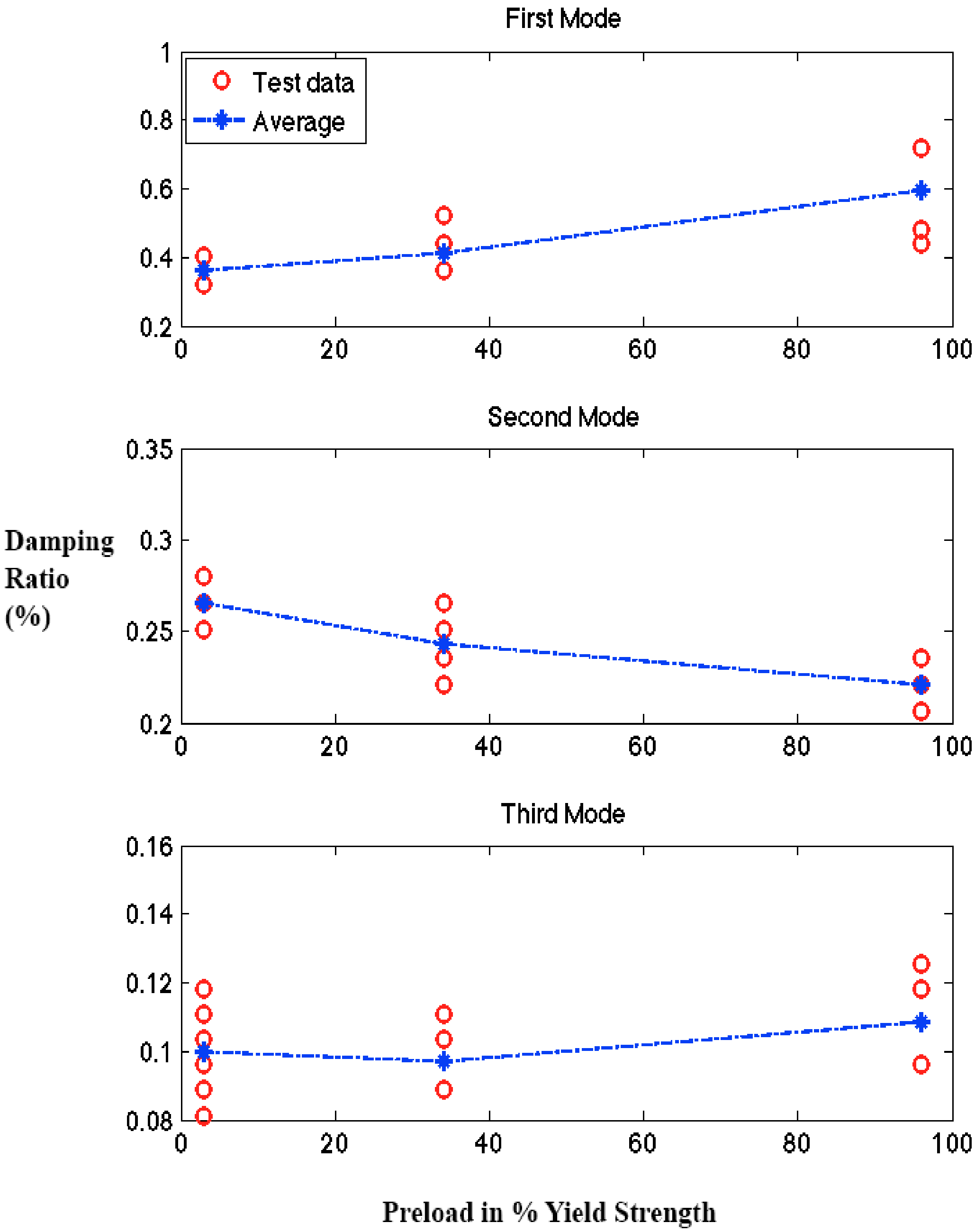


Figure 4.28 The first three modal damping ratios versus preload in % yield strength for monolithic aluminum plate with Grade 5 bolt

Table 4.8 Test results for monolithic aluminum plate with a Grade 5 bolt

Preload in % Yield Strength	No	1st Mode Frequency (Hz)	1st Mode Damping (%)	2nd Mode Frequency (Hz)	2nd Mode Damping (%)	3rd Mode Frequency (Hz)	3rd Mode Damping (%)
3%	1	124.2	0.4	338.8	0.28	676.4	0.081
	2	124.2	0.4	338.8	0.27	676.4	0.089
	3	124.2	0.4	338.8	0.27	676.4	0.096
	4	124.4	0.32	338.8	0.25	677	0.12
	5	124.4	0.32	338.8	0.27	676.9	0.11
	6	124.4	0.32	338.8	0.27	676.9	0.1
34%	1	124.4	0.36	339.5	0.24	676.3	0.089
	2	124.4	0.36	339.5	0.22	676.4	0.089
	3	124.4	0.36	339.5	0.24	676.3	0.089
	4	124.7	0.44	339.2	0.25	677.3	0.1
	5	124.7	0.52	339.2	0.27	677.3	0.11
	6	124.7	0.44	339.2	0.25	677.2	0.1
96%	1	124.5	0.48	339.5	0.24	676.8	0.096
	2	124.5	0.44	339.5	0.24	676.8	0.096
	3	124.5	0.48	339.5	0.21	676.8	0.096
	4	125	0.72	339.7	0.22	676.6	0.12
	5	125	0.72	339.7	0.22	676.4	0.13
	6	125	0.72	339.7	0.21	676.6	0.12

Table 4.9 Mean and standard deviation (SD) of the test results for monolithic aluminum plate with a Grade 5 bolt

% Preload		First Mode Frequency (Hz)	First Mode Damping (%)	Second Mode Frequency (Hz)	Second Mode Damping (%)	Third Mode Frequency (Hz)	Third Mode Damping (%)
Mean	3%	124.3	0.36	338.8	0.27	676.7	0.1
	34%	124.6	0.41	339.4	0.24	676.8	0.097
	96%	124.8	0.59	339.6	0.22	676.7	0.11
SD	3%	0.11	0.044	0	0.0093	0.29	0.014
	34%	0.16	0.065	0.16	0.016	0.51	0.0097
	96%	0.27	0.14	0.11	0.013	0.16	0.014

or damage to the bolt thread. The test procedure for performing the monolithic plate impact testing is identical with the previous case. The bandwidth and frequency resolution settings for baseline tests on monolithic plates were the same for all four cases as discussed in section 4.3.1. Six impact tests were performed on each torque value for monolithic aluminum plate Grade 8 bolt testing and again for the purpose of averaging the measurements there were four hits per single impact test.

The modal frequency and modal damping ratio results for the first three vibrational modes are shown in Table 4.10 and the mean and standard deviation (SD) of the test results for monolithic aluminum plate with a Grade 8 bolt are presented in Table 4.11. In this part a "loose bolt" is defined as the bolt with preload of 5% in bolt yield strength while a "tightened bolt" is defined as the bolt with preload of 68% in bolt yield strength. The following analysis will use these two definitions of loose bolt and tightened bolt as the basis of comparison.

The data of a Grade 8 bolt with aluminum monolithic plate for the first three vibration modes was exhibited as frequency versus varying preloads shown in Figure 4.29. A similar trend can be observed that the modal frequencies slightly increase as the preload increase, but with the preload increase from 5% to 68% in bolt yield strength. Thus the test structure with a tightened bolt exhibits a higher modal frequency than one with a loose bolt. And similarly, the influence of the bolt preload on modal frequency in the monolithic plate case was small. It shows in the figure that small frequency variations between three preload levels. The frequency difference between a lap joint structure with a tightened bolt and with a loose bolt for the first three modes are 0.3Hz for the first mode, 0.4Hz for the second mode and 0.3Hz for the third mode.

Table 4.10 Test results for monolithic aluminum plate with a Grade 8 bolt

n % Preload		1st Mode		2nd Mode		3rd Mode	
	No	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
5%	1	124.5	0.6	339.7	0.24	677.1	0.14
	2	124.5	0.64	339.5	0.27	677.3	0.14
	3	124.5	0.64	339.5	0.25	677.6	0.14
	4	124.7	0.32	339.4	0.21	677.3	0.13
	5	124.7	0.4	339.4	0.22	677.4	0.14
	6	124.7	0.32	339.4	0.24	677.2	0.14
39%	1	124.7	0.48	339.7	0.21	677.3	0.11
	2	124.7	0.48	339.7	0.24	677.4	0.13
	3	124.8	0.48	339.7	0.22	677.4	0.12
	4	124.8	0.36	339.7	0.19	677.8	0.11
	5	125	0.76	339.7	0.29	677.8	0.13
	6	125	0.76	339.7	0.28	677.9	0.13
68%	1	125	0.36	340	0.21	677.9	0.089
	2	125	0.36	340	0.19	677.9	0.096
	3	125	0.36	340	0.19	677.8	0.092
	4	124.8	0.36	339.8	0.21	677.3	0.11
	5	124.8	0.36	339.8	0.21	677.3	0.11
	6	124.8	0.4	339.8	0.21	677.4	0.12

Table 4.11 Mean and standard deviation (SD) of the test results for monolithic aluminum plate with a Grade 8 bolt

n % Preload		First Mode		Second Mode		Third Mode	
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
Mean	5%	124.6	0.49	339.5	0.24	677.3	0.14
	39%	124.8	0.55	339.7	0.24	677.6	0.12
	68%	124.9	0.37	339.9	0.2	677.6	0.1
SD	5%	0.11	0.16	0.12	0.0011	0.17	0.0011
	39%	0.14	0.17	0	0.0014	0.26	0.0014
	68%	0.11	0.016	0.11	0.0011	0.3	0.0011

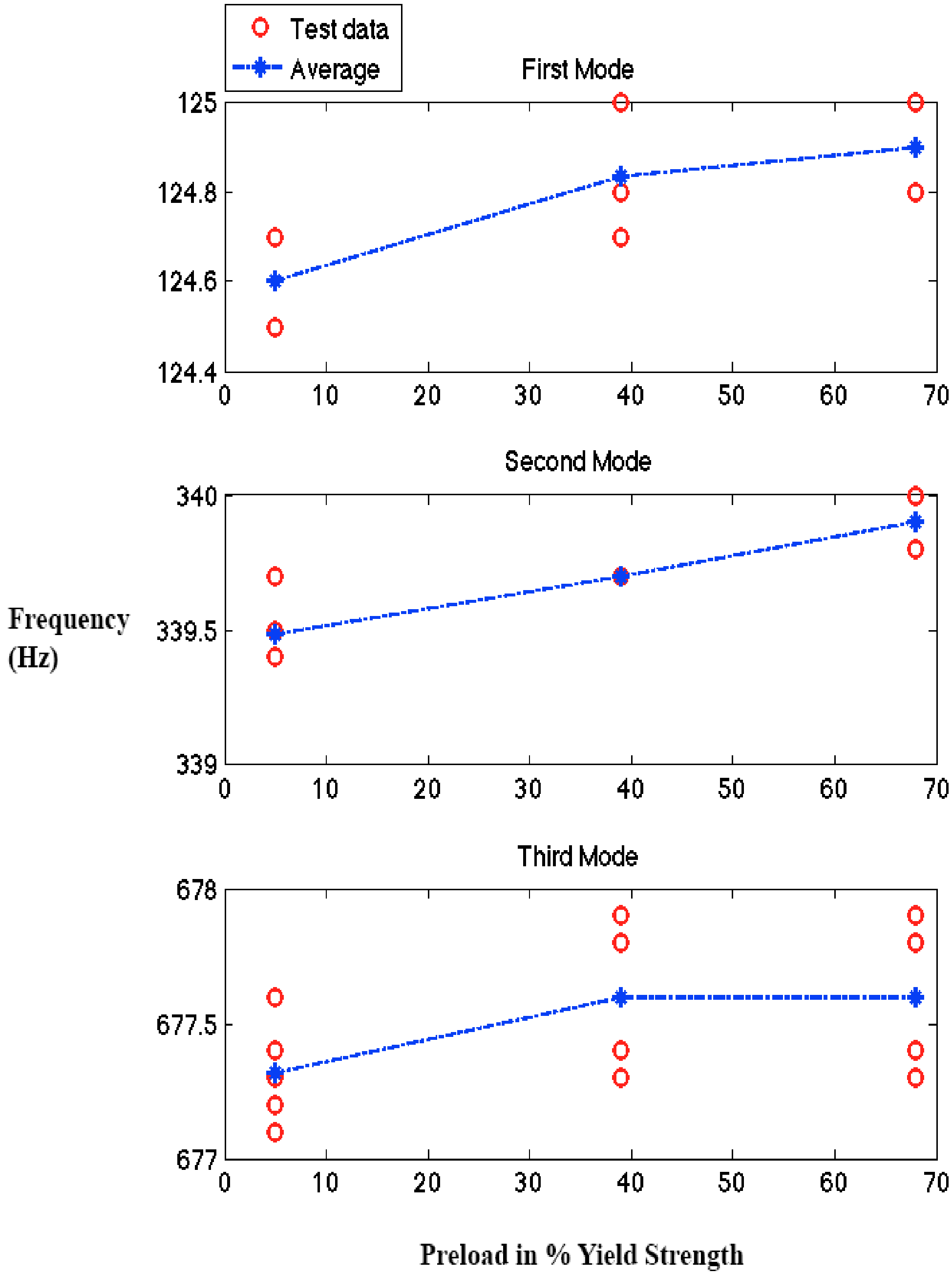


Figure 4.29 The first three modal frequencies versus preload in % yield strength for monolithic aluminum plate with Grade 8 bolt

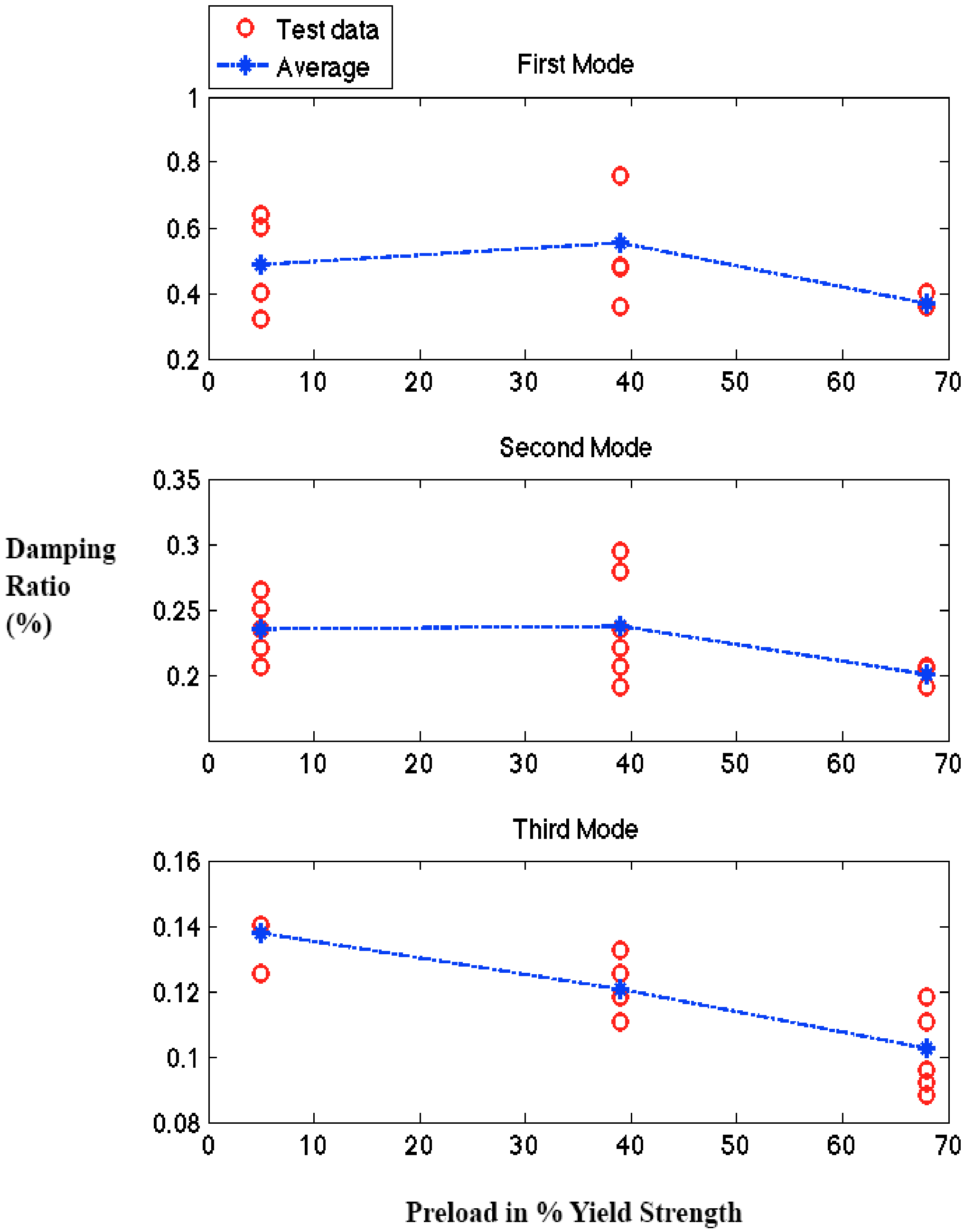


Figure 4.30 The first three modal damping ratios versus preload in % yield strength for monolithic aluminum plate with Grade 8 bolt

Similarly the third modal frequency stays relatively constant with increasing preload on the bolt. Figure 4.30 exhibits the data of Grade 8 bolt with aluminum monolithic plate as modal damping versus preload for the first three vibration modes. It can be observed that the damping ratios slightly decrease as the preload increase from 5% to 68% in bolt yield strength. The effect of varying preload on damping in a monolithic plate structure was also small, since there were only small damping differences between a test structure with a tightened bolt and with a loose bolt.

4.5.3 Monolithic Steel Plate Bolted With a Grade 5 Bolt

As mentioned previously, four sets of baseline tests with aluminum and steel monolithic plates were performed for the purpose of comparison. The test results for the monolithic steel plate bolted with a Grade 5 bolt will be presented in this section. This test combination was tested for three different torque values: 5 in-lbs., 50 in-lbs. and 140 in-lbs. The tightening preloads on the shank are 100lb, 1000lb and 2800lb and the corresponding preload in percent yield strength are 3%, 34% and 96%. The three preload values, the average axial tensile stresses on the bolt shank caused by these preloads, the test procedure, and the frequency resolution settings are all identical as the monolithic aluminum plate bolted with a Grade 5 bolt case discussed in section 4.3.1. The modal frequency and modal damping results for the first three vibrational modes are shown in Table 4.12 and the mean and standard deviation (SD) for those test results are presented in Table 4.13. "Loose bolt" is defined as the bolt with preload of 3% in bolt yield strength while "tightened bolt" is defined as the bolt with preload of 96% in bolt yield strength in this case. The following analysis used these two definitions of loose bolt and tighten bolt as the basis of comparison.

Six impact tests were performed on a Grade 5 bolt with a monolithic steel plate structure, and again the data was averaged for 4 hits in each trial. In order to better compare and interpret the test results, Figure 4.31 and Figure 4.32 was plotted from Table 4.12 and Table 4.13 as modal frequency versus different levels of preload in yield strength percentage and modal damping versus different levels of preload in yield strength percentage for the first three modes. While there were six impact tests performed, there were overlapping results in the test data plots as indicated by the appearance of fewer markers on those plots.

Figure 4.31 displays the preload effects for Grade 5 bolt on steel monolithic plate in the first three vibration modes as modal frequency versus varying preloads in percent yield strength. It shows a similar trend that the modal frequencies slightly increase as bolt preload increase from 3% to 96% in bolt yield strength, except for the first mode. This inconsistency might due to the fact that the impact striking location is very close to a node on the test plate for the first mode. Figure 4.32 displays the preload effects for Grade 5 bolt on steel monolithic plate as modal damping versus varying preloads in percent yield strength in a similar way. On average, the first three modal damping ratios stay relatively constant with respect to the increasing preload on the bolt. The effect of varying bolt preload on damping in a monolithic plate structure was minimal.

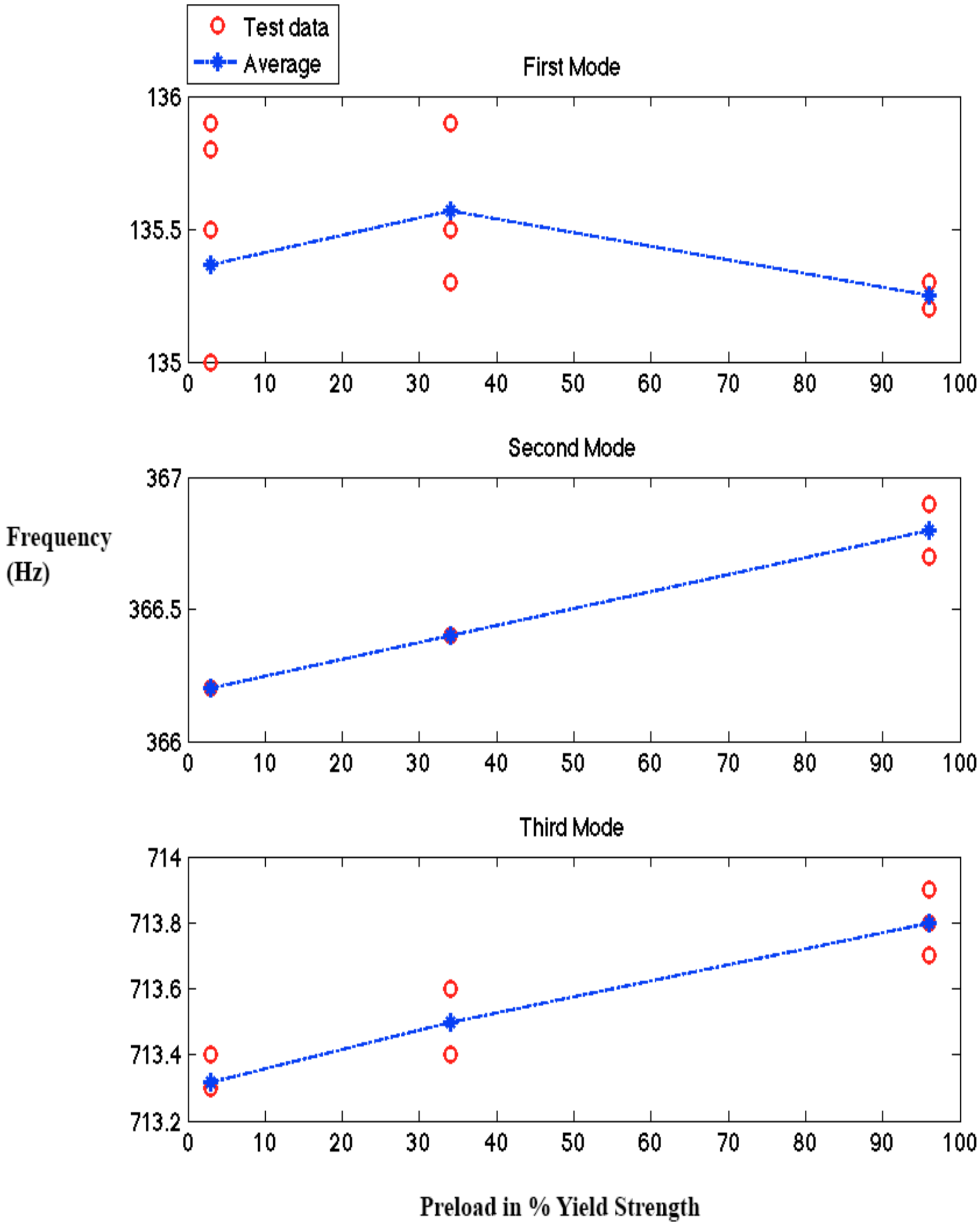


Figure 4.31 The first three modal frequencies versus preload in % yield strength for monolithic steel plate with Grade 5 bolt

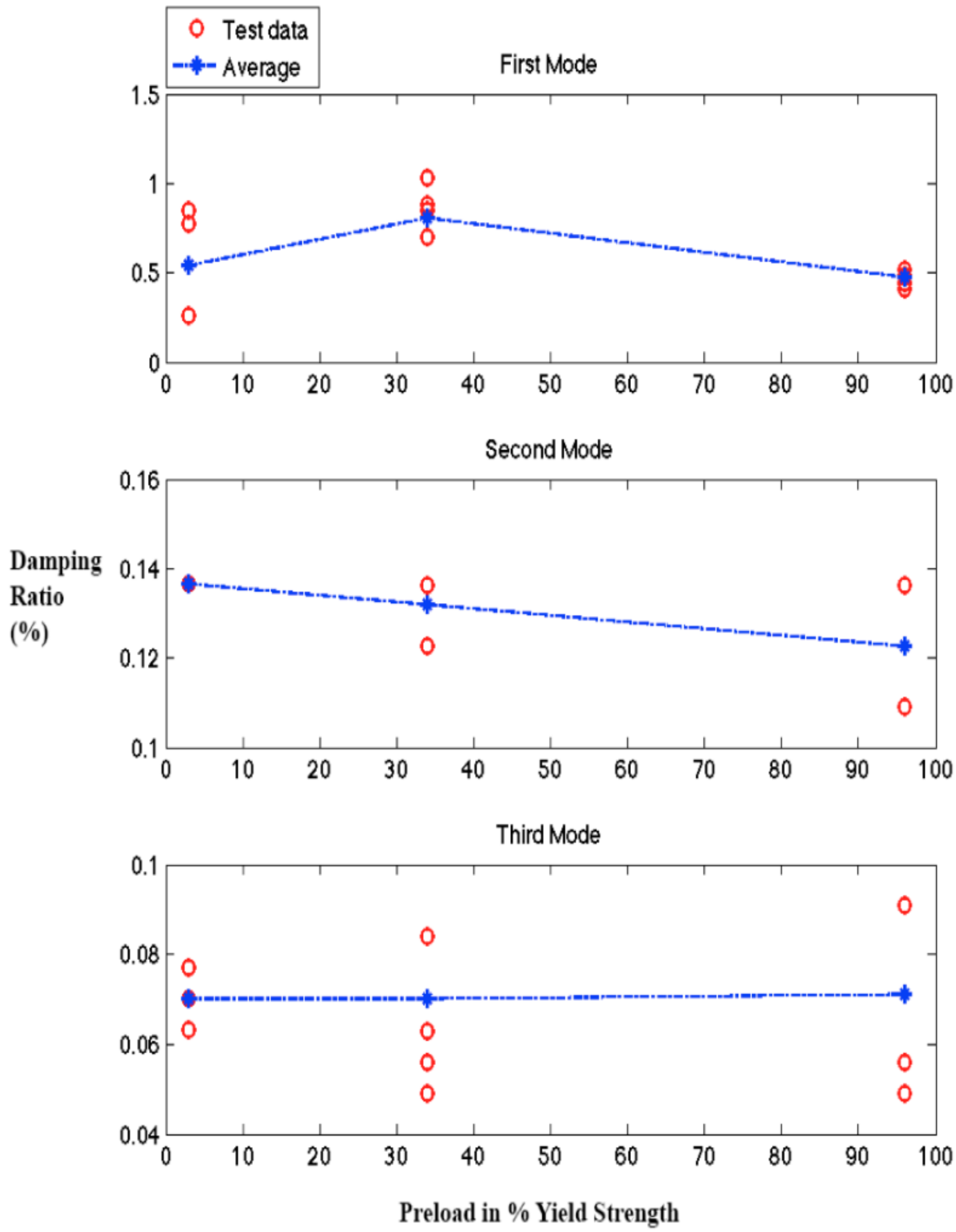


Figure 4.32 The first three modal damping ratios versus preload in % yield strength for monolithic steel plate with Grade 5 bolt

Table 4.12 Test results for monolithic steel plate with a Grade 5 bolt

n % Preload		1st Mode		2nd Mode		3rd Mode	
	No	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
3%	1	135	0.26	366.2	0.14	713.3	0.063
	2	135	0.26	366.2	0.14	713.3	0.07
	3	135	0.26	366.2	0.14	713.3	0.07
	4	135.9	0.85	366.2	0.14	713.3	0.07
	5	135.8	0.85	366.2	0.14	713.3	0.077
	6	135.5	0.77	366.2	0.14	713.4	0.07
34%	1	135.5	0.7	366.4	0.14	713.4	0.084
	2	135.3	0.7	366.4	0.14	713.4	0.084
	3	135.3	0.7	366.4	0.14	713.4	0.084
	4	135.9	0.85	366.4	0.14	713.6	0.063
	5	135.5	1	366.4	0.12	713.6	0.049
	6	135.9	0.88	366.4	0.12	713.6	0.056
96%	1	135.3	0.52	366.7	0.14	713.8	0.091
	2	135.3	0.48	366.7	0.14	713.9	0.091
	3	135.3	0.44	366.7	0.14	713.9	0.091
	4	135.2	0.41	366.9	0.11	713.8	0.049
	5	135.2	0.48	366.9	0.11	713.7	0.056
	6	135.2	0.52	366.9	0.11	713.7	0.049

Table 4.13 Mean and standard deviation (SD) of the test results for monolithic steel plate with a Grade 5 bolt

n % Preload		First Mode		Second Mode		Third Mode	
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
Mean	3%	135.4	0.54	366.2	0.14	713.3	0.07
	34%	135.6	0.81	366.4	0.13	713.5	0.07
	96%	135.3	0.47	366.8	0.12	713.8	0.071
SD	3%	0.42	0.31	0	0	0.041	0.0044
	34%	0.27	0.14	6.2E-14	0.007	0.11	0.016
	96%	0.055	0.043	0.11	0.015	0.089	0.022

4.5.4 Monolithic Steel Plate Bolted With a Grade 8 Bolt

The effect of varying preload on monolithic steel plate was also investigated by replacing the Grade 5 bolt with a Grade 8 bolt. The last baseline test combination was performed under three torque values of 10 in-lbs., 80 in-lbs. and 140 in-lbs. The tightening preload on the bolt shank is 200lb, 1600lb and 2800lb respectively and the corresponding preload in percent bolt yield strength is 5%, 39% and 68% respectively. The torque and preload values, the average axial tensile stresses on the shank caused by these preloads, the test procedure, and the frequency resolution settings are all identical as the monolithic aluminum plate bolted with a Grade 8 bolt case discussed in the previous section 4.5.2. The first three modal frequencies and modal damping ratios results for the monolithic steel plate bolted with a Grade 8 bolt structure are shown in Table 4.14 and the mean and standard deviation (SD) for the test data are presented in Table 4.15. Figure 4.33 and Figure 4.34 were plotted from the data taken from Table 4.14 and Table 4.15, and show the trends associated with increasing preload in percent yield strength (5%, 39% and 68% in this case). The following section will use two definitions, a loose bolt and a tightened bolt. The loose bolt is categorized as a bolt with the preload of only 5% in bolt yield strength.

Similarly, the tightened bolt is categorized as a bolt with the preload of 68% in bolt yield strength. In total, six impact tests were performed and the data from these tests were averaged using four different hits in each trial.

The test data of Grade 8 bolt with monolithic steel plate for the first three vibration modes was exhibited as frequency versus preloads shown in Figure 4.33. Note that there were overlapping results in the test data plots as indicated by the appearance of

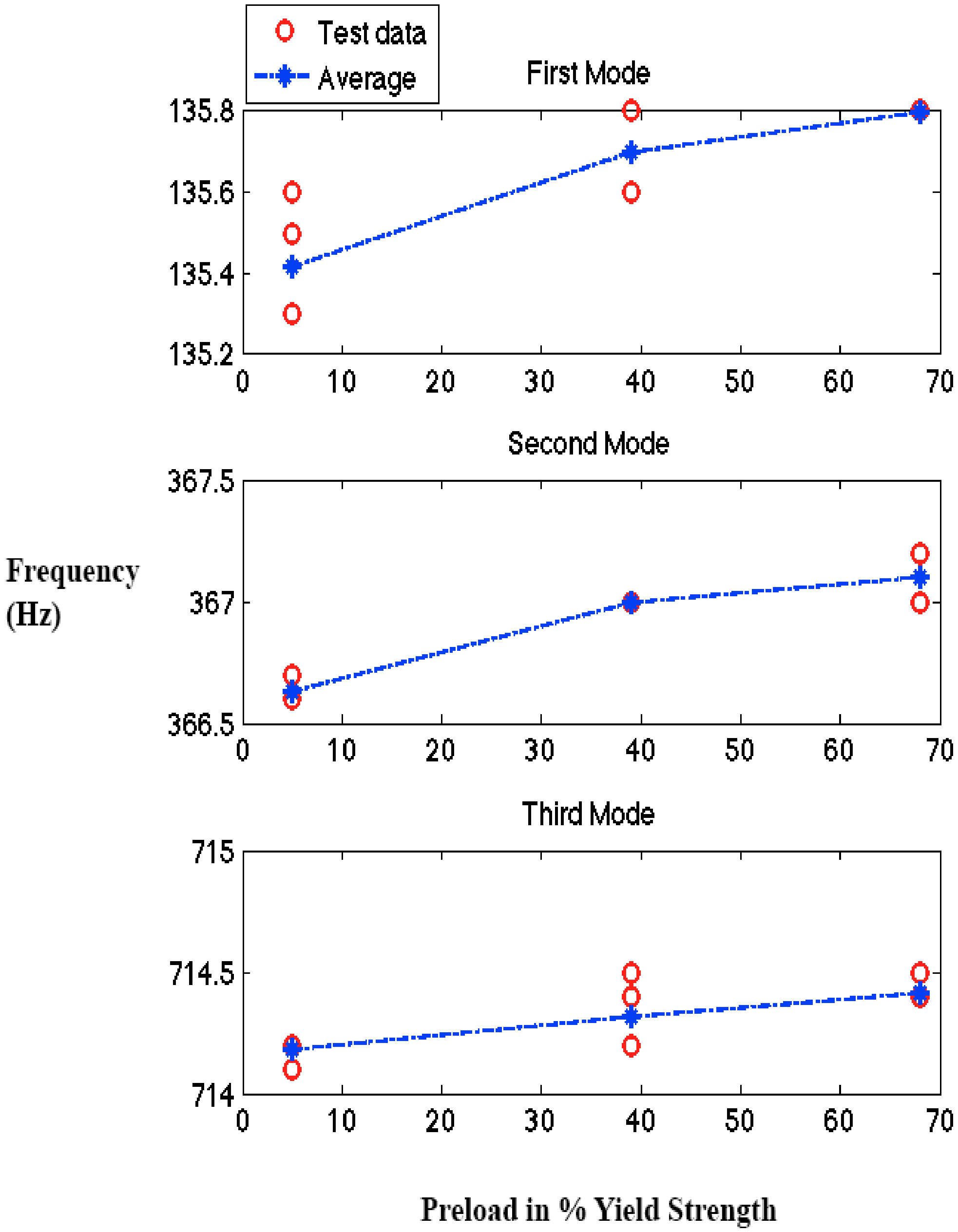


Figure 4.33 The first three modal frequencies versus preload in % yield strength for monolithic steel plate with Grade 8 bolt

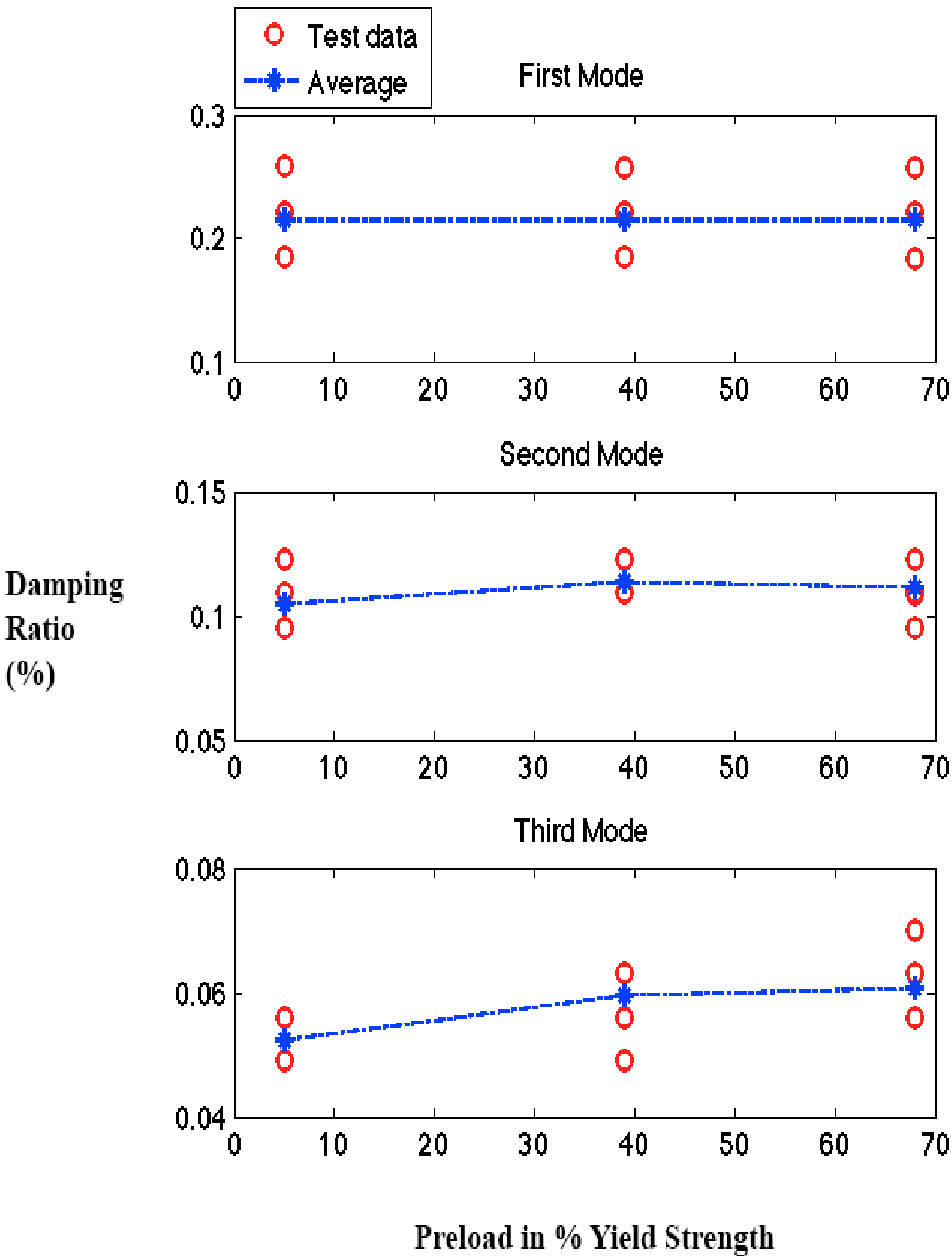


Figure 4.34 The first three modal damping ratios versus preload in % yield strength for monolithic steel plate with Grade 8 bolt

Table 4.14 Test results for monolithic steel plate with a Grade 8 bolt

n % Preload		1st Mode		2nd Mode		3rd Mode	
	No	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
5%	1	135.5	0.18	366.6	0.11	714.2	0.056
	2	135.5	0.22	366.7	0.12	714.2	0.056
	3	135.6	0.18	366.7	0.11	714.2	0.056
	4	135.3	0.22	366.6	0.095	714.2	0.049
	5	135.3	0.22	366.6	0.095	714.2	0.049
	6	135.3	0.26	366.6	0.095	714.1	0.049
39%	1	135.6	0.18	367	0.11	714.5	0.056
	2	135.6	0.18	367	0.11	714.4	0.063
	3	135.6	0.18	367	0.11	714.4	0.049
	4	135.8	0.22	367	0.11	714.2	0.063
	5	135.8	0.26	367	0.12	714.2	0.063
	6	135.8	0.26	367	0.12	714.2	0.063
68%	1	135.8	0.22	367	0.095	714.4	0.056
	2	135.8	0.26	367	0.11	714.4	0.063
	3	135.8	0.26	367	0.11	714.5	0.056
	4	135.8	0.18	367.2	0.11	714.4	0.063
	5	135.8	0.18	367.2	0.12	714.4	0.056
	6	135.8	0.18	367.2	0.12	714.4	0.07

Table 4.15 Mean and standard deviation (SD) of the test results for monolithic steel plate with a Grade 8 bolt

n % Preload		First Mode		Second Mode		Third Mode	
		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
Mean	5%	135.4	0.2154	366.6	0.1046	714.2	0.05251
	39%	135.7	0.2149	367	0.1135	714.3	0.0595
	68%	135.8	0.2148	367.1	0.1112	714.4	0.06066
SD	5%	0.13	0.028	0.052	0.011	0.041	0.0038
	39%	0.11	0.036	0	0.007	0.13	0.0059
	68%	3.1E-14	0.036	0.11	0.01	0.041	0.0057

less data points presented on those figures. A similar increase can be seen in the figure that the modal frequencies slightly increase as the preload increase from 5% to 68% in bolt yield strength.

The modal frequency of the test structure with a tightened bolt is 0.4Hz higher in the first mode, 0.5Hz in the second mode, and 0.2Hz higher in the first third mode than with a loose bolt. Additionally, the influence of the bolt preload on modal frequency in the monolithic plate case was minor. The third modal frequency stays relatively constant with increasing preload on the bolt. Figure 4.34 shows that the damping ratios stay relatively the same as the bolt preload increase from 5% to 68% in bolt yield strength. The damping difference between a test structure with a tightened bolt and with a loose bolt was very small, thus the effect of varying preload on damping in a monolithic plate structure was also minimal, similar to what was seen in the previous case.

CHAPTER 5: DATA COMPARISON AND DISCUSSION

5.1 Overview

This chapter provides a further discussion of the data presented in Chapter 4. As mentioned before, eight different configurations were tested to study the bolt preload effect for modal frequency and modal damping. These eight different cases are:

- Case 1: Monolithic steel plate bolted with a Grade 5 bolt
- Case 2: Monolithic steel plate bolted with a Grade 8 bolt
- Case 3: Two steel plates bolted with a Grade 5 bolt
- Case 4: Two steel plates bolted with a Grade 8 bolt
- Case 5: Two aluminum plates bolted with a Grade 5 bolt
- Case 6: Two aluminum plates bolted with a Grade 8 bolt
- Case 7: Monolithic aluminum plate bolted with a Grade 5 bolt
- Case 8: Monolithic aluminum plate bolted with a Grade 8 bolt

In this section, data from those eight cases were plotted together based on different test plate materials. The scatter plots from Case 1 to Case 8 are presented in Appendix D for reference. The graphs show the general trend of the increasing preload. Only the test data from vibration modes 2 and 3 are presented and discussed here, as the impact excitation point was unintentionally near a node of the first mode, which yielded different results and more fluctuations than the test results from other modes.

5.2 Effect of Bolt Preload on Modal Frequency

The effect of bolt preload on modal frequency was investigated in the eight different cases mentioned above. The general trend observed in each case was similar: the modal frequencies of the bolted lap joint structure increased with the increased bolt preload for the first three vibrational modes, and this increase was nonlinear. Figure 5.1 and Figure 5.2 show the relationships between varying preload and modal frequencies on steel material and on aluminum material, respectively, for the second and third modes.

It can be observed that the cases of the two steel plates bolted with either a Grade 5 bolt or with a Grade 8 bolt showed the similar increase of modal frequencies versus the increased preload in Figure 5.1. Specifically, the modal frequencies for the second and third modes increased by 4Hz (1.15%) and 2.6Hz (0.4%), respectively in the two steel plates bolted with a Grade 5 bolt (Case 1). For the two steel plates bolted with a Grade 8 bolt (Case 2), the modal frequencies for the second and third modes increased by 4.1Hz (1.2%) and 4.3Hz (0.62%), respectively. The modal frequencies for the second and third modes in the monolithic baseline tests recorded higher modal frequencies than in the cases of the two plates bolted with a single bolt for different preload levels as shown in Figure 5.1. Generally, there is an average increase of about15Hz from two steel plates bolted with a single bolt to monolithic steel plates with a single bolt (without presence of a joint). This was expected and can be explained by the fact that a single plate is stiffer than two plates bolted together, as long as they have identical geometry and material conditions.

A similar trend of modal frequencies increasing with increased preload was observed in Figure 5.2. This was consistent with the trend of the frequency plots

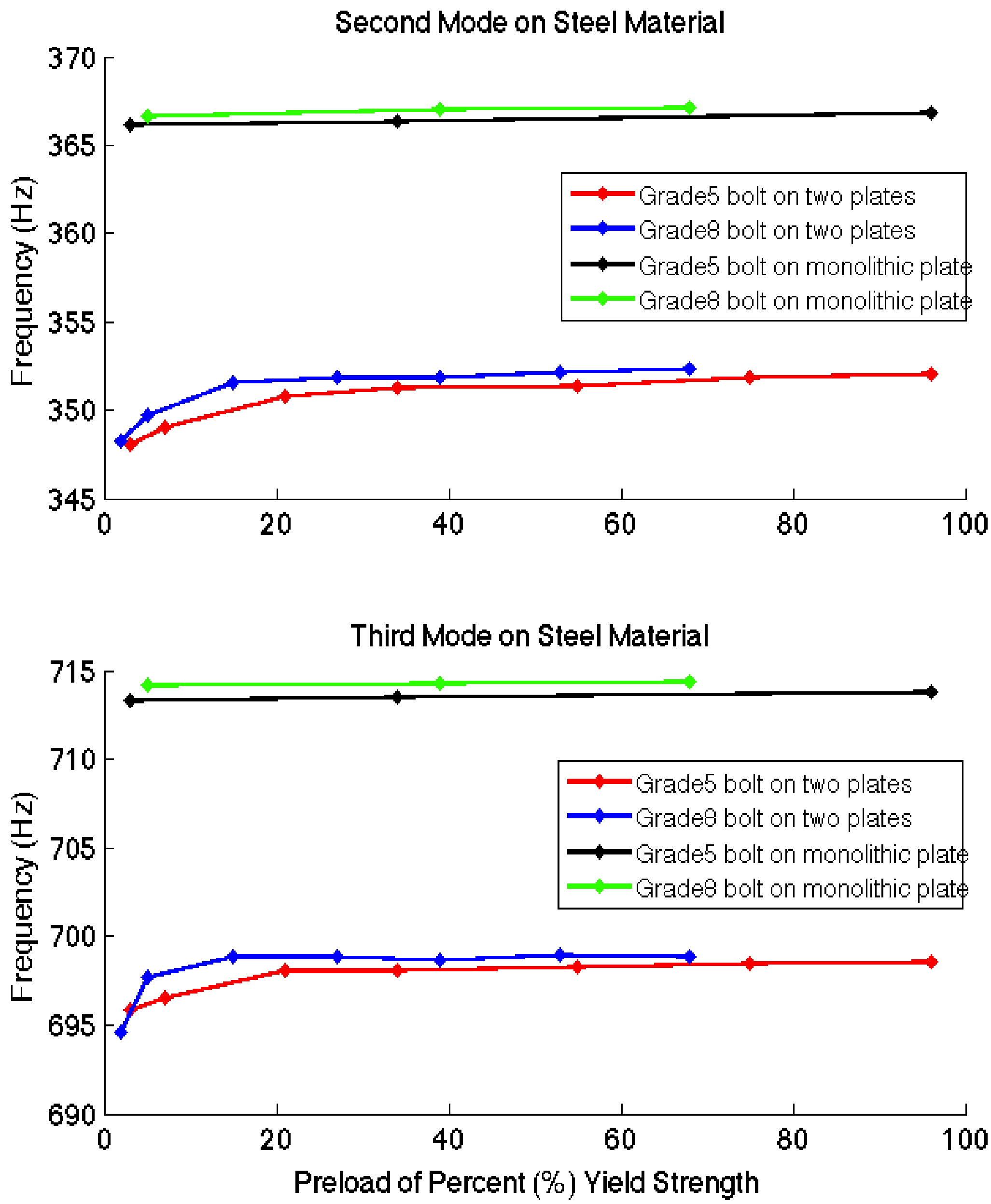


Figure 5.1 Frequency versus preload on steel material for the second and third modes

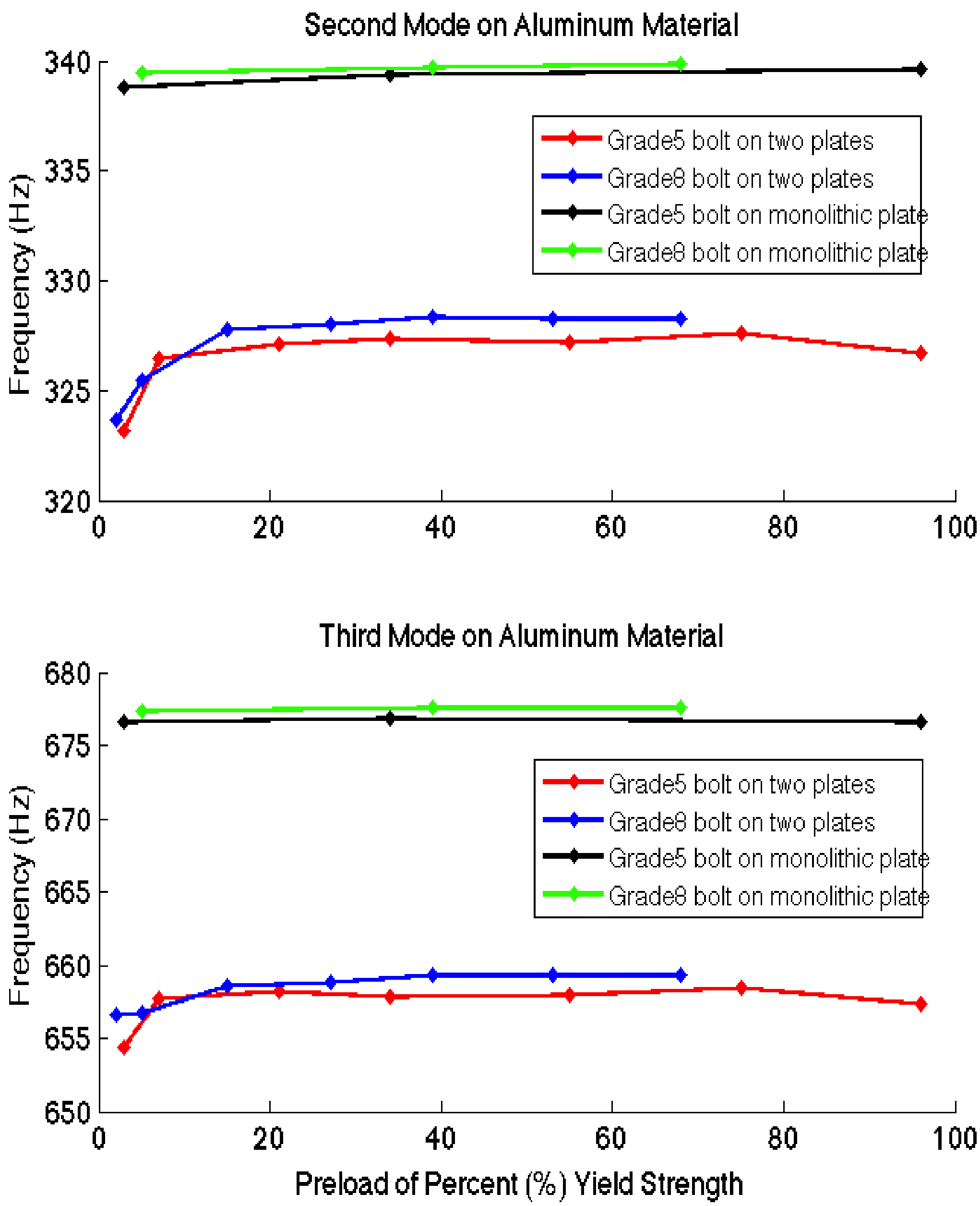


Figure 5.2 Frequency versus preload on Al material for the second and third modes

discussed earlier. Specifically, the modal frequencies increased by 4.5Hz (1.4%) in the second mode and 4Hz (0.6%) in the third mode for the two aluminum plates bolted with a Grade 5 bolt (Case 5). For the two aluminum plates bolted with a Grade 8 bolt (Case 6), the modal frequencies increased by 4.6Hz (1.4%) in the second mode and 2.7Hz (0.4%) in the third mode. The modal frequencies of the aluminum monolithic plate were higher than in the cases of the two plates bolted with a single bolt in different preload levels as indicated in Figure 5.2. Similarly, there is also an average increase of about 15Hz from the two aluminum plates bolted together to a monolithic equivalent plate with a single bolt.

It was observed that at a lower preload range of 0% to 30% of the bolt yield strength, the modal frequencies increased with the increased preload. At a higher preload range of 30% to 68% in a Grade 8 bolt yield strength (or 75% in a Grade 5 bolt yield strength), the modal frequencies stayed relatively constant with the increased preload. A reason for this difference is that the bolted structure had already reached its maximum stiffness at the higher preload range, so the contact stiffness could not continue increasing.

In this section, ‘‘loose bolt’’ is defined as the bolt with a preload range of 0% to 30% in bolt yield strength, while ‘‘tightened bolt’’ is defined as the bolt with a preload range of 68% to 96% in bolt yield strength. The bolted lap-joint structure with a tightened bolt possessed higher modal frequencies than the test structure with a loose bolt, as observed in all the frequency plots presented in Chapter 4.4. According to the equations of natural frequency given in *Engineering Vibration* [16] for single degree of freedom, the natural frequency (modal frequency) is proportional to the stiffness of the test structure. Thus, as the bolt preload increased, the structural stiffness increased, which resulted in the increase in modal frequencies. This is consistent with the theory described in *Stiffness and Damping in Mechanical Design* [20], which states that ‘‘preloaded joints behave as linear angular springs, stiffening with increasing preload force’’ (p.98).

5.3 Effect of Bolt Preload on Modal Damping

The effect of bolt preload on modal damping was also investigated in those eight different cases. Modal damping ratios were calculated for the first three modes of interest using the half-bandwidth method discussed in Chapter 4. Examination of the damping results for the eight different configurations indicated that the modal damping ratios changed with both the applied preload and the jointing materials.

There was a general decrease of damping ratios as the preload increased. This trend, in every case, was very similar. The damping ratios dropped dramatically when preload was increased at the lower preload range of 0% to 30% in the bolt yield strength. However, the damping ratios had fewer variations at the higher preload range of 30% to 75% in the bolt yield strength in Case 1, Case 2, Case 5 and Case 6.

Similar to before, ‘‘loose bolt’’ is defined as a bolt with a preload range of 0% to 30% in bolt yield strength, while ‘‘tightened bolt’’ is defined as a bolt with a preload of 68% to 75% in bolt yield strength. The bolted lap joint structure with a tightened bolt had lower modal damping ratios than with a loose bolt as observed in all of the damping plots presented in Chapter 4.4.

Figure 5.3 and Figure 5.4 present the preload effect on modal damping for the steel and aluminum materials for the second and third modes. The damping ratios for the second and the third modes increased by 85% and 74%, respectively, from the test structure with a tightened bolt to the structure with a loosened bolt in two steel plates bolted with a Grade 5 bolt situation (Case 1). For the two steel plates bolted with a Grade 8 bolt configuration (Case 2), the modal damping from the bolted structure with a tightened bolt to the structure with a loosened bolt for the second and the third modes increased by 27% and 83%, respectively. The second and the third modal damping ratios in the monolithic baseline tests were lower than in the cases of the two plates bolted with a single bolt as shown in Figure 5.1. This can be explained by the theory of damping in mechanical contacts. As the preload increases, the pressure of the interfaces (including the interface between the plates and the interfaces between the two washers and the plates) also increases. This will result in a reduction of micro-slip or macro-slip on the contacting surfaces, which will result in less energy loss due to the friction effect. Energy loss during micro-slip or macro-slip in the interfaces is one of the major contributors to damping in the bolted joint structure.

A similar trend of modal damping increasing with preload loss was shown in Figure 5.4. This was consistent with the figures discussed earlier. Specifically, the modal damping increased by 42% in the second mode and 46% in the third mode for the two aluminum plates bolted with a tightened Grade 5 bolt to the structure with a loosened one. For the two aluminum plates bolted with a Grade 8 bolt, the damping ratios increased by 41% in the second mode and 44% in the third mode with respect to the decreased preload from 68% to 2% in bolt yield strength. Again, the modal damping ratios of the aluminum monolithic plate were lower than in the cases of the two plates bolted with a single bolt as presented in Figure 5.4. It can be concluded that, due to more micro-slip or sliding friction at a preload range of 0% to 10% of the bolt yield strength, the damping ratios of the first two preload levels have greater standard deviation than damping ratios estimated from the higher preload levels.

The first modal frequency and damping of the bolted structure connected by a single bolt did not behave like other modes. Additionally, the standard deviation values for the first modal damping ratios are 2-10 times larger than the values of the second and third modes. This is because the hammer impact location, as discussed in Chapter 3, is very close (0.2 inch) to a node for the first mode on the bolted joint structure; thus, the result from the first mode is excluded from this section.

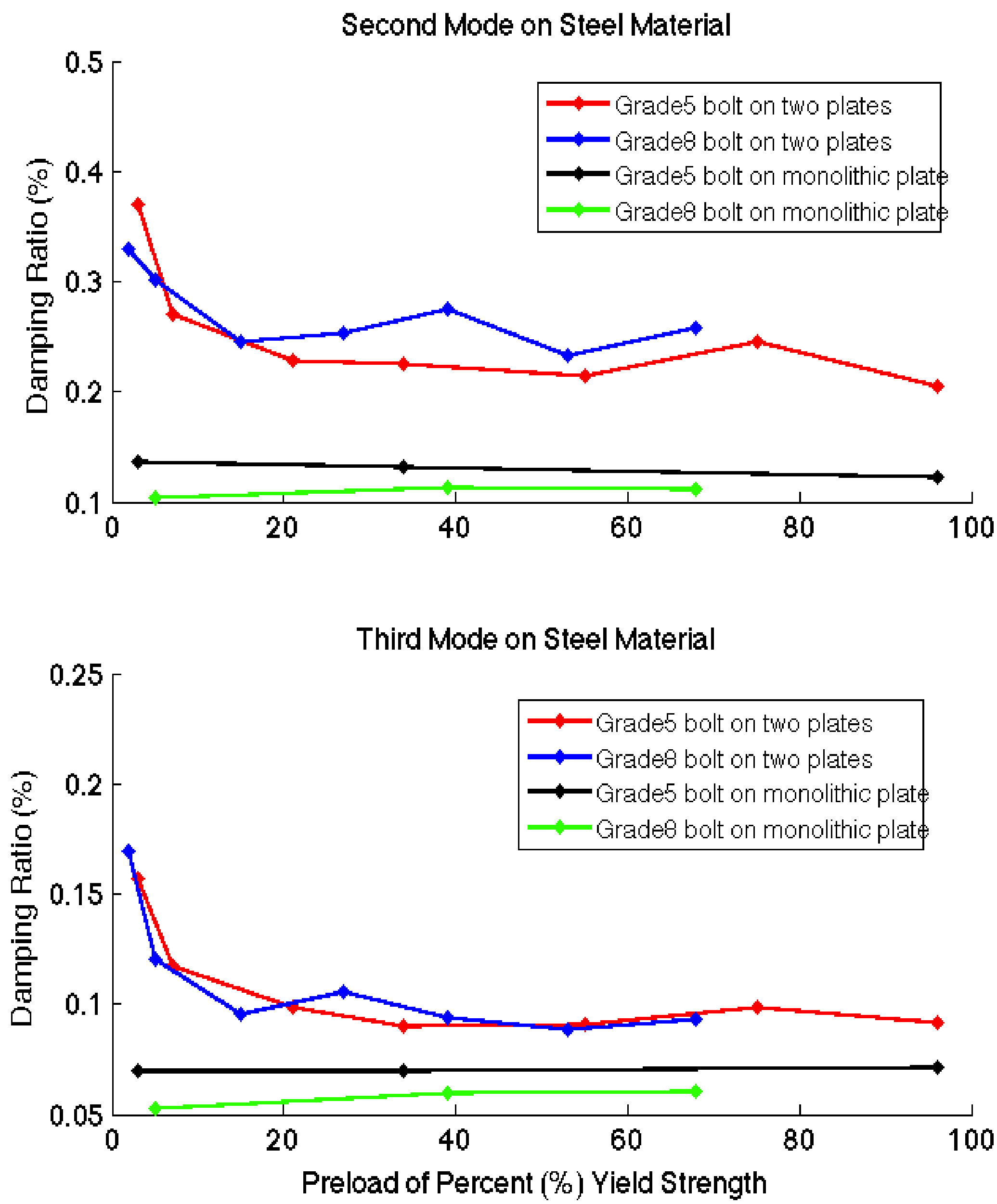


Figure 5.3 Damping versus preload on steel material for the second and third modes

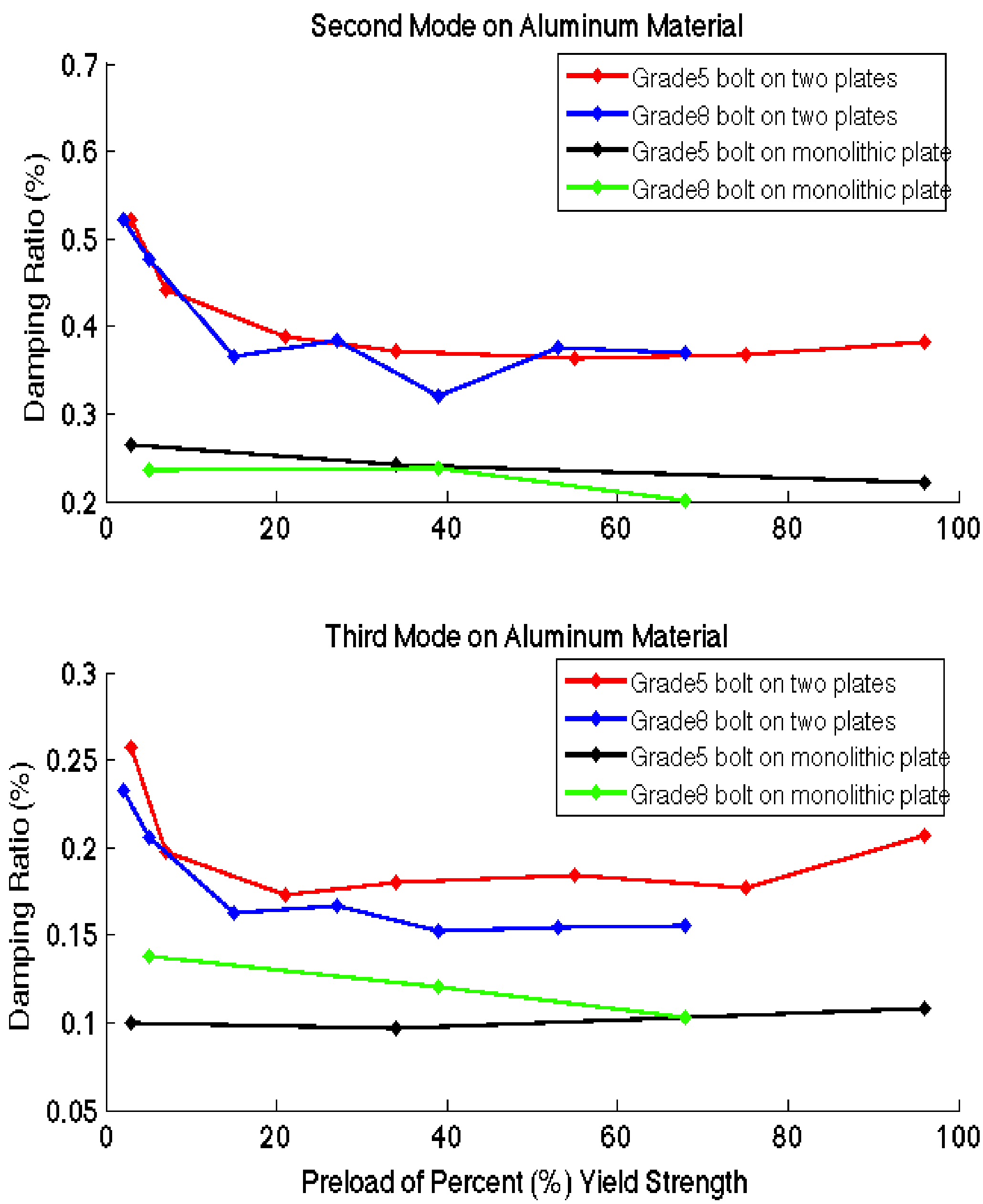


Figure 5.4 Damping versus preload on Al material for the second and third modes

CHAPTER 6: CONCLUSIONS

This thesis presented results from extensive impact hammer tests conducted on a simple bolted lap joint structure. These tests assess changes in modal damping and natural frequency with respect to seven different bolt preload levels, two different strength bolts, and two different structural materials. The natural frequencies and damping ratios were extracted from frequency response functions (FRFs) at their first three vibrational modes. It can be observed that both natural frequency and modal damping shifted with bolt loosening. Therefore, monitoring the modal parameters of the test structure provides useful assessments of the bolted joint preload and the structural integrity. The main findings of this work are as follows:

- Modal frequencies generally increased by 2% in the second mode and 1% in the first mode in aluminum and steel test plates with increasing preload. Modal frequencies increased more dramatically when increasing preload level to the range of 0% to 30% in bolt yield strength, but stayed approximately constant when preload was increased up to 30% or more in bolt yield strength. The explanation is that as the bolted joint preload increases, the interfacial pressure between the bolted components increases. This will lead to the increase in the natural frequencies of the test structure, for the stiffness increases due to higher interfacial pressure. The reason why the natural frequencies stayed approximately constant when the applied preload was beyond 30% in bolt yield strength is that the test structure has already reached its maximum structural stiffness when the bolt preload level is high.

- Modal damping of the first three vibrational modes generally increased by 45% in aluminum test plates, and 85% in steel test plates as the preload was decreased. By decreasing the preload between the bolted joint, the structural damping ratios increase nonlinearly, thus the energy dissipated through the joint increased with bolt loosening. Modal damping decreased rapidly when the increased preload level was in the range of 0% to 30% in bolt yield strength, and the ratios stayed within a constant value when preload was continued to increase up to 50% or more in bolt yield strength. The explanation is that as the bolted joint preload decreases, the interfacial pressure between the bolted components decreases. This will result in an increase of micro-slip or macro-slip on the bolted interfaces, which will lead to more energy loss through slip mechanism (friction). The reason why the modal damping stayed fairly a constant when applied preload level is high is that there was little difference in micro-slip effect when the preload was continued to increase in the high preload level of 50% or higher in bolt yield strength.
- The natural frequencies of the first three vibrational modes for a simple bolted lap joint structure were about 15Hz smaller (5% lower in the second mode and 2.5% lower in the third mode) than that of the monolithic test plate with identical geometric dimensions. Thus, the structural stiffness of a bolted joint structure is lower than that of a geometrically identical solid one.

- The modal damping ratios of the first three vibrational modes for a simple bolted lap joint structure were larger (doubled) than that of the monolithic test plates with identical geometric dimensions.
- Severe bolt loosening, or bolted joint preload loss with a preload level of less than 40% in bolt yield strength, can be indicated by either a notable decrease in the natural frequency or a large increase in damping ratios of the bolted plates. The bolted test plates were made from conventional structural materials, such as aluminum and steel.
- When preload is large enough to induce yielding (plastic deformation) in structural aluminum components, the modal damping increases with increased preload in two aluminum plates bolted with a Grade 5 bolt. Otherwise, damping increases with decreased preload, which leads to an increase in slip mechanism of damping.
- The ability to use impact hammer testing for loose bolt detection has been investigated and this method was demonstrated to be effective for loose bolt detection and estimating different preload levels in a simple lap joint structure. However, this method can only detect a loose bolt with a preload of less than 30% in bolt yield strength.
- The feasibility of using modal parameters, such as natural frequency and modal damping, for loose bolt detection and preload loss estimation has been confirmed. Modal damping was found to be a more sensitive indicator than natural frequency for bolt loosening in a single bolted structure. However, natural frequency and

damping are only accurate for evaluating a preload level of less than 30% in bolt yield strength.

REFERENCES

[1] Gaul L. The influence of damping on waves and vibrations. Mech Syst Signal Pr. 1999;13:1-30.

[2] Beards C. Damping in structural joints. Shock and Vibration Information Center The Shock and Vibration Digest. 1982;14:9-11.

[3] Gaul L, Becker J. Damping prediction of structures with bolted joints. Shock and Vibration. 2010;17:359-71.

[4] ITO Y, MASUKO M. Study on the Damping Capacity of Bolted Joints: Effects of the Joint Surfaces Condition. Bulletin of JSME. 1975;18:319-26.

[5] Simmons W. 'Bolt Failure Studies at Aberdeen Proving Ground, Analyzing Failures: Problems and Solutions. International Conference and Exposition on Cracks and Fatigue, Corrosion and Cracking, Fracture Mechanics and Failure Analysis1986.

[6] Nanda B. Study of the effect of bolt diameter and washer on damping in layered and jointed structures. J Sound Vib. 2006;290:1290-314.

[7] Esteban J, Rogers CA. Energy dissipation through joints: theory and experiments. Comput Struct. 2000;75:347-59.

[8] Butner C, Adams D, Foley J. Understanding the Effect of Preload on the Measurement of Forces Transmitted Across a Bolted Interface. In: Proulx T, editor. Modal Analysis Topics, Volume 3: Springer New York; 2011. p. 567-78.

[9] Butner C, Adams D, Foley JR. Simplified Nonlinear Modeling Approach for a Bolted Interface Test Fixture. Topics in Nonlinear Dynamics, Volume 3. 2012:71-82.

[10] Jaques J, Adams D. Using Impact Modulation to Identify Loose Bolts on a Satellite. DTIC Document; 2011.

[11] Caccese V, Mewer R, Vel SS. Detection of bolt load loss in hybrid composite/metal bolted connections. Eng Struct. 2004;26:895-906.

[12] Bickford JH, Nassar S. Handbook of bolts and bolted joints: CRC press; 1998.

[13] The Fundamentals of Modal Testing Application Note 243-3.

[14] Criteria for preloaded bolts. National Aeronautics and Space Administration.

[15] Rajendra C. Analysis of Bolt Torquing. Progress Energy, Southport, NC 28461.

[16] Inman DJ. Engineering vibrations. Prentice-Hall. 2010;2001.

[17] Ewins DJ. Modal testing : theory and practice / D.J. Ewins. Letchworth, Hertfordshire, England : New York: Research Studies Press ; Wiley; 1984.

[18] Katipally ACR. Damping estimation of plates joined at a point using statistical energy analysis. 2011.

[19] Williamson DF, Parker RA, Kendrick JS. The box plot: a simple visual method to interpret data. Annals of internal medicine. 1989;110:916-21.

[20] Rivin EI. Stiffness and damping in mechanical design: CRC Press; 1999.

APPENDICES

Appendix A: Weight of the Test Components

Table A.1 Weight of the test components

Weight Unit: g	Two Al plates bolted with a Grade 5 bolt	Two Al plates bolted with a Grade 8 bolt	Two steel plates bolted with a Grade 5 bolt	Two steel plates bolted with a Grade 8 bolt	Monolithic Al plate bolted with a Grade 5 bolt	Monolithic Al plate bolted with a Grade 8 bolt	Monolithic steel plate bolted with a Grade 5 bolt	Monolithic steel plate bolted with a Grade 8 bolt
Grade 5 bolt	6.5		6.5		6.5		6.5	
Grade 8 bolt		5.8		5.8		5.8		5.8
Washers (2) (5.5-6)	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Nut	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Monolithic Al Plate					80.7	80.7		
Monolithic Steel Plate							236.9	236.9
Two Al Plates	79.8	79.8						
Two Steel Plates			234.6	234.6				
Total Weight	**95**	**94.3**	**249.8**	**249.1**	**95.9**	**95.2**	**252.1**	**251.4**

Appendix A (Continued)

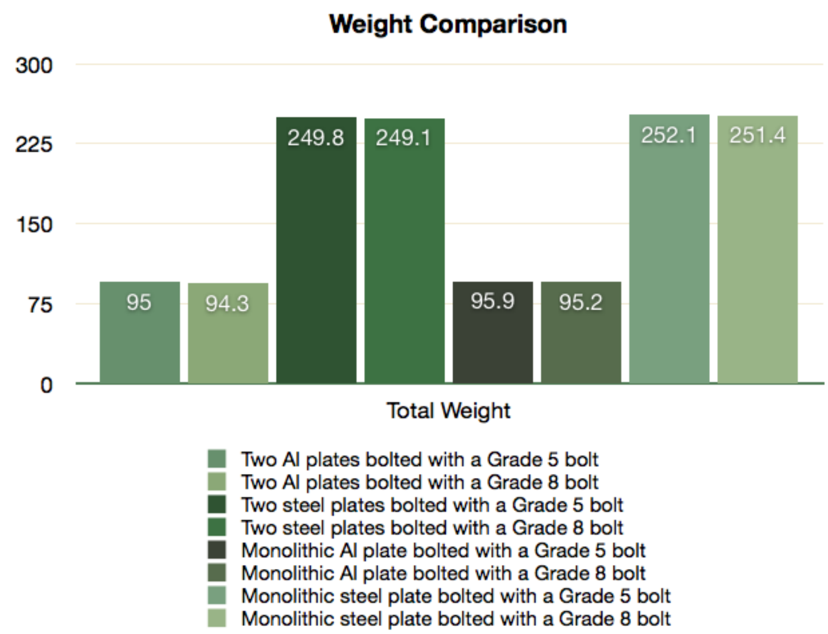


Figure A.1 Weight comparison for different sets of experiments

Appendix B: Test Results for Two Plates Bolted With a Single Bolt

Table B.1 Aluminum test plates with a Grade 8 bolt

Preload of % Yield Strength		1st Mode		2nd Mode		3rd Mode	
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
2%	1	116.9	0.81	323.1	0.62	655.8	0.22
	2	116.9	0.77	323.1	0.6	656	0.24
	3	116.9	0.81	323.1	0.62	656.2	0.24
	4	116.6	0.6	322.7	0.46	656.2	0.24
	5	116.6	0.64	322.7	0.51	655.8	0.24
	6	116.7	0.86	323.4	0.51	656.2	0.27
	7	116.7	0.81	323.8	0.48	657.4	0.22
	8	116.7	0.81	323.8	0.43	657.6	0.2
	9	116.5	0.64	325.6	0.52	657.6	0.24
	10	117.2	0.68	325.3	0.46	657.6	0.23
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
5%	1	117	0.6	325.6	0.41	657.2	0.18
	2	117.2	0.6	325.6	0.41	656.9	0.2
	3	117.2	0.55	325.8	0.52	657	0.2
	4	116.6	0.69	325.6	0.52	656.5	0.21
	5	116.6	0.73	325.6	0.52	657.1	0.22
	6	116.6	0.69	325.2	0.46	657.1	0.21
	7	117.3	0.68	325.2	0.45	656.2	0.22
	8	117.3	0.72	325.5	0.48	656.1	0.24
	9	117.2	0.68	325.5	0.51	656.7	0.18
	10	117.3	0.72	325.5	0.49	657.1	0.21
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
15%	1	118.8	0.63	328.4	0.37	658.9	0.13
	2	118.8	0.8	328.4	0.35	658.9	0.13
	3	118.8	0.8	328.4	0.35	658.3	0.18
	4	118.4	0.72	327.3	0.35	658.2	0.18
	5	118.4	0.72	327.5	0.4	658.5	0.2
	6	118.4	0.68	327.3	0.38	658	0.18
	7	118.4	0.68	327.3	0.37	659	0.14

Appendix B (Continued)

Table B.1 (Continued)

	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
27%	1	118.8	0.72	328.6	0.37	658.9	0.14
	2	118.9	0.71	328.6	0.33	658.8	0.14
	3	118.9	0.71	328.6	0.33	659	0.14
	4	118.6	0.72	327.2	0.43	658.9	0.21
	5	118.6	0.67	327.2	0.44	658.8	0.21
	6	118.6	0.76	327.2	0.46	658.7	0.2
	7	118.9	0.63	328.6	0.32	658.9	0.13
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
39%	1	118.6	0.55	328.6	0.27	659.6	0.14
	2	118.9	0.34	328.3	0.34	659.7	0.16
	3	118.9	0.34	328.1	0.37	659.8	0.14
	4	118.9	0.38	328.3	0.37	658.6	0.16
	5	118.9	0.63	328.3	0.32	659	0.17
	6	118.9	0.59	328.4	0.33	658.7	0.18
	7	118.9	0.59	328.4	0.33	659.3	0.14
	8	118.6	0.46	328.6	0.23	659.5	0.12
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
53%	1	118.9	0.5	328.3	0.4	659.1	0.15
	2	118.9	0.55	328.3	0.38	659.3	0.17
	3	118.9	0.55	328.3	0.38	659.2	0.17
	4	118.8	0.51	328.3	0.37	659.4	0.14
	5	118.8	0.51	328.3	0.37	659.5	0.15
	6	118.8	0.51	328.3	0.37	660	0.14
	7	118.9	0.5	328.3	0.38	658.9	0.17
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
68%	1	118.8	0.84	328.4	0.38	658.9	0.14
	2	118.8	0.88	328.4	0.4	659	0.16
	3	118.8	0.84	328.3	0.38	659.2	0.13
	4	118.6	0.46	328.1	0.37	659	0.17
	5	118.6	0.51	327.8	0.38	658.7	0.19
	6	118.6	0.51	327.7	0.38	658.7	0.17
	7	119.1	0.67	328.9	0.32	660.3	0.15
	8	119.1	0.71	328.8	0.32	660.6	0.14
	9	118.6	0.8	328.4	0.4	659.4	0.14

Appendix B (Continued)

Table B.2 Steel test plates with a Grade 5 bolt

Preload of % Yield Strength	No.	2nd Mode Frequency (Hz)	2nd Mode Damping (%)	3rd Mode Frequency (Hz)	3rd Mode Damping (%)
3%	1	347.8	0.36	696	0.15
	2	347.5	0.37	696	0.15
	3	347.5	0.36	695.8	0.16
	4	347.3	0.35	695.7	0.16
	5	347.6	0.4	695.8	0.16
	6	347.5	0.42	694.9	0.18
	7	347.8	0.4	695	0.18
	8	348.1	0.37	696.6	0.15
	9	349.6	0.33	696.5	0.15
	10	349.5	0.33	696.5	0.14
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
7%	1	349.7	0.24	696.7	0.12
	2	349.4	0.26	696.7	0.12
	3	349.7	0.26	696.9	0.14
	4	347.6	0.27	696.9	0.16
	5	347.6	0.27	696.4	0.072
	6	348.8	0.24	696.4	0.079
	7	348.9	0.24	695.9	0.14
	8	348.9	0.33	695.9	0.14
	9	348.9	0.33	696.9	0.1
	10	350.6	0.26	696.9	0.11
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
21%	1	350.7	0.21	698.5	0.1
	2	350.8	0.21	698.4	0.1
	3	350.8	0.21	698.5	0.1
	4	350.6	0.3	698.3	0.1
	5	350.6	0.26	698.3	0.1
	6	350.4	0.26	698.2	0.1
	7	351.1	0.2	698.1	0.086
	8	351.1	0.19	698.1	0.079
	9	351	0.23	697.2	0.11
	10	351.1	0.21	697.1	0.11

Appendix B (Continued)

Table B.2 (Continued)

	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
34%	1	351.9	0.19	698	0.086
	2	351.9	0.19	698	0.086
	3	351.1	0.24	697.9	0.086
	4	351.2	0.23	698.1	0.1
	5	350.1	0.27	698	0.1
	6	350.2	0.27	698	0.1
	7	351.4	0.26	698.2	0.093
	8	351.5	0.24	698.2	0.093
	9	351.9	0.19	698.4	0.072
	10	351.9	0.19	697.7	0.086
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
55%	1	351.8	0.21	698.1	0.093
	2	351.8	0.21	698.1	0.093
	3	351.8	0.21	698.5	0.093
	4	351.5	0.26	698.5	0.093
	5	351.4	0.27	698.2	0.086
	6	350.6	0.21	698.2	0.086
	7	350.8	0.19	698.2	0.086
	8	350.6	0.2	698.2	0.079
	9	351.9	0.19	698.5	0.1
	10	351.9	0.2	698.6	0.1
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
75%	1	351.9	0.21	698.4	0.086
	2	351.9	0.21	698.4	0.086
	3	351	0.23	698.1	0.093
	4	351.1	0.23	698.1	0.093
	5	352.1	0.28	698.6	0.11
	6	352	0.26	698.6	0.1
	7	352.2	0.27	698.4	0.1
	8	352.1	0.26	698.8	0.11
	9	352.1	0.26	698.8	0.11
	10	352	0.26	698.8	0.11

Appendix B (Continued)

Table B.2 (Continued)

	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
96%	1	351.2	0.23	698.1	0.093
	2	351.1	0.21	698.1	0.1
	3	351.1	0.23	698.1	0.093
	4	352.5	0.17	698.8	0.079
	5	352.4	0.17	698.8	0.079
	6	352.6	0.23	698.5	0.1
	7	352.6	0.23	698.5	0.11
	8	352.1	0.21	698.8	0.093
	9	352.1	0.2	698.8	0.086
	10	352.7	0.17	698.9	0.086

Appendix B (Continued)

Table B.3 Steel test plates with a Grade 8 bolt

Preload of % Yield Strength		1st Mode		2nd Mode		3rd Mode	
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
2%	1	125.6	0.44	348.1	0.32	694.1	0.17
	2	125.6	0.44	348.1	0.33	694.1	0.17
	3	125.6	0.44	348.1	0.3	694.1	0.16
	4	125.6	0.44	348.1	0.32	694.2	0.16
	5	125.8	0.6	348.6	0.36	695	0.18
	6	125.8	0.64	348.6	0.37	694.9	0.17
	7	125.8	0.6	348.6	0.36	694.9	0.17
	8	125.3	0.92	348	0.32	695.1	0.17
	9	125.3	1	348	0.32	694.9	0.17
	10	125.3	0.96	348	0.32	694.8	0.17
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
5%	1	128.1	0.47	350.6	0.24	698.8	0.11
	2	128	0.55	350.5	0.26	697.6	0.1
	3	128.1	0.55	350.6	0.24	697.6	0.1
	4	127.2	0.63	350	0.47	697.6	0.1
	5	127	0.35	349.7	0.51	697.6	0.12
	6	127	0.31	349.7	0.34	697.4	0.14
	7	128.4	0.93	348.6	0.33	697.5	0.14
	8	128.3	0.82	348.8	0.32	697.7	0.14
	9	128.3	0.97	348.8	0.33	697.6	0.14
	10	127.3	0.47	349.5	0.34	697.7	0.13
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
15%	1	128.6	0.31	352.2	0.23	698.8	0.1
	2	128.6	0.35	352	0.23	698.8	0.1
	3	128.6	0.35	352	0.21	698.8	0.1
	4	128.8	0.35	351.1	0.26	698.8	0.1
	5	128.6	0.31	350.9	0.27	698.8	0.1
	6	128.6	0.31	351.1	0.26	698.8	0.1
	7	128.6	0.35	350.9	0.26	698.8	0.093
	8	128.4	0.39	351.7	0.26	699	0.086
	9	128.4	0.43	351.7	0.24	699	0.086
	10	128.4	0.39	351.7	0.26	699	0.093

Appendix B (Continued)

Table B.3 (Continued)

	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
27%	1	128.8	0.23	351.9	0.31	698.8	0.11
	2	128.8	0.23	352.2	0.33	698.9	0.11
	3	128.8	0.23	352	0.26	698.8	0.11
	4	128.4	0.35	351.2	0.21	698.8	0.11
	5	128.6	0.35	351.2	0.2	698.8	0.11
	6	128.6	0.31	351.2	0.23	698.8	0.11
	7	128.1	0.86	351.6	0.3	698.8	0.11
	8	128.8	0.5	352.5	0.23	699.1	0.079
	9	128.8	0.5	352.5	0.24	699	0.11
	10	128.8	0.5	352.5	0.23	699	0.1
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
39%	1	128.6	0.23	352.3	0.26	698.9	0.086
	2	128.6	0.27	352.2	0.24	698.9	0.079
	3	128.6	0.27	352.3	0.27	698.9	0.093
	4	128.1	0.39	351.1	0.36	698.5	0.1
	5	128.3	0.39	351.2	0.31	698.5	0.1
	6	128.1	0.39	351.1	0.36	698.5	0.093
	7	128.1	0.39	351.2	0.3	698.2	0.11
	8	128.1	0.43	351.4	0.33	698.1	0.11
	9	128.9	0.85	352.8	0.17	699.3	0.086
	10	128.8	0.78	352.8	0.17	699.3	0.086
	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
53%	1	128.4	0.31	351.6	0.28	698.8	0.1
	2	128.3	0.39	351.4	0.26	698.8	0.1
	3	128.3	0.43	351.2	0.26	698.8	0.1
	4	128.3	0.31	352.7	0.24	699.1	0.093
	5	128.3	0.47	352.7	0.24	699.1	0.086
	6	128.8	0.62	351.2	0.26	698.4	0.086
	7	128.8	0.54	351.7	0.24	698.4	0.086
	8	129.2	0.46	353	0.18	699.4	0.079
	9	129.2	0.46	353	0.18	699.4	0.079
	10	129.2	0.46	353	0.18	699.4	0.079

Appendix B (Continued)

Table B.3 (Continued)

	No.	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
68%	1	128.6	0.47	352.2	0.27	698.8	0.1
	2	128.4	0.43	351.9	0.26	698.8	0.1
	3	128.4	0.47	352	0.26	698.8	0.093
	4	128.6	0.47	351.9	0.24	698.8	0.1
	5	128.8	0.54	351.9	0.31	698.7	0.079
	6	128.8	0.54	351.9	0.31	698.8	0.079
	7	128.4	0.55	351.9	0.31	698.8	0.086
	8	129.4	0.31	353.1	0.21	699.2	0.1
	9	129.4	0.31	353.1	0.2	699.1	0.093
	10	129.4	0.31	353.1	0.21	699.2	0.1

Appendix C: Geometric Dimension and Tolerance Drawings of Test Plates

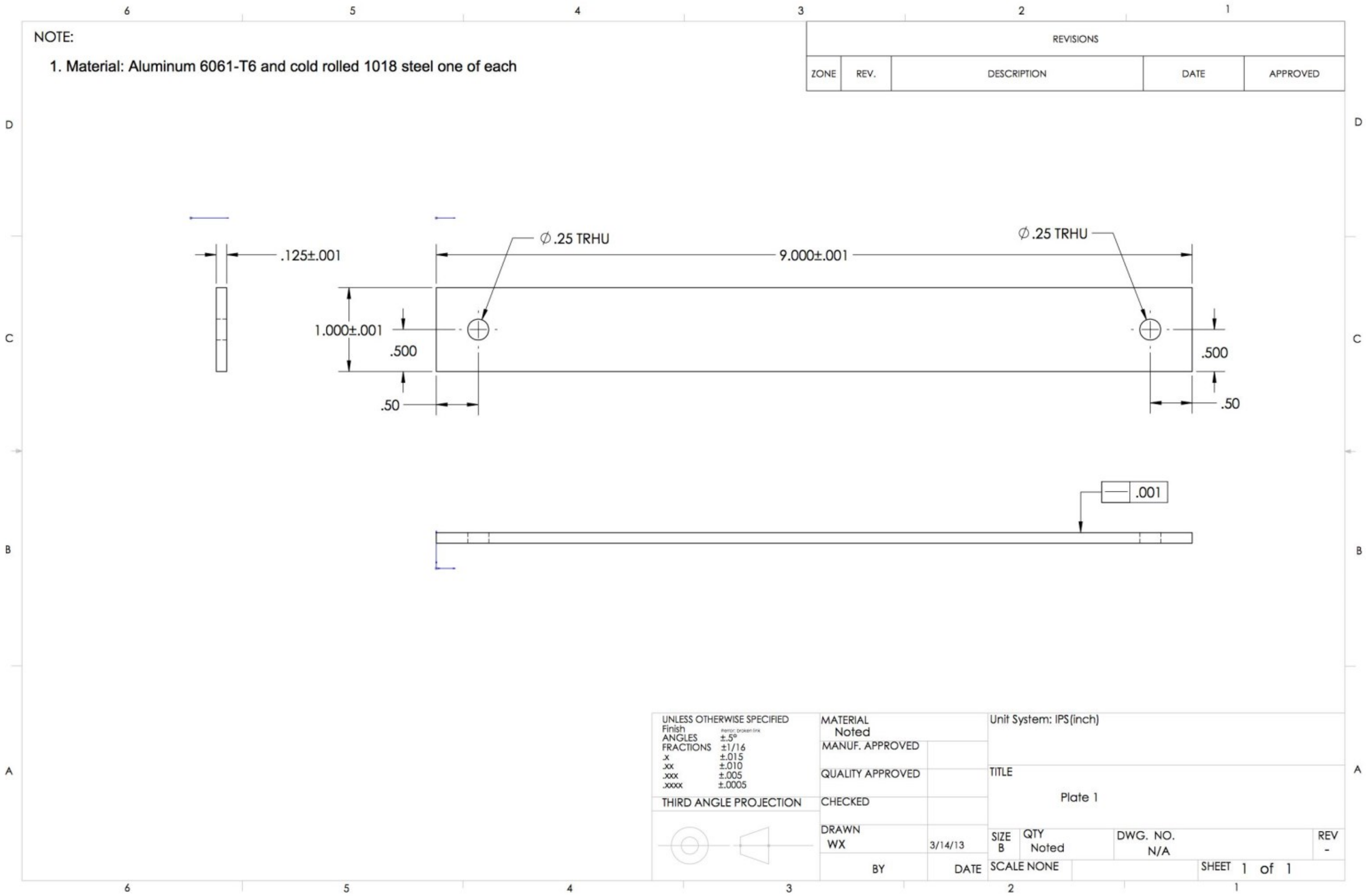


Figure C.1 Geometric dimension and tolerance for plate 1

Appendix C (Continued)

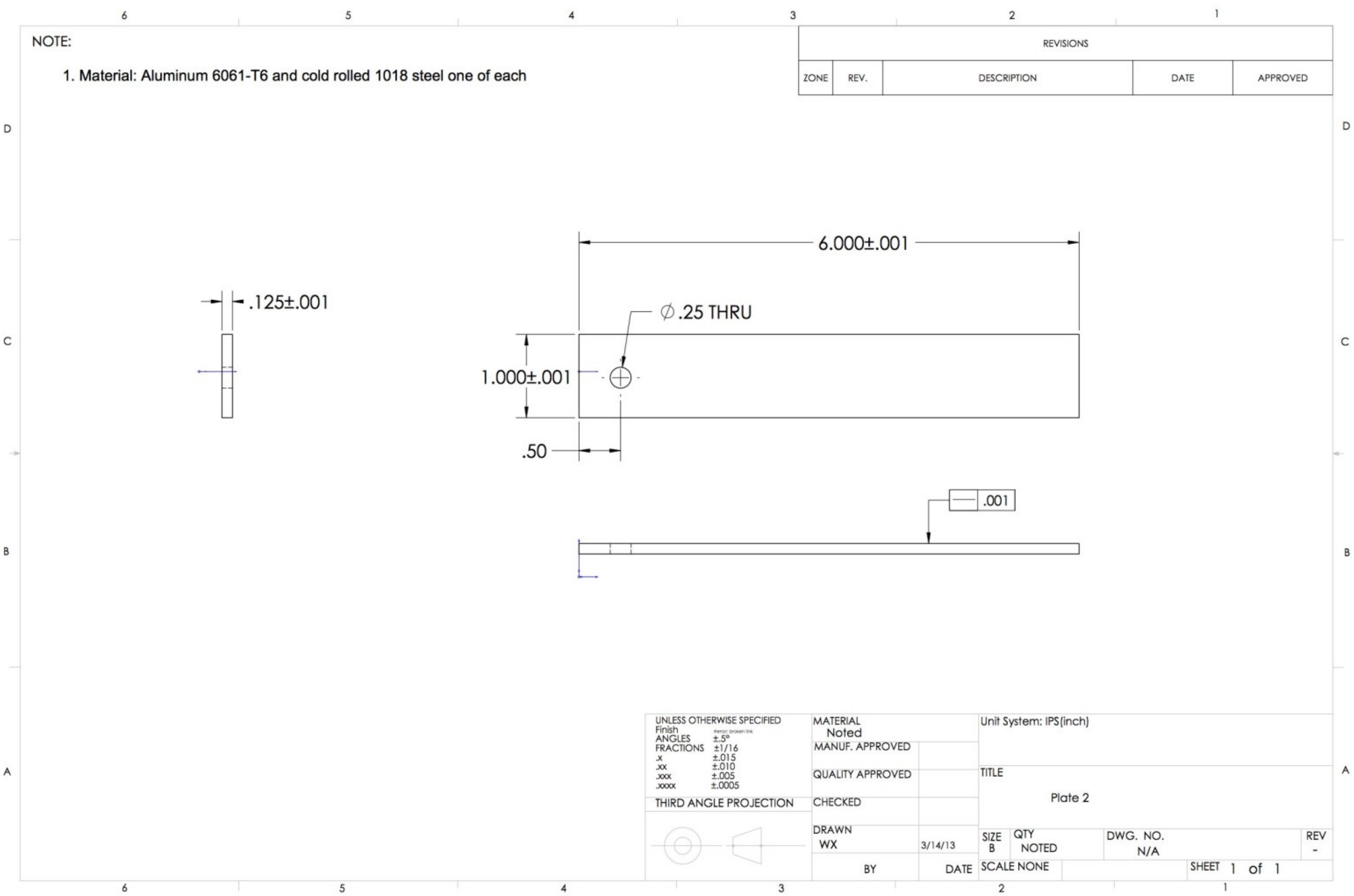


Figure C.2 Geometric dimension and tolerance for plate 2

Appendix C (Continued)

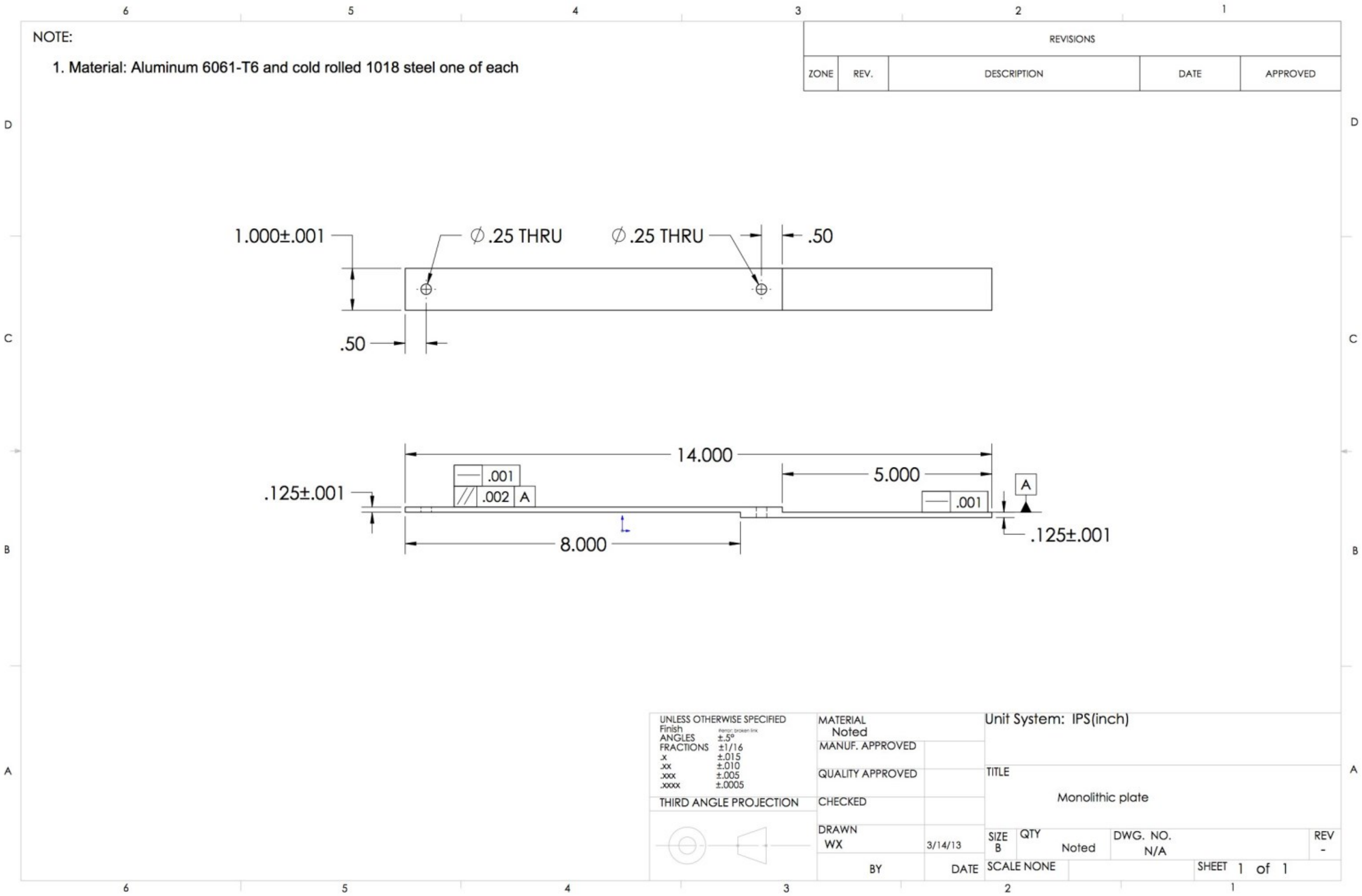


Figure C.3 Geometric dimension and tolerance for monolithic plate

Appendix D: Aluminum and Steel Scatter Plots

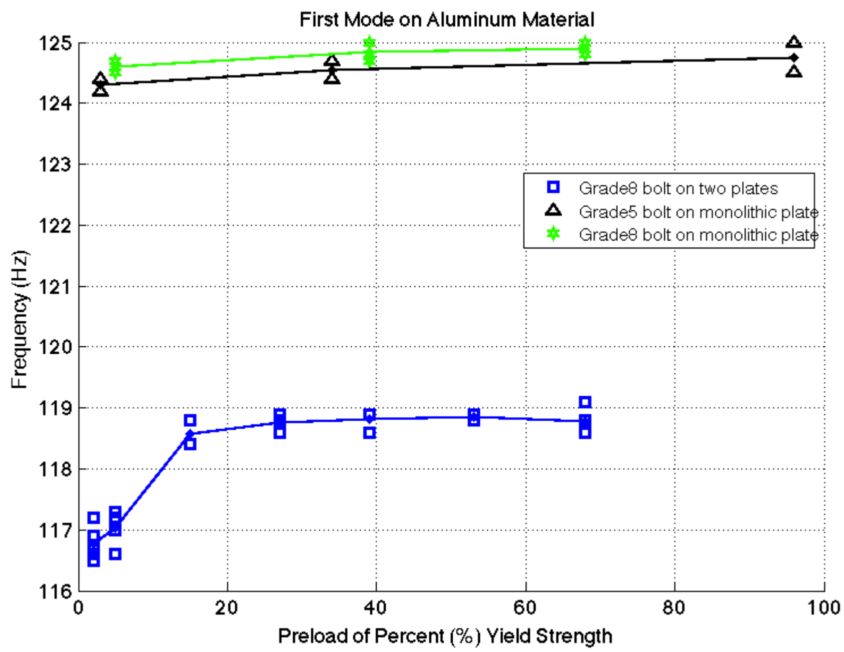


Figure D.1 All aluminum – modal frequency versus preload on Vibration Mode 1

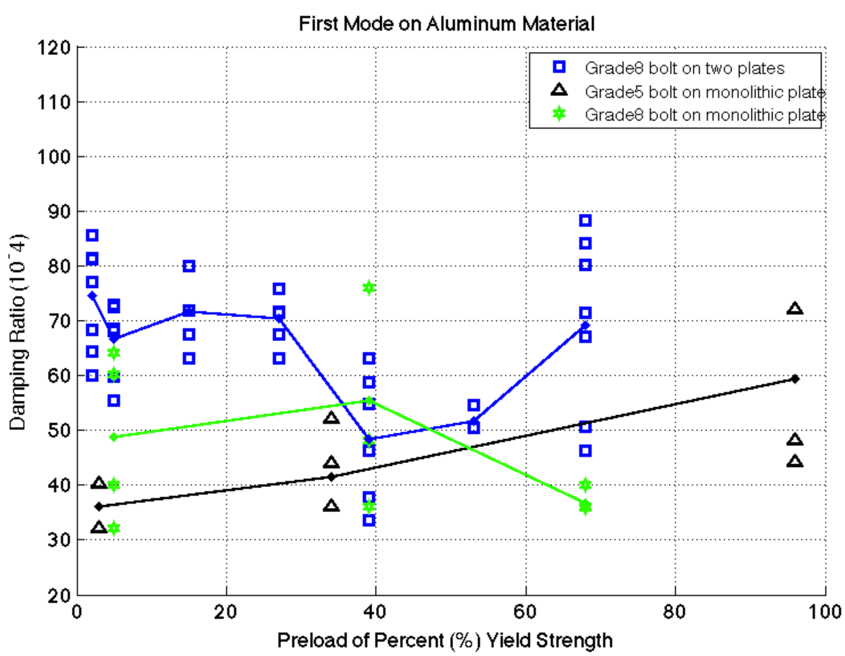


Figure D.2 All aluminum – modal damping versus preload on Vibration Mode 1

Appendix D (Continued)

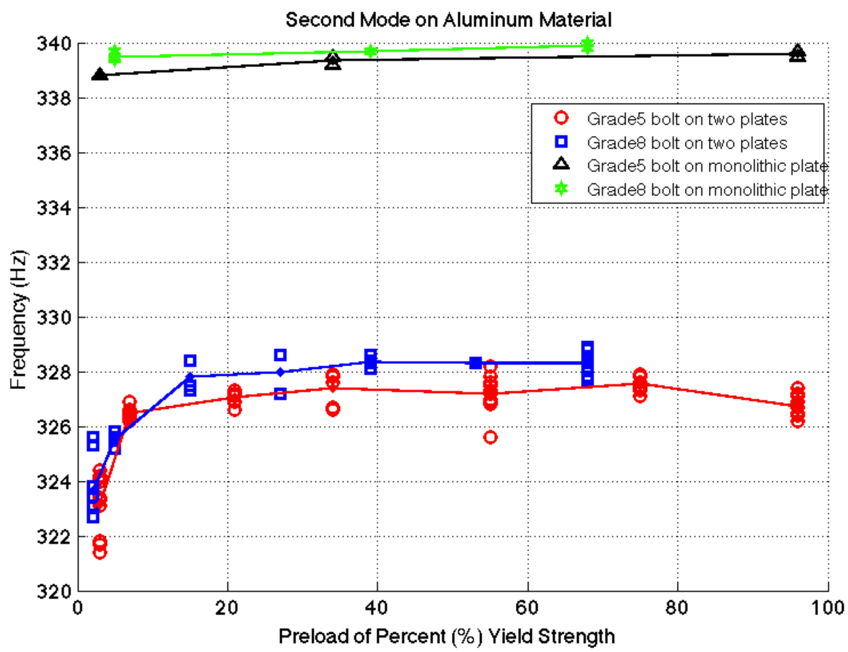


Figure D.3 All aluminum – modal frequency versus preload on Vibration Mode 2

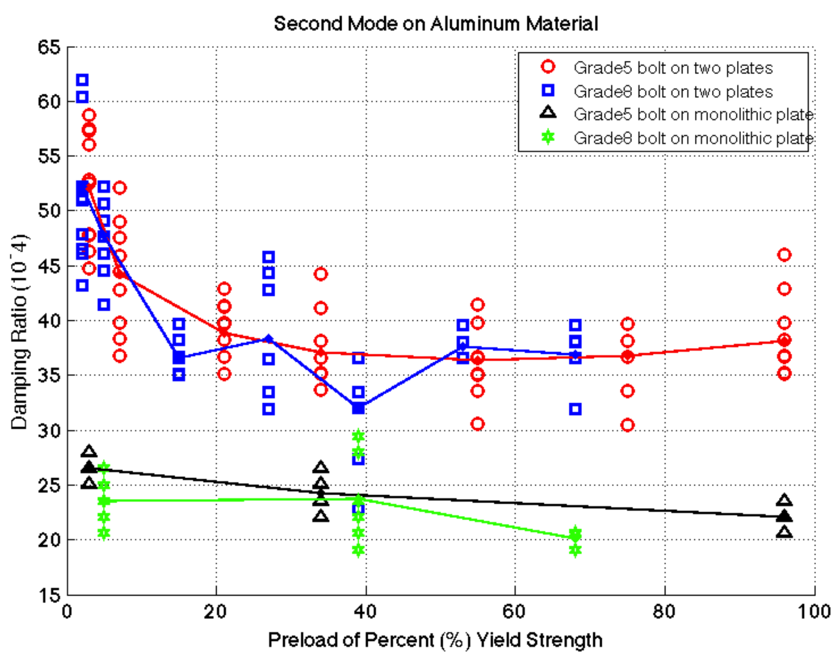


Figure D.4 All aluminum – modal damping versus preload on Vibration Mode 2

Appendix D (Continued)

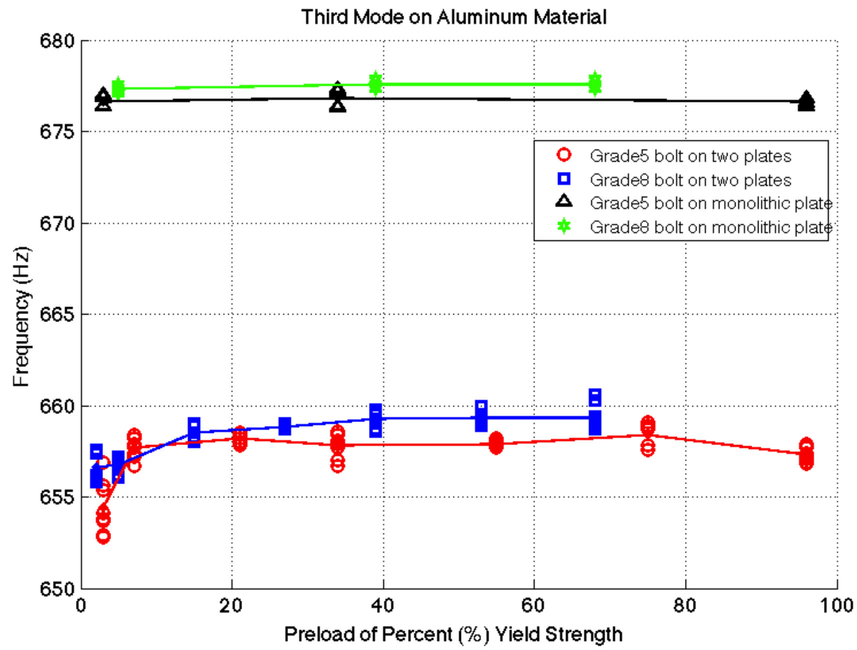


Figure D.5 All aluminum – modal frequency versus preload on Vibration Mode 3

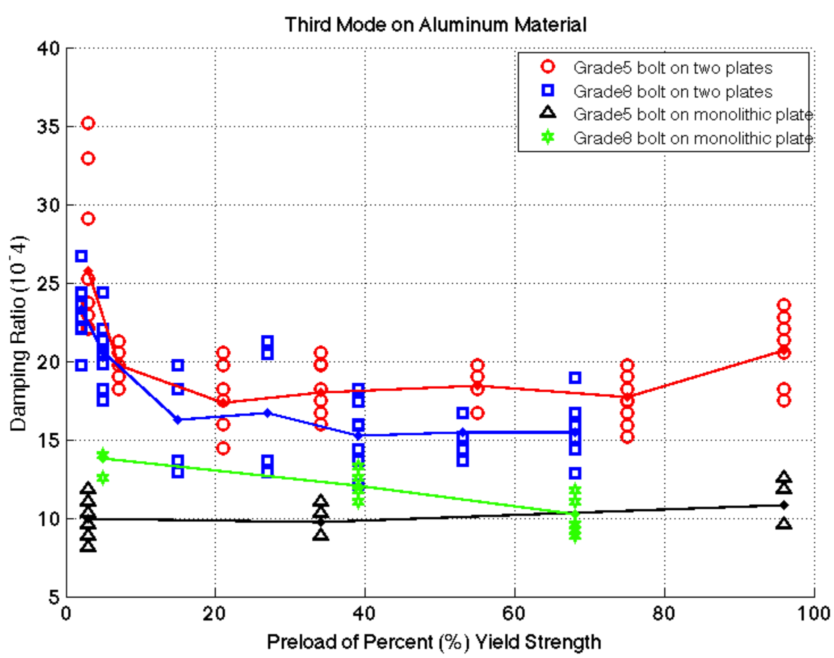


Figure D.6 All aluminum – modal damping versus preload on Vibration Mode 3

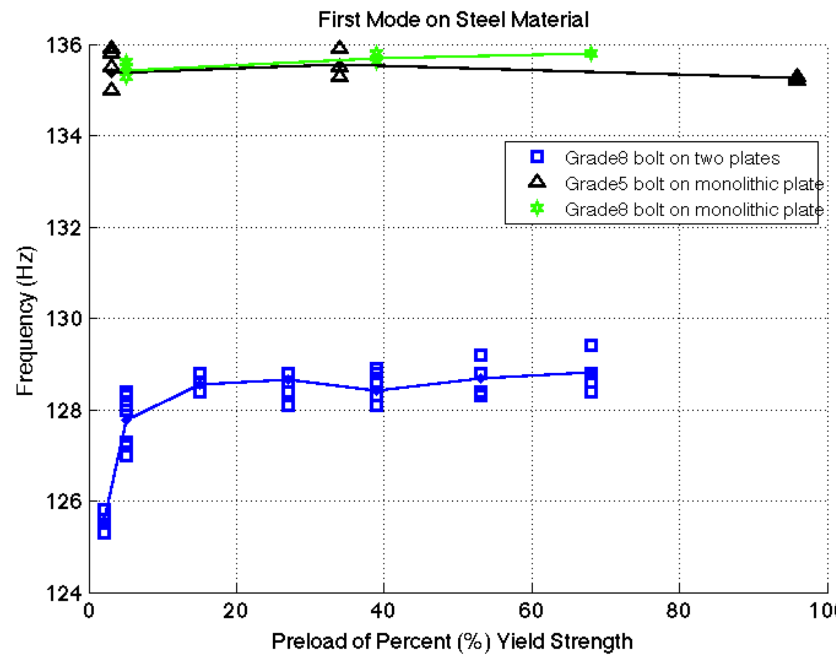


Figure D.7 All steel– modal frequency versus preload on Vibration Mode 1

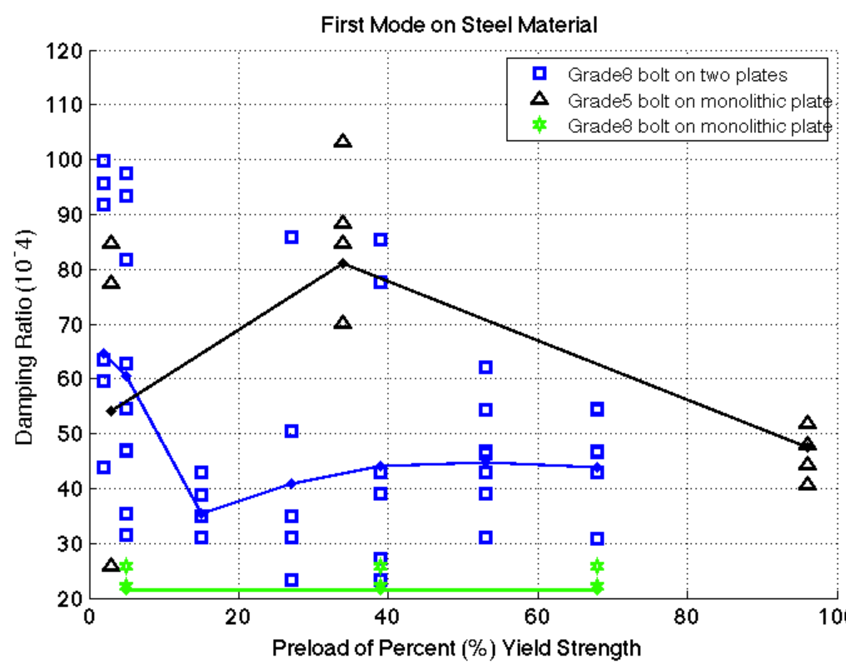


Figure D.8 All steel– modal damping versus preload on Vibration Mode 1

Appendix D (Continued)

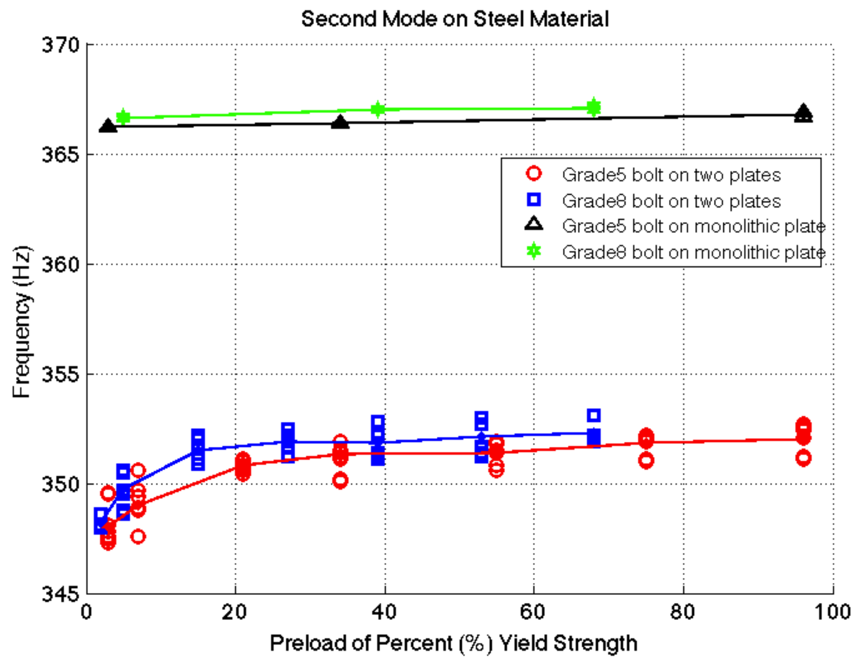


Figure D.9 All steel– modal frequency versus preload on Vibration Mode 2

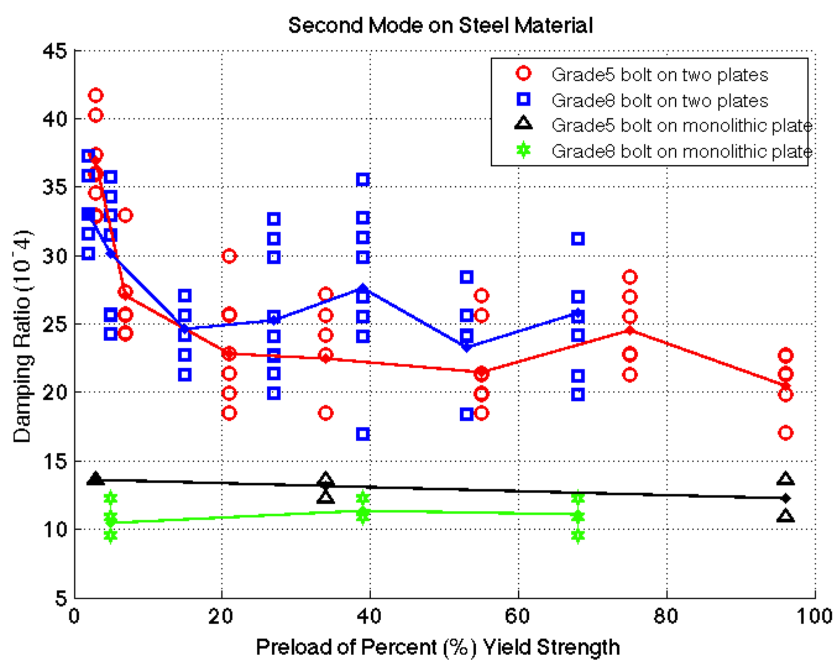


Figure D.10 All steel– modal damping versus preload on Vibration Mode 2

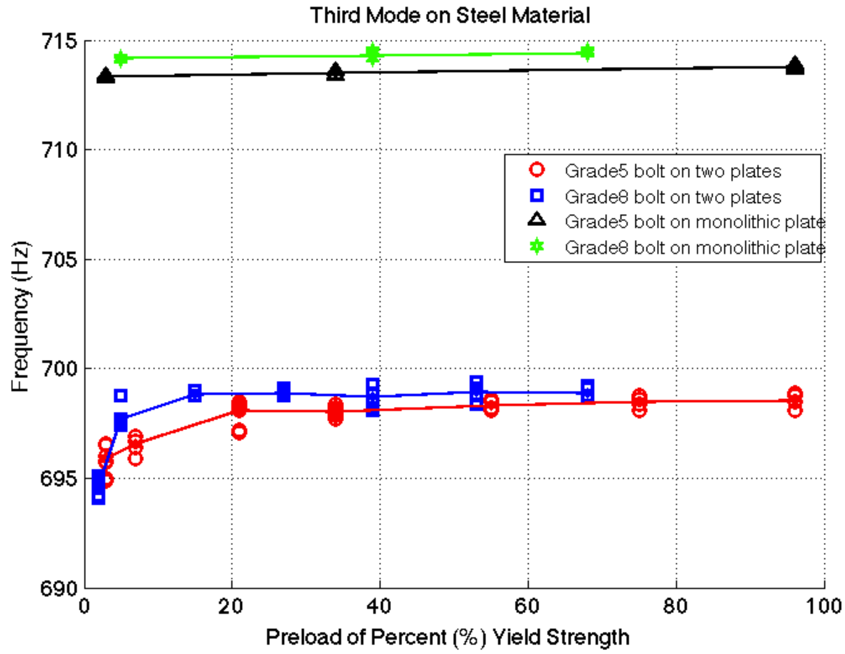


Figure D.11 All steel– modal frequency versus preload on Vibration Mode 3

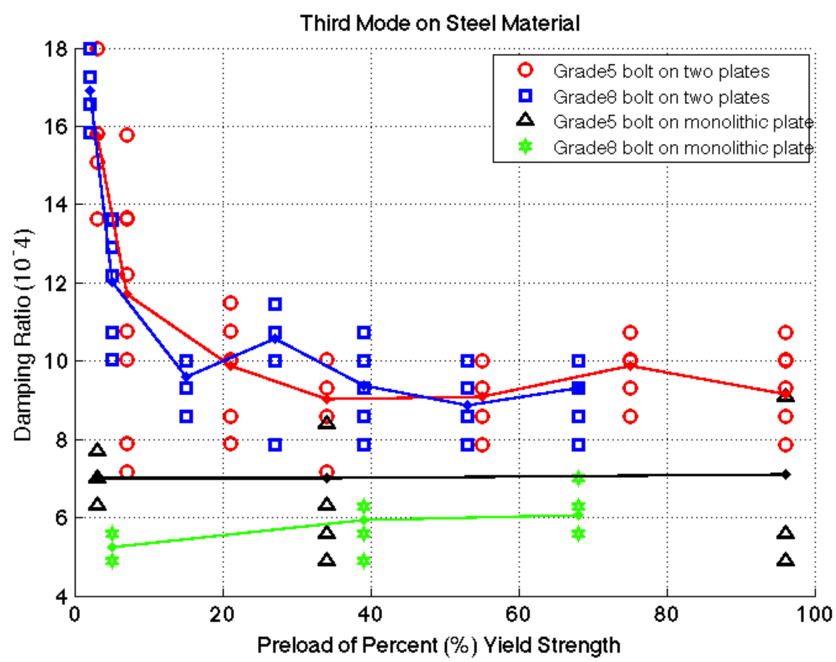


Figure D.12 All steel– modal damping versus preload on Vibration Mode 3

Appendix E: ANOVA Analysis

This section provides the results from the one-way analysis of variance (ANOVA) for the preload levels of 75% and 96% in bolt yield strength for aluminum test plates bolted with a Grade 5 bolt. The following ANOVA tables contain the following information:

- DF = Degrees of freedom
- SS = The sum of the squares
- Mean Square = mean squared deviations from the mean
- F Value = The ratio of the mean squares
- Prob > F = The probability value under the assumption (the null hypothesis) that all samples from the groups have an equal mean. If the probability is almost zero, the null hypothesis is false, and at least one group's mean is different from the others. The common significance levels are 0.05 or 0.01. In this thesis, the significance level of 0.01 is chosen. Thus, if the p-value of this analysis is found less than 0.01, the means from the two preload levels are significantly different from each other. If the p-value of this analysis if found larger than 0.01, the means from these two preload levels are equal.

The results show that the frequency and the damping ratios from these two preload levels were significantly different from each other, except for the means from the second modal damping ratios of 75% and 96% in bolt yield strength for aluminum test plates bolted with a Grade 5 bolt.

The results show that the frequency and the damping ratios from these two preload levels were significantly different from each other, except for the means from the second modal damping ratios of 75% and 96% in bolt yield strength for aluminum test plates bolted with a Grade 5 bolt.

There is a 0.0001 chance that the means from those two preload levels are the same. The ANOVA Table for this calculation is provided in Table E.1. Alternatively, there is a 99.99% chance that the second modal frequencies for preloads of 75% and 96% in bolt yield strength in aluminum test plates bolted with a Grade 5 bolt case were significantly different due to the applied preload. The distribution of frequency of second modal frequency data for preloads of 75% and 96% in bolt yield strength is presented in Figure E.1.

Table E.1 The ANOVA Table of second modal frequency data for preloads of 75% and 96% in bolt yield strength

Source	DF	SS	Mean Square	F Value	Prob > F
Preload	1	3.61250000	3.61250000	31.92	< 0.0001

Appendix E (Continued)

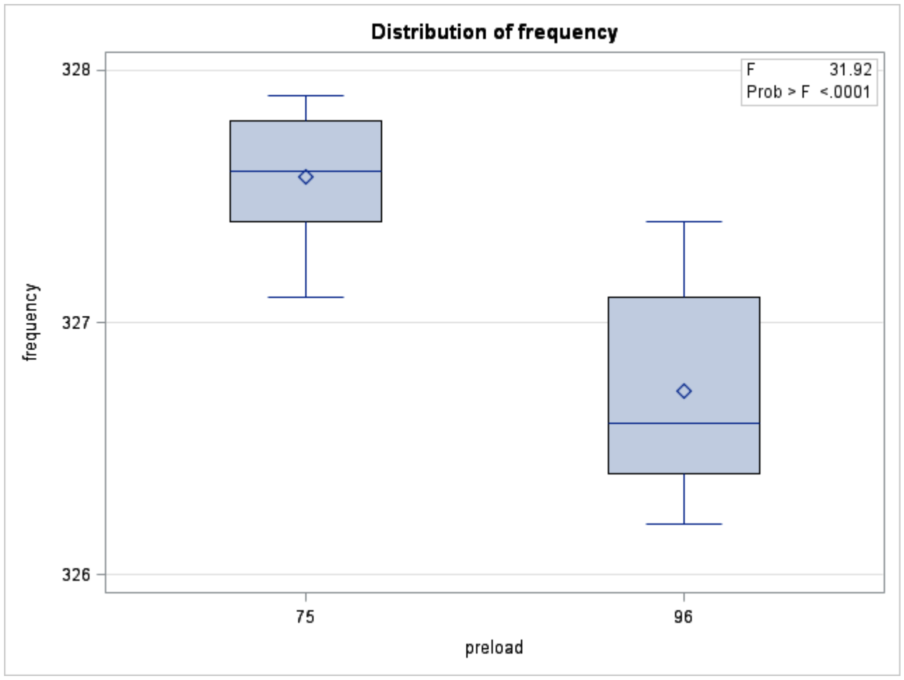


Figure E.1 Distribution of frequency of second modal frequency data for preloads of 75% and 96% in bolt yield strength

There is a 0.0003 chance that the means from those two preload levels are the same. The ANOVA Table for this calculation is provided in Table E.2. Alternatively, there is a 99.97% chance that the third modal frequencies for preloads of 75% and 96% in bolt yield strength in aluminum test plates bolted with a Grade 5 bolt case were significantly different due to the applied preload. The distribution of frequency of third modal frequency data for preloads of 75% and 96% in bolt yield strength is provided in Figure E.2.

Table E.2 The ANOVA Table of third modal frequency data for preloads of 75% and 96% in bolt yield strength

Source	DF	SS	Mean Square	F Value	Prob > F
Preload	1	5.72450000	5.72450000	19.97	0.0003

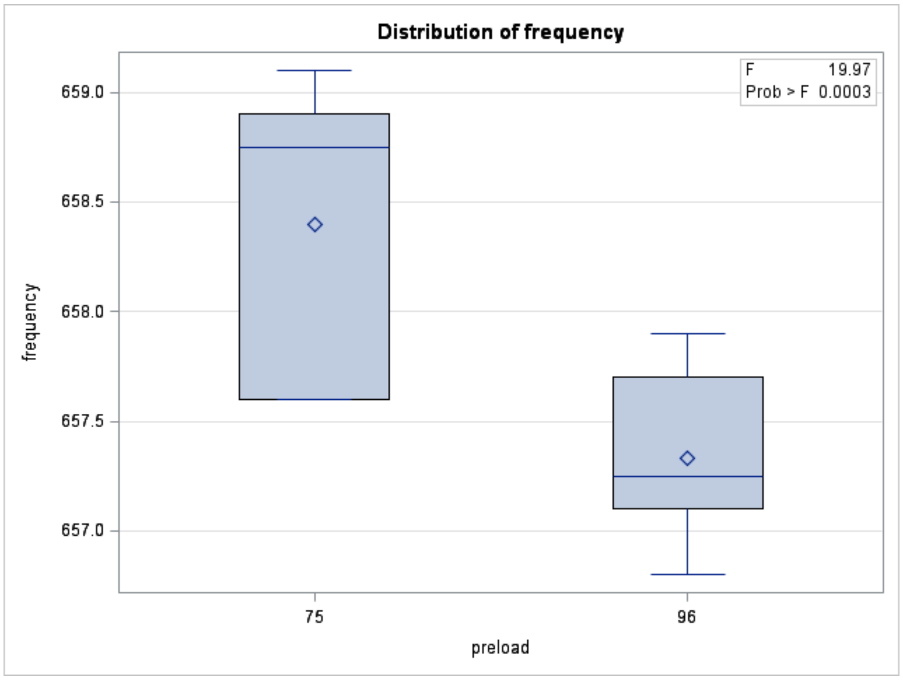


Figure E.2 Distribution of frequency of third modal frequency data for preloads of 75% and 96% in bolt yield strength

There is a 0.3846 chance that the means from those two preload levels are the same. The ANOVA Table for this calculation is provided in Table E.3. Alternatively, there is only a 61.54% chance that the second modal damping ratios for preloads of 75% and 96% in bolt yield strength in aluminum test plates bolted with a Grade 5 bolt case were significantly different due to the applied preload. The p-value here is larger than 0.01, so the means of damping ratios from these two preload levels are considered to be equal. The distribution of damping of second modal frequency data for preloads of 75% and 96% in bolt yield strength is presented in Figure E.3.

Appendix E (Continued)

Table E.3 The ANOVA Table of second modal damping data for preloads of 75% and 96% in bolt yield strength

Source	DF	SS	Mean Square	F Value	Prob > F
Preload	1	8.74388071	8.74388071	0.79	0.3846

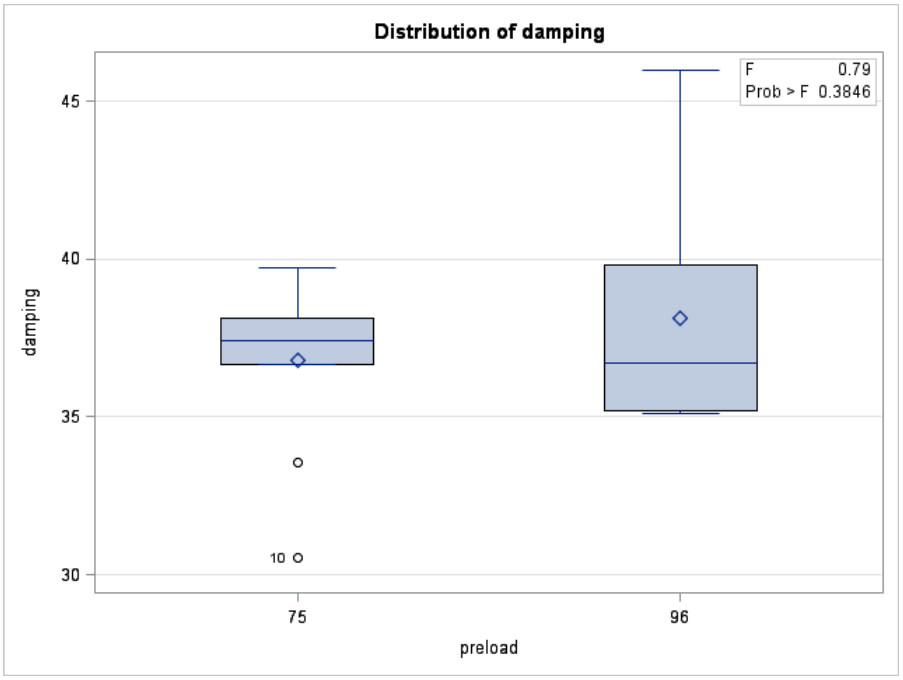


Figure E.3 Distribution of damping of second modal frequency data for preloads of 75% and 96% in bolt yield strength

There is a 0.0018 chance that the means from those two preload levels are the same. The ANOVA Table for this calculation is provided in Table E.4. Alternatively, there is a 99.82% chance that the third modal damping ratios for preloads of 75% and 96% in bolt yield strength in aluminum test plates bolted with a Grade 5 bolt case were significantly different due to the applied preload. The distribution of damping of third modal frequency data for preloads of 75% and 96% in bolt yield strength is provided in Figure E.4.

Appendix E (Continued)

Table E.4 The ANOVA Table of third modal damping data for preloads of 75% and 96% in bolt yield strength

Source	DF	SS	Mean Square	F Value	Prob > F
Preload	1	44.87157176	44.87157176	13.44	0.0018

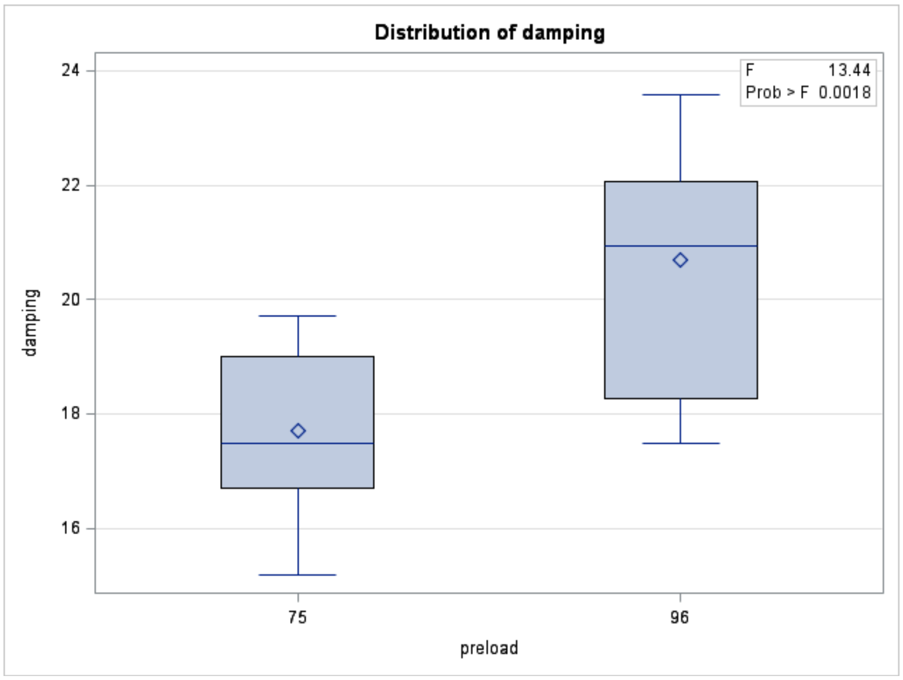


Figure E.4 Distribution of damping of third modal frequency data for preloads of 75% and 96% in bolt yield strength

Appendix F: Test Data Box Plots

F.1 Aluminum Plates Bolted With a Grade 5 Bolt

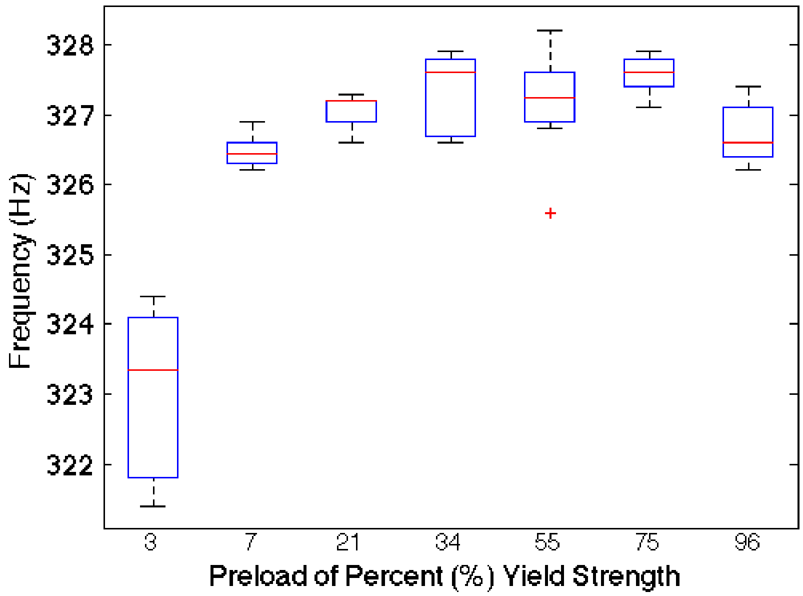


Figure F.1 Distribution of frequency for Al plates with a Grade 5 bolt on Mode 2

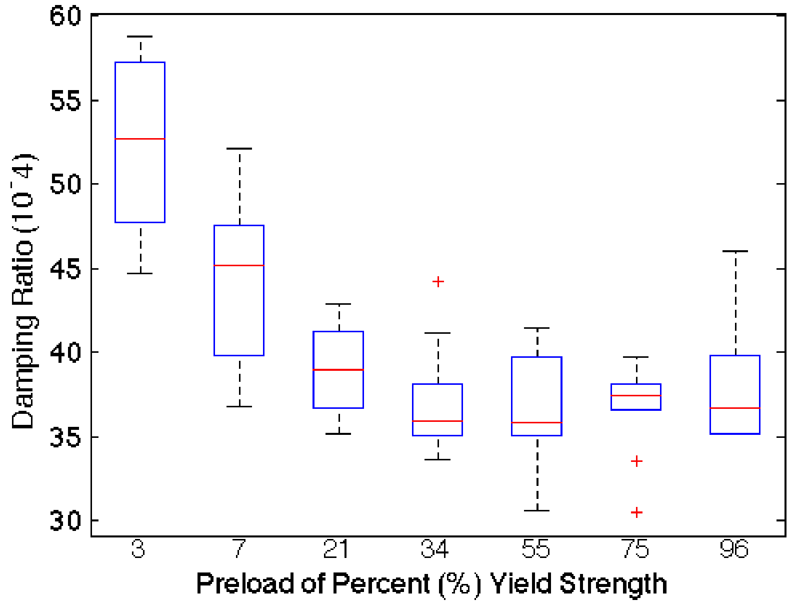


Figure F.2 Distribution of damping for Al plates with a Grade 5 bolt on Mode 2

Appendix F (Continued)

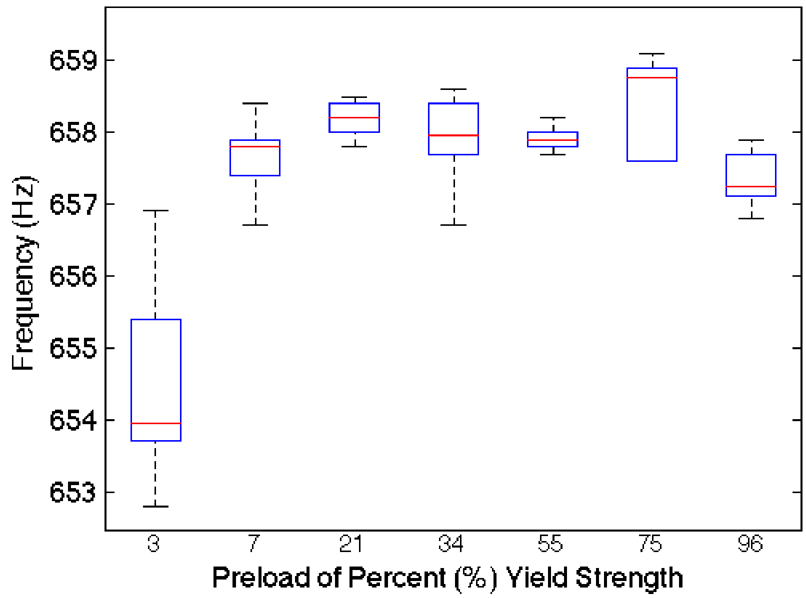


Figure F.3 Distribution of frequency for Al plates with a Grade 5 bolt on Mode 3

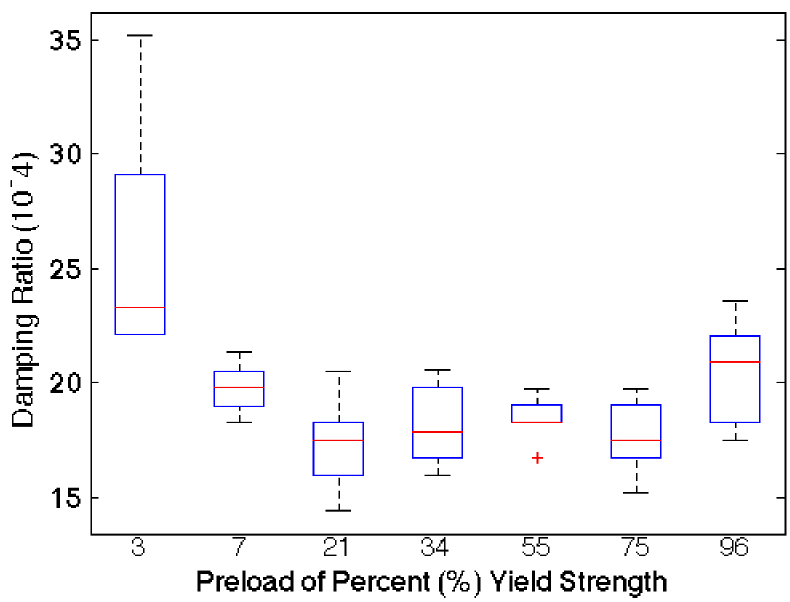


Figure F.4 Distribution of damping for Al plates with a Grade 5 bolt on Mode 3

Appendix F (Continued)

F.2 Aluminum Plates Bolted With a Grade 8 Bolt

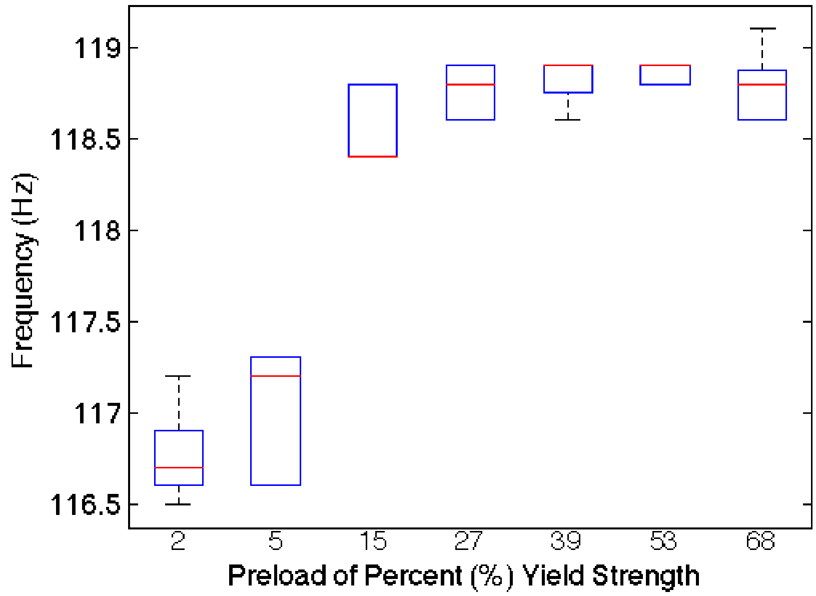


Figure F.5 Distribution of frequency for Al plates with a Grade 8 bolt on Mode 1

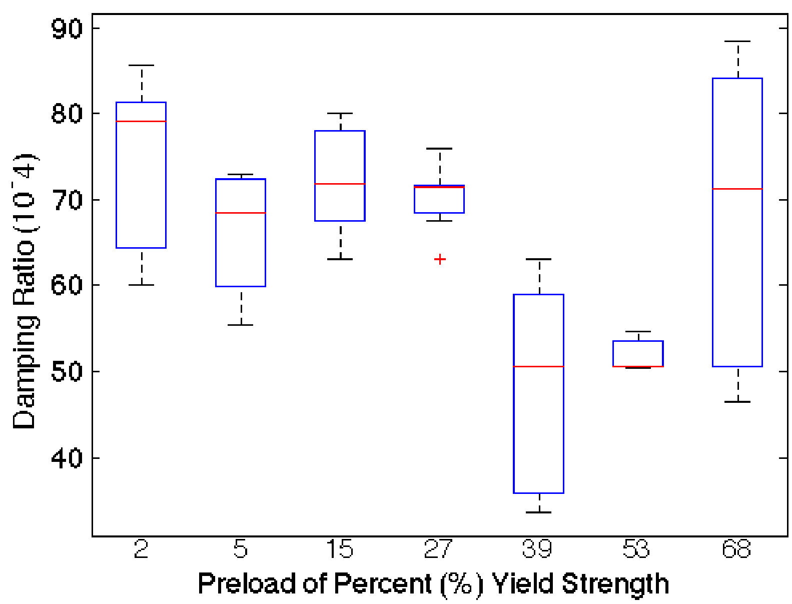


Figure F.6 Distribution of damping for Al plates with a Grade 8 bolt on Mode 1

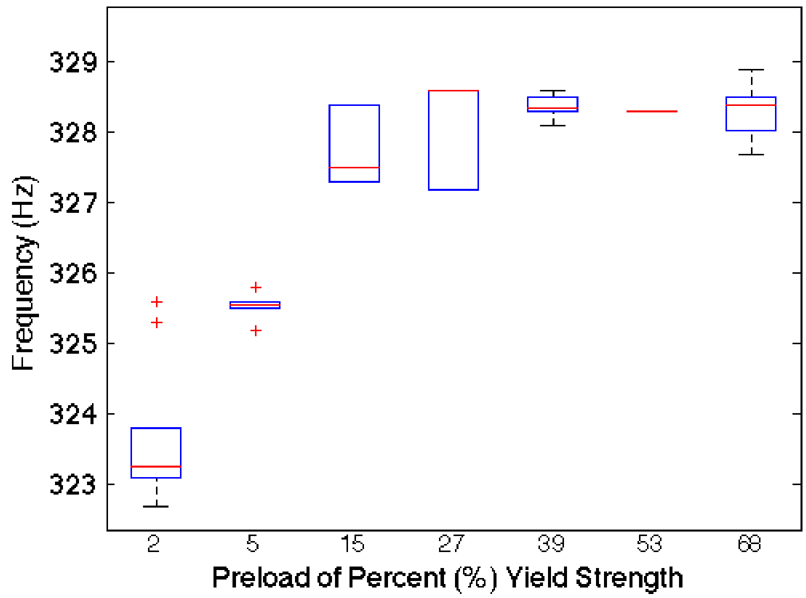


Figure F.7 Distribution of frequency for Al plates with a Grade 8 bolt on Mode 2

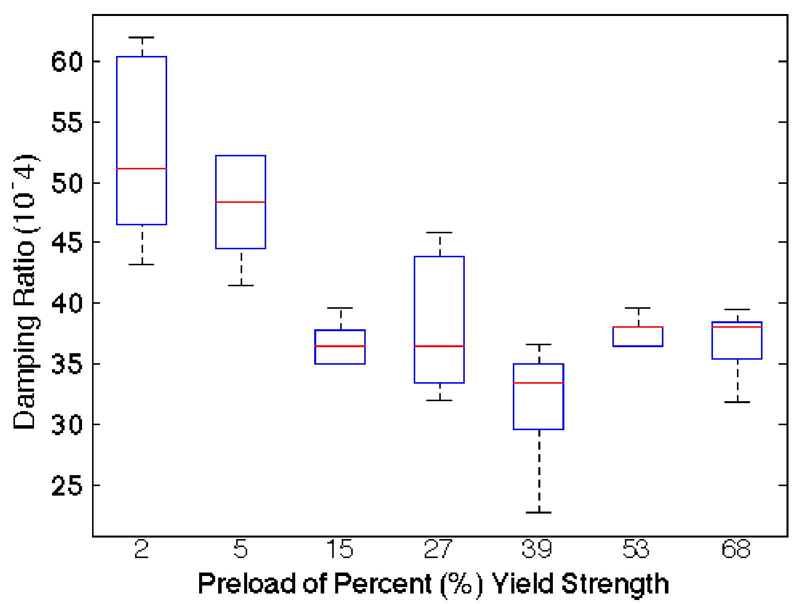


Figure F.8 Distribution of damping for Al plates with a Grade 8 bolt on Mode 2

Appendix F (Continued)

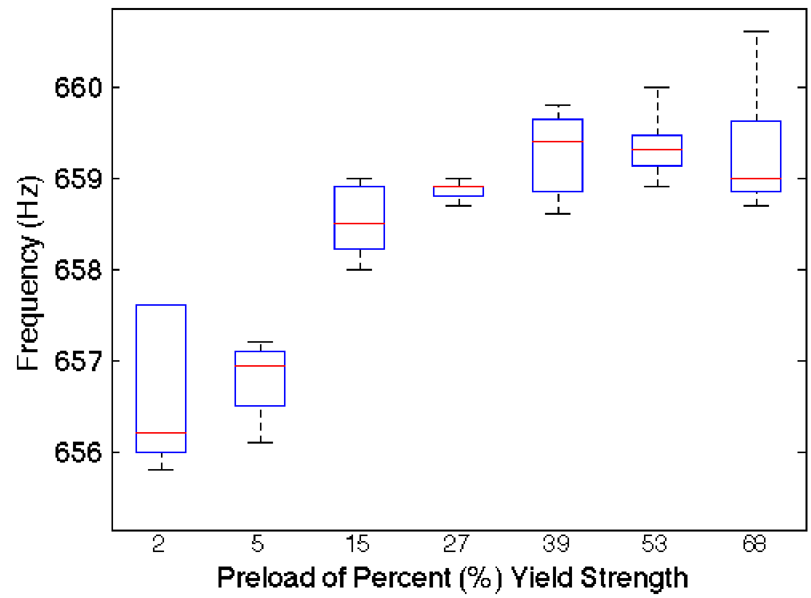


Figure F.9 Distribution of frequency for Al plates with a Grade 8 bolt on Mode 3

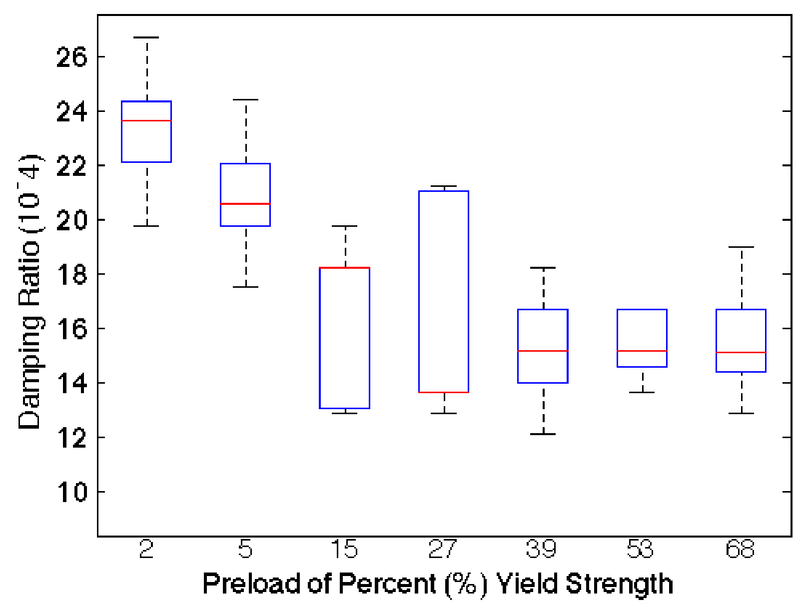


Figure F.10 Distribution of damping for Al plates with a Grade 8 bolt on Mode 3

F.3 Steel Plates Bolted With a Grade 5 Bolt

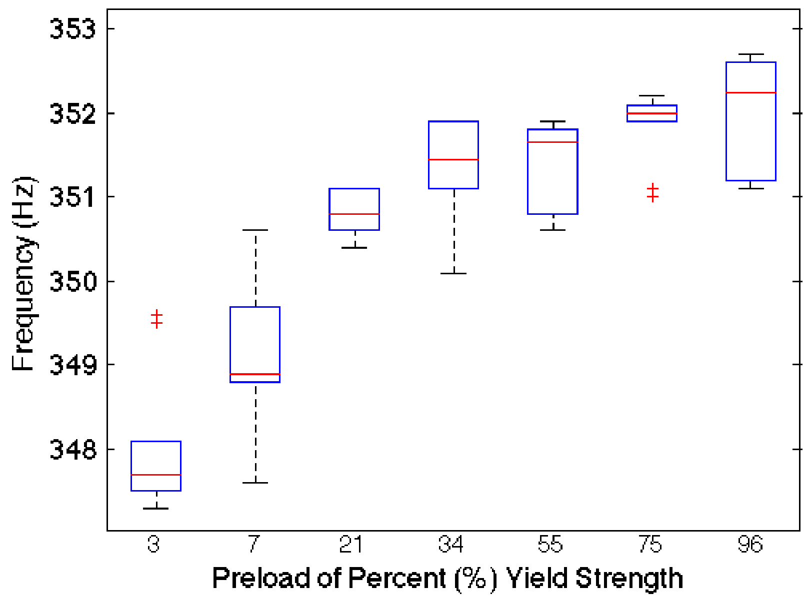


Figure F.11 Distribution of frequency for steel plates with a Grade 5 bolt on Mode 2

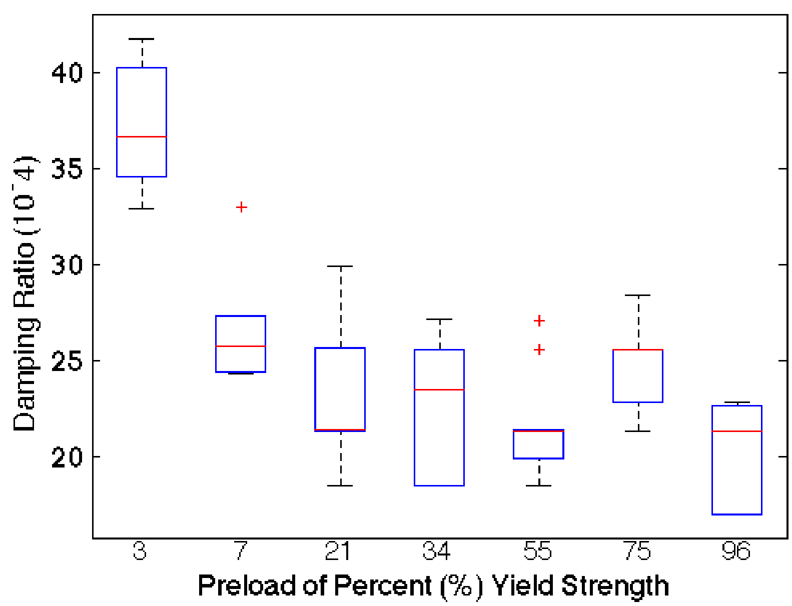


Figure F.12 Distribution of damping for steel plates with a Grade 5 bolt on Mode 2

Appendix F (Continued)

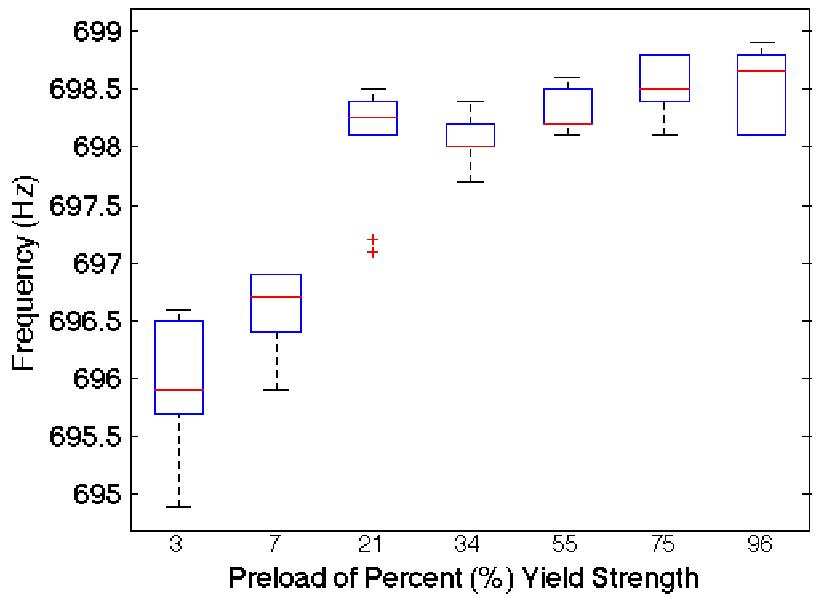


Figure F.13 Distribution of frequency for steel plates with a Grade 5 bolt on Mode 3

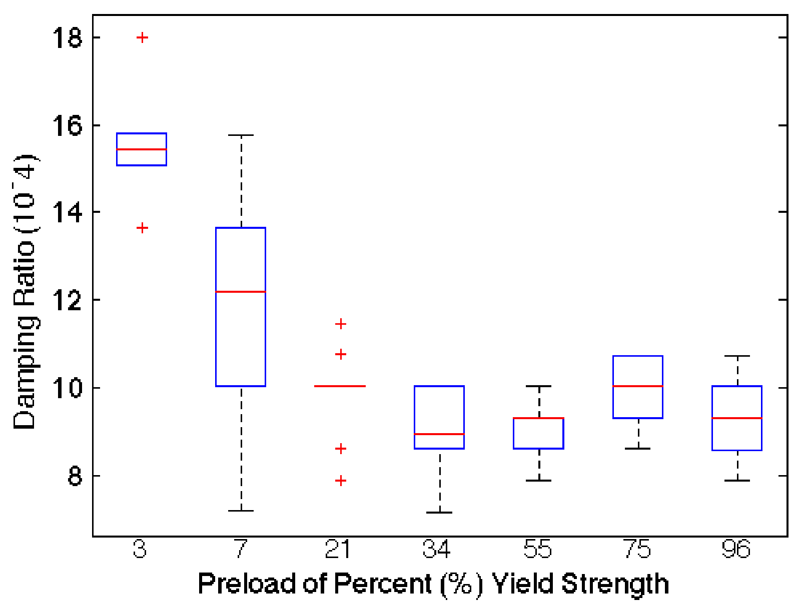


Figure F.14 Distribution of damping for steel plates with a Grade 5 bolt on Mode 3

Appendix F (Continued)

F.4 Steel Plates Bolted With a Grade 8 Bolt

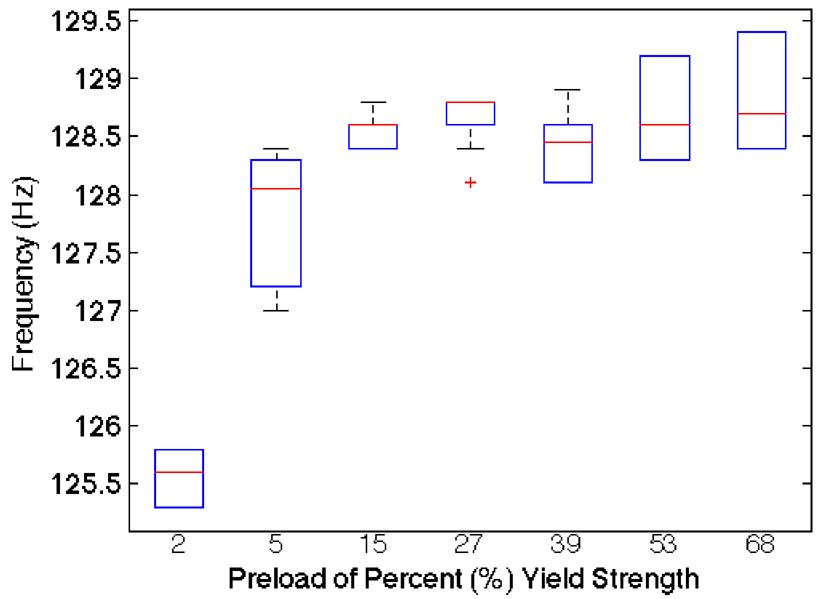


Figure F.15 Distribution of frequency for steel plates with a Grade 8 bolt on Mode 1

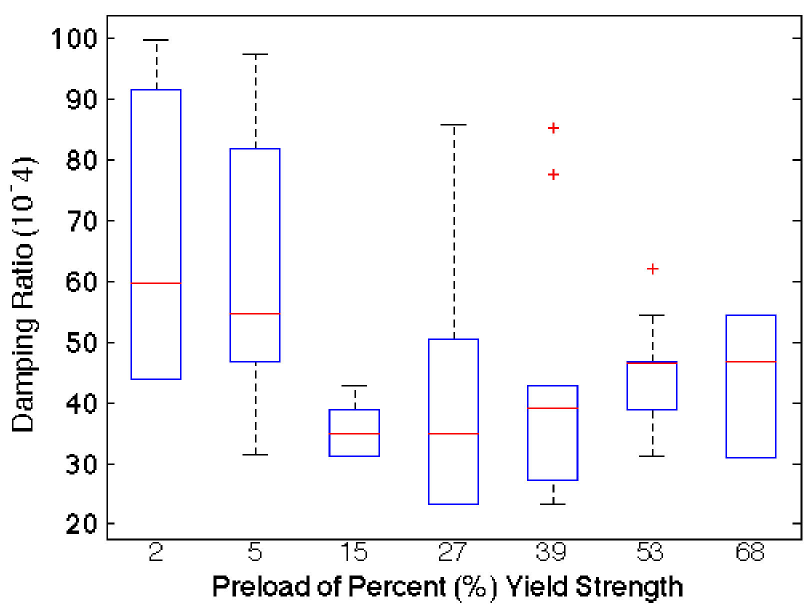


Figure F.16 Distribution of damping for steel plates with a Grade 8 bolt on Mode 1

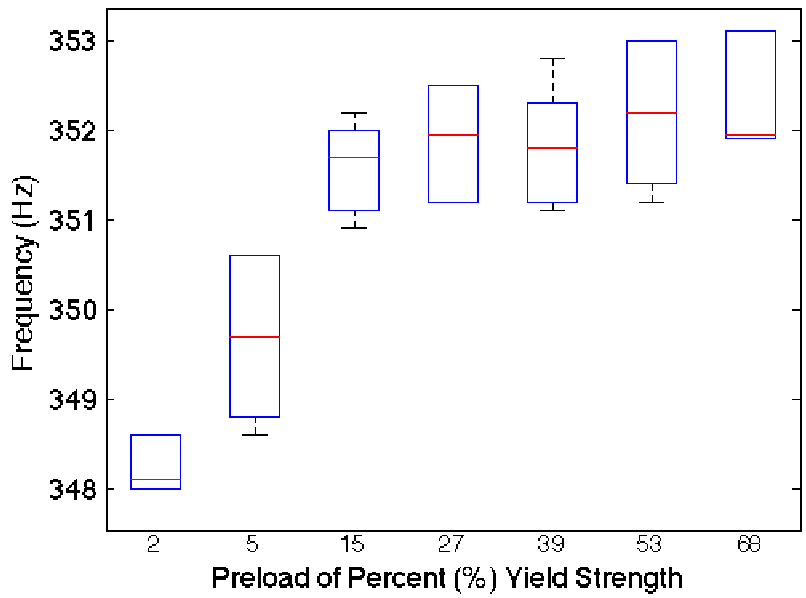


Figure F.17 Distribution of frequency for steel plates with a Grade 8 bolt on Mode 2

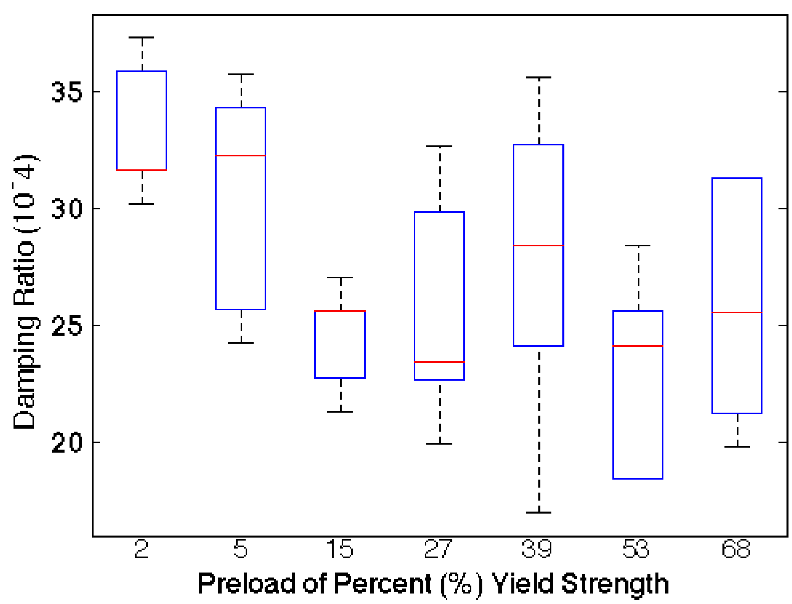


Figure F.18 Distribution of damping for steel plates with a Grade 8 bolt on Mode 2

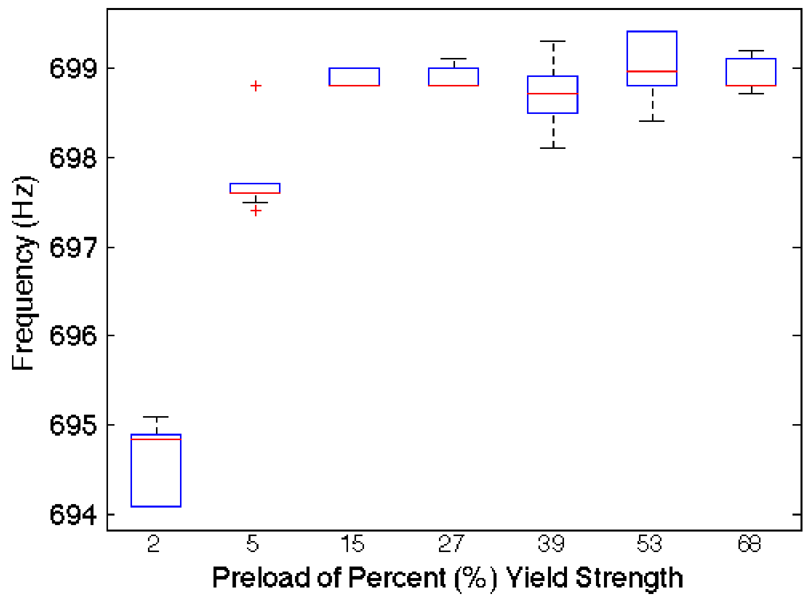


Figure F.19 Distribution of frequency for steel plates with a Grade 8 bolt on Mode 3

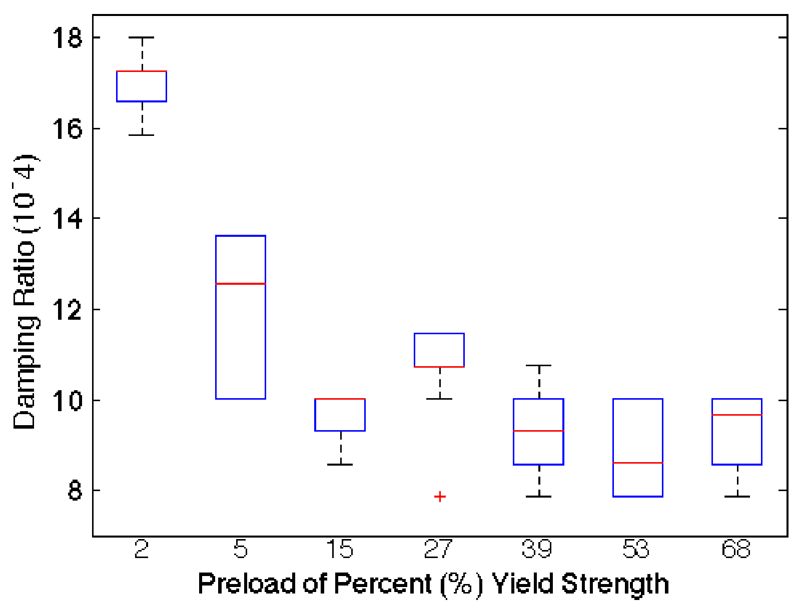


Figure F.20 Distribution of damping for steel plates with a Grade 8 bolt on Mode 3