SAND2020-13563C

A Comparative Study of Joint Modeling Methods and Analysis of Fasteners

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ABSTRACT

One of the more crucial aspects of any mechanical design is the joining methodology of parts. During structural dynamic environments, the ability to analyze the joint and fasteners in a system for structural integrity is fundamental, especially early in a system design during design trade studies. Different modeling representations of fasteners include spring, beam, and solid elements. In this work, we compare the various methods for a linear system to help the analyst decide which method is appropriate for a design study. Ultimately, if stresses of the parts being connected are of interest, then we recommend the use of the *Ring Method* for modeling the joint. If the structural integrity of the fastener is of interest, then we recommend the *Spring Method.*

Keywords: Finite Element Modeling, Joint Modeling, Fasteners, Structural Dynamics

NOMENCLATURE

FEM	Finite Element Method

1. INTRODUCTION

One of the key components of any system in a structural dynamics analysis is the joints of the system. This work explores different techniques for modeling the joint system that use fasteners for linear models. There are several studies regarding the best methods to model these types of joints. Most of the research work attempts to address the nonlinearities in the system [1] caused by the joint. To be accurately predictive, it is important to eventually capture the nonlinearities. However, this work attempts to explore typical methods of modeling the joint in large structural dynamic system models, where one cannot computationally afford a high-fidelity model at the joint. These linear models are well suited for design studies and development of component specifications early on in a system's initial design developments.

During design studies, it is imperative that the analyst can generate several quick models of design parameters that can be assessed for structural dynamical performances. These structural performances can range from an assessment of the structural integrity of the parts and the fasteners to the motion of parts of the system to avoid impacts. During the design studies, the analyst is often faced with various methods of modeling the fastener. The analyst is often not afforded the time for deep study on the various methods of joining the materials. Consequently, this work explores various methods for one particular lap joint with fasteners.

There are two typical concerns during design studies for the fastener. The first is the structural integrity of the parts being joined and the second is the structural integrity of the fasteners and nut or insert. Stresses in the parts of interest are required to assess the structural integrity. However, some typical methods used for modeling the joints introduce stress singularities in the parts due to the use of rigid elements. This can lead to reporting incorrect stresses, especially as one appropriately refines the mesh. Hence, this work ultimately recommends using a method that assures proper reporting of the stress and can report the structural integrity of the fastener.

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2. MODELING METHODS FOR FASTENER JOINTS

There are several methods for modeling fastener joints, see Fig. 1. Here we compare some common methods with the proposed method *(Ring Method)*. The methods we explore are the following:

1. Tied surfaces at joint *(Tied Contact Method)*
2. Spring model of fastener *(Spring Method)*
3. Beam model of fastener *(Beam Method)*
4. Solid model of fastener *(Plug Method)*
5. Cylinder of solid elements *(Ring Method)*
6. Including preload and fastener properties *(Ring-Beam Method)*

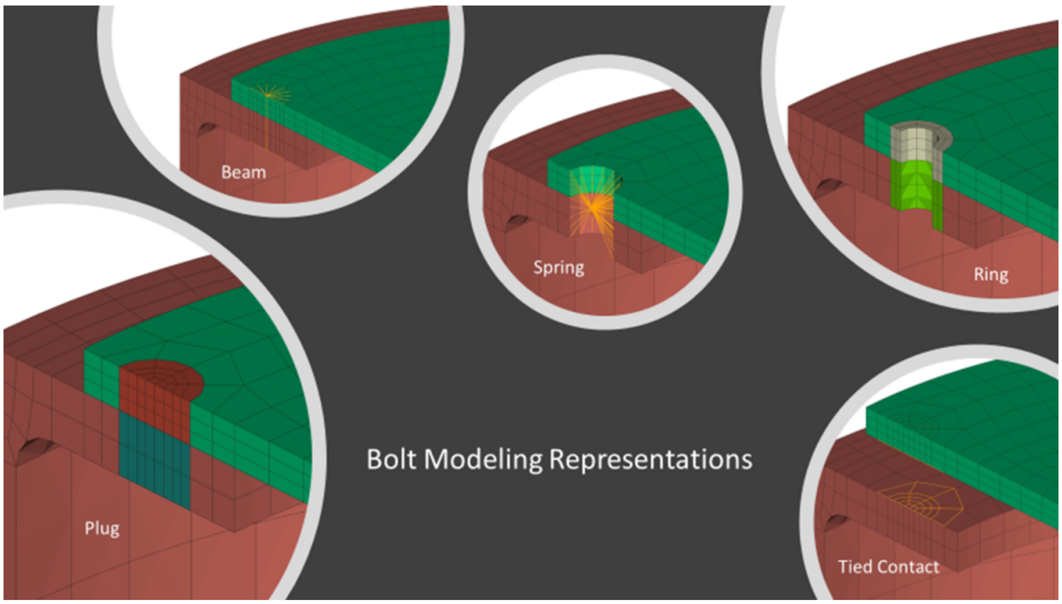


Fig. 1 Bolt modeling representations used in study

2.1 Tied Surfaces at Joint: *Tied Contact Method*

A straightforward method is to ignore the fastener and simply constrain the surfaces at the joint interface to move together. This removes the ability to do any post processing of the fastener itself. However, it is a typical method when the joint is not in an area of concern. In finite element terminology, this is typically referred to as "tied surfaces", "glued surfaces", or "tied contact". Tying the surfaces at the joint together in this study is referred to as the *Tied Contact Method.*

2.2 Spring Model of Fastener: *Spring Method*

In this technique a spring element is used to connect the mating surfaces at the fastener shaft area and is the representation of the fastener. Rigid elements are used to connect one end of the spring element to the fastener location in one of the joining materials. A similar procedure is used for the other joining material. This is all depicted in Fig. 2. The fastener is not modeled with solid elements but represented with the spring element. If weight of the fastener is of a concern, concentrated masses can be added to the nodes of the spring element to account for the mass. This method is referred to as the *Spring Method* in this study.

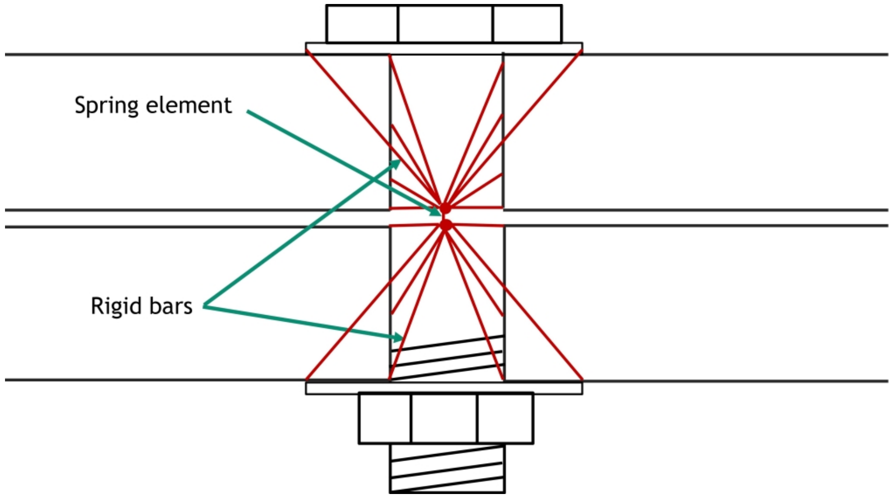


Fig. 2 Spring method for representing fastener

2.3 Beam Model of Fastener: *Beam Method*

Another common method for modeling the fastener joint for structural dynamics applications is the use of beam elements in place of the fastener. Typically, the beam is discretized to at least four to five elements to allow for preload application into one of the elements. Enough elements are also needed to capture the bending stiffness. A contact zone or connected surfaces can be represented at the interface of the joint from Shigley's contact pressure frustrum formula [2]. This is depicted in Fig. 3. The fastener is not modeled with solid elements but represented with the beam elements. In this method, preload can or does not have to be considered. In this study, we compare a beam with preload referred to as the *Beam Method.*

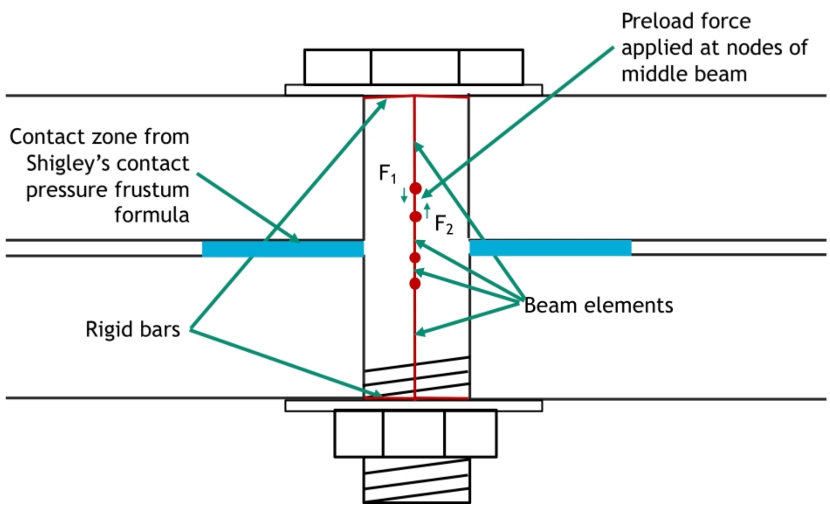


Fig. 3 Beam method for representing fastener

Preload is found as [3]:

$$F_i = \frac{T}{K_t d_{bolt}}, \#(1)$$

where T is the torque, K_t is the torque coefficient, and d_{bolt} is the bolt diameter. The torque coefficient, K_t, also known as the nut factor, is a factor applied to account for the effects of friction. Typically, the torque coefficient for UNS Standard threads with coefficients of friction at 0.15 is 0.22 [4]. Calculating the forces to apply to the middle beam, see Fig. 3, is an iterative process to assure the correct force in the beams.

2.4 Solid Model of Fastener: *Plug Method*

It is also common to see the fastener in a finite element model (FEM) to be represented with solid elements. In full system FEM that can have millions of elements, the threads are typically not modeled and are defeatured. The nut and head of the fastener are also defeatured and represented with cylinders. Including the washer is generally dictated by the analysis being conducted and the level of concern for the stress/strain near the fastener. Determining what is in contact or connected surfaces can also vary among analysts. We recommended using the contact zones shown in Fig. 4. In this study, we refer to this method as the *Plug Method*, since the solid fastener resembles a plug in the finite element model.

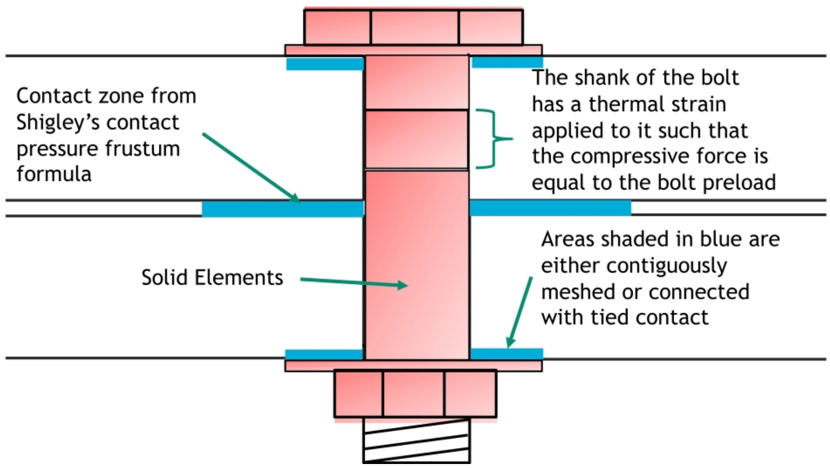


Fig. 4 Plug method for representing fastener

Preload can be applied to a portion of the fastener shank. This is commonly introduced with a thermal strain on a portion of the solid elements representing the shank of the fastener, see Fig. 4. By knowing the desired preload force from Equation (1) and the area of the shank, the desired stress in the shank can be determined and used for the iteration to find the appropriate thermal strain to get the correct preload.

2.5 Cylinder of Solid Elements: *Ring Method*

The first two methods discussed, using spring or beam and rigid bar elements, Section 2.2 and 2.3, can potentially lead to erroneous stress predictions due to stress singularities. Though there are common methods to avoid reporting incorrect stresses in these cases, it is rather time consuming and difficult to automate. A simple method around this is to generate a cylinder of solid elements. Shigley's formula for calculating the frustum can be used for determining the radius of the cylinder. In this study, the *Ring Method* is explored.

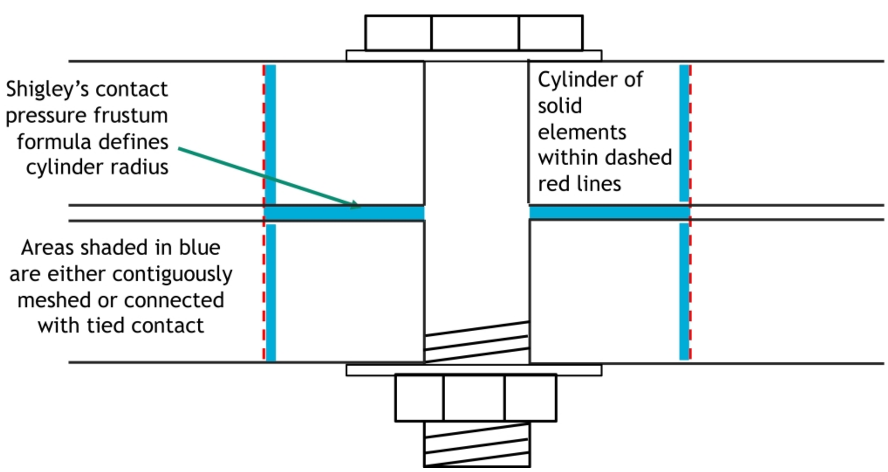


Fig. 5 Ring method for representing fastener

2.6 Including Preload and Fastener Properties: *Ring-Beam Method*

It is possible to include this technique with the previous mentioned methods. If it is desired to include a preload or obtain fastener forces, one can use this method in conjunction with the beam method, Section 2.3. This allows for obtaining the fastener loads for analysis. When reporting the stress in the joining parts, the analyst can easily remove the ring part that would have the stress singularities due to the rigid elements for the beam. This method is referred to as the *Ring-Beam Method.*

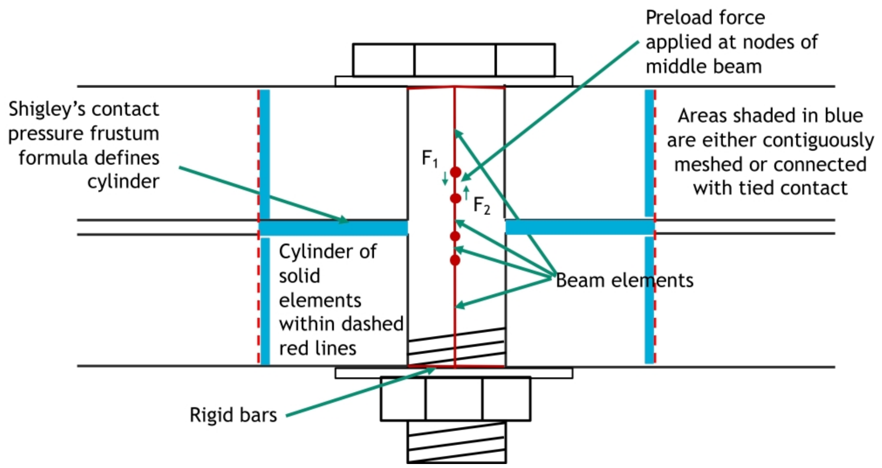


Fig. 6 Ring method with beam for preload or obtaining fastener forces

2.7 Frustrum Calculation

The method recommended for finding the geometry of the frustrum is that by Shigley [2]. In this method, the stiffness in a layer is obtained by assuming the stress field looks like a frustum of a hollow cone, see Fig. 7. Shigley recommends an angle, α of $30°$, where the angle is typically between 25 and 33 degrees.

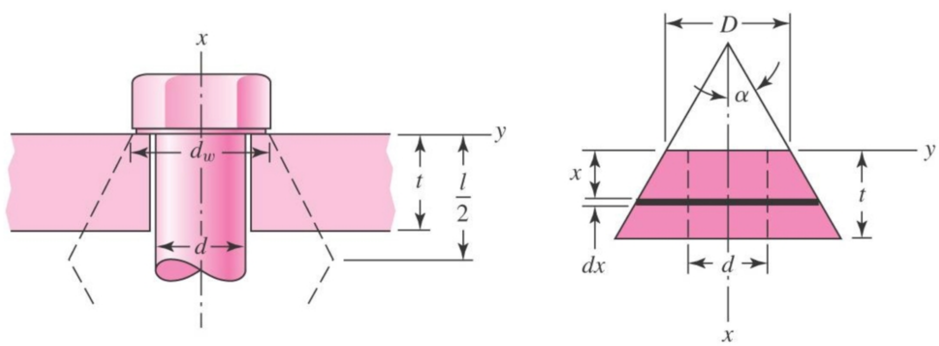


Fig. 7 Shigley's frustum calculation [2]

3. EXAMPLE PROBLEM

An example problem is used in this study to demonstrate the applicability of the different methods. It is represented as a cylinder with a plate at one end and a beam on top of the plate, see Fig. 8. There are eight ¼-20 fasteners used to connect the plate to the cylinder. The fastener properties used are those of steel. For this study, the fastener models were made to be very stiff in the attempt of obtaining stiffness values on the order of $1.0\text{x}10^7$ lb/in. The plate, cylinder, and rectangular beam are aluminum.

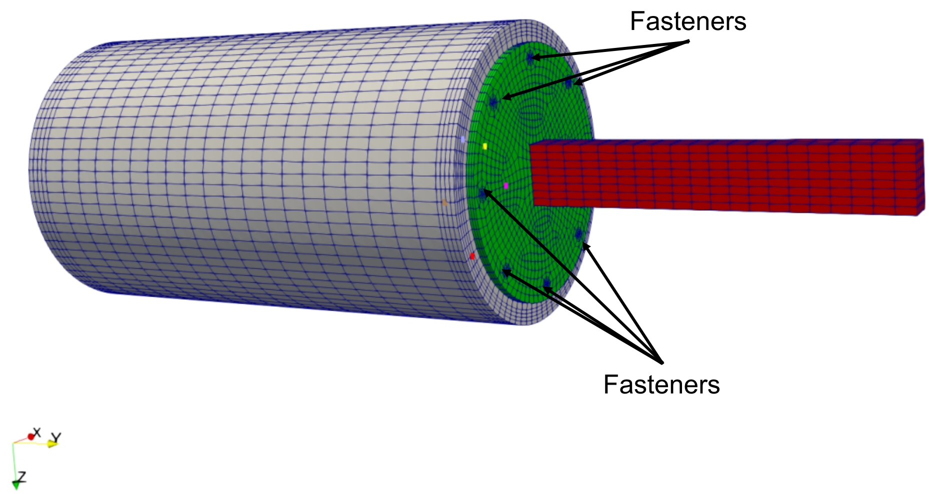


Fig. 8 Cylinder-Plate-Beam example with fasteners connecting plate to cylinder

The photos shown in Fig. 9 are representative of the test model.

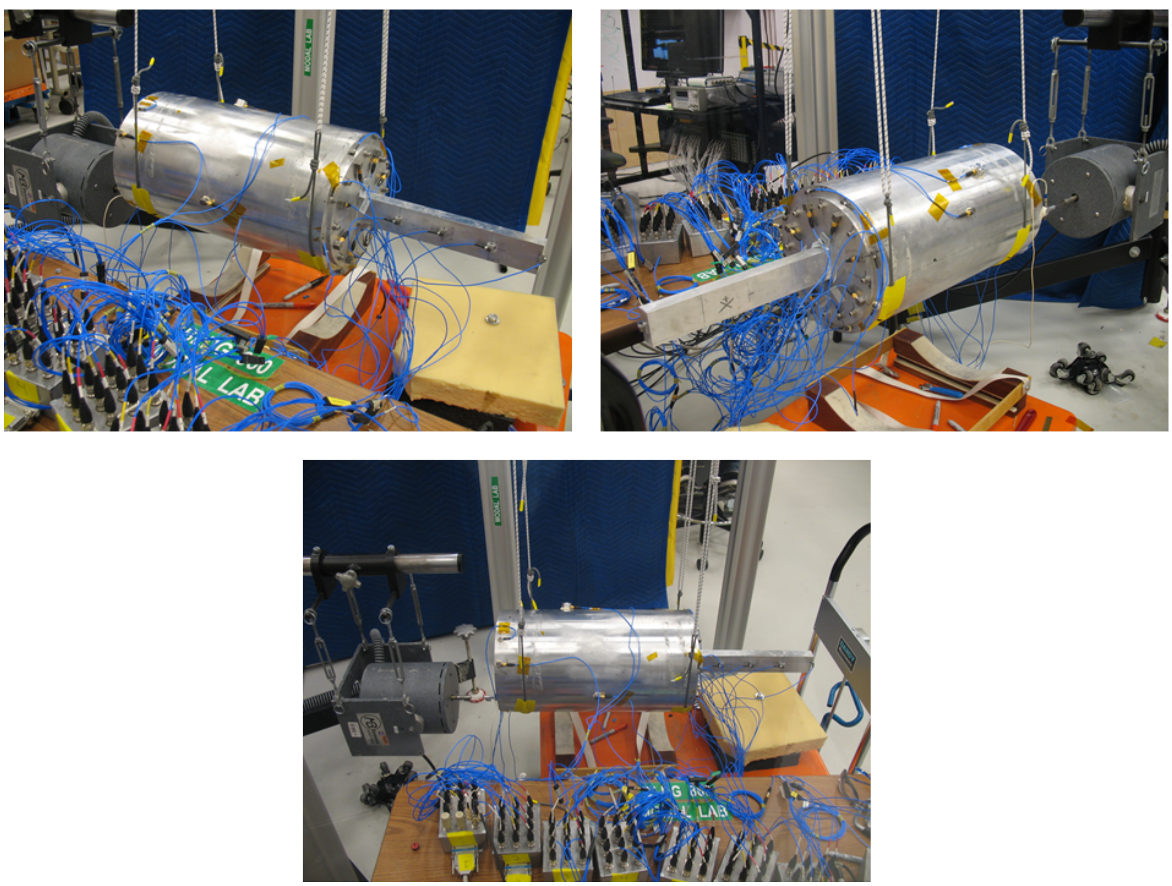


Fig. 9 Test model photos

There were two experiments conducted. The first was a free boundary condition modal experiment. The second experiment performed was a burst random excitation at the base of the cylinder with the force applied in the Y-direction, as shown in Fig. 10. The burst random excitation signal was signal processed and removed the off times to provide an ergodic, stationary random signal.

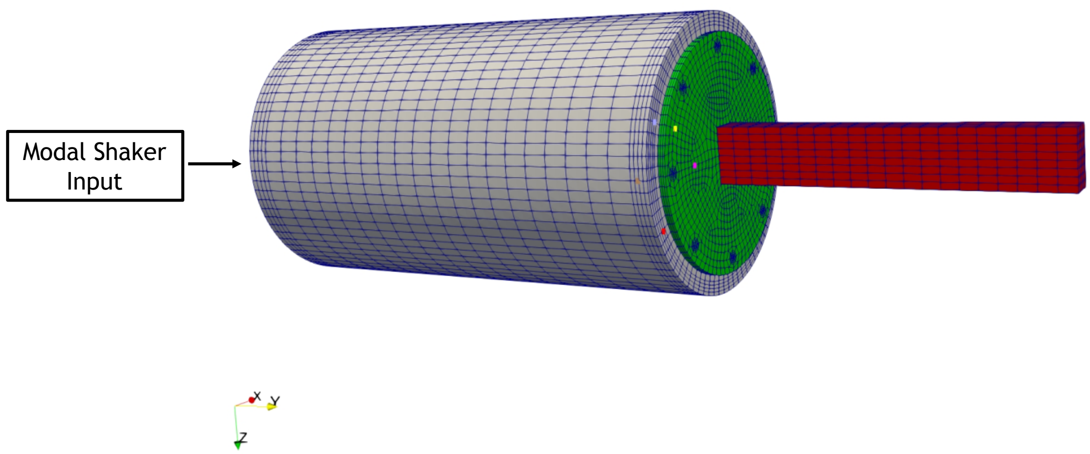


Fig. 10 Modal shaker input

There are twenty-eight attached triaxial accelerometers used in the experiment. However, this study focused on five triaxial accelerometers that were surrounding one of the fasteners as shown in Fig. 11. Fig. 12 depicts the specific accelerometer gage number noted in this study. There are three gages noted as aft that are on the excitation side of the joint. There are two gages on the forward end of the joint near the beam. The forward/aft designation is from missile terminology, where the shaker and beam represent the rocket motors and the missile payload, respectively.

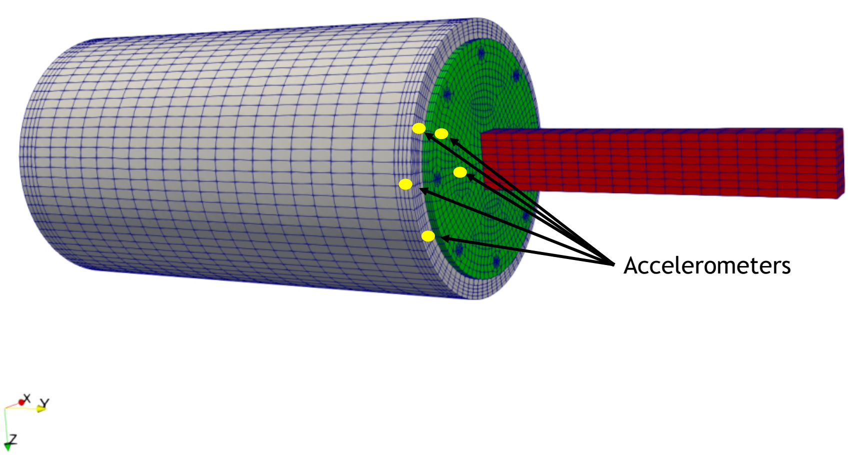
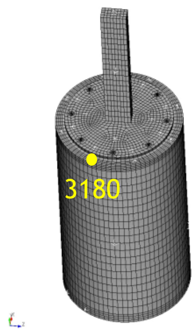
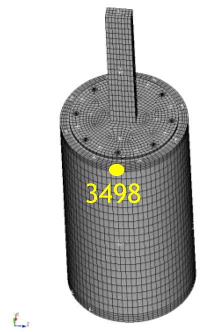


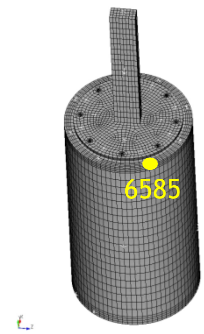
Fig. 11 Accelerometer locations used in study



(A) Aft Left Gage



(B) Aft Center Gage



(C) Aft Right Gage

(D) Forward Left Gage

(E) Forward Center Gage

Fig. 12 Specific accelerometer gages

4. RESULTS

4.1 Modal Comparisons

The first comparison of the methods is a modal analysis. The modal analysis for a free boundary condition is shown in Table 1 with the first six modes being rigid body. In the modal analyses, the initial model (*Tied Contact Method*) was correlated to the test data by a previous analyst. Recall that the model for the *Tied Contact Method* was developed with surfaces at the joints constrained by multipoint constraints typically referred to as tied surfaces or glued surfaces. Then, the other models were developed with no tuning of the fastener method. The idea was to generate the methods as if no test data was available and see which performed the most accurate.

As indicated in Table 1, the mode frequencies were insensitive to the modeling method used. The error percentage difference of each method compared to the test is shown Fig. 13. Generally, the largest error was noted at modes 11 and 15, which are an axial and ovaling mode of the system, respectively. This may be a question of material properties as opposed to fastener issues.

Mode	Test Data	Tied Contact	Plug	Ring	Ring-Beam	Spring	Beam
7	139	141	141	141	139	142	139
8	182	182	182	183	180	185	180
9	385	398	398	398	393	399	393
10	390	398	398	398	398	399	398
11	590	543	543	551	544	568	551
12	945	948	948	948	949	949	949
13	951	948	948	948	952	949	952
14	1039	1045	1045	1046	1030	1047	1031
15	1221	1323	1323	1322	1293	1325	1293
16	1288	1323	1323	1322	1320	1325	1320

Table 1 Modal frequency (Hz) comparison between test and simulation

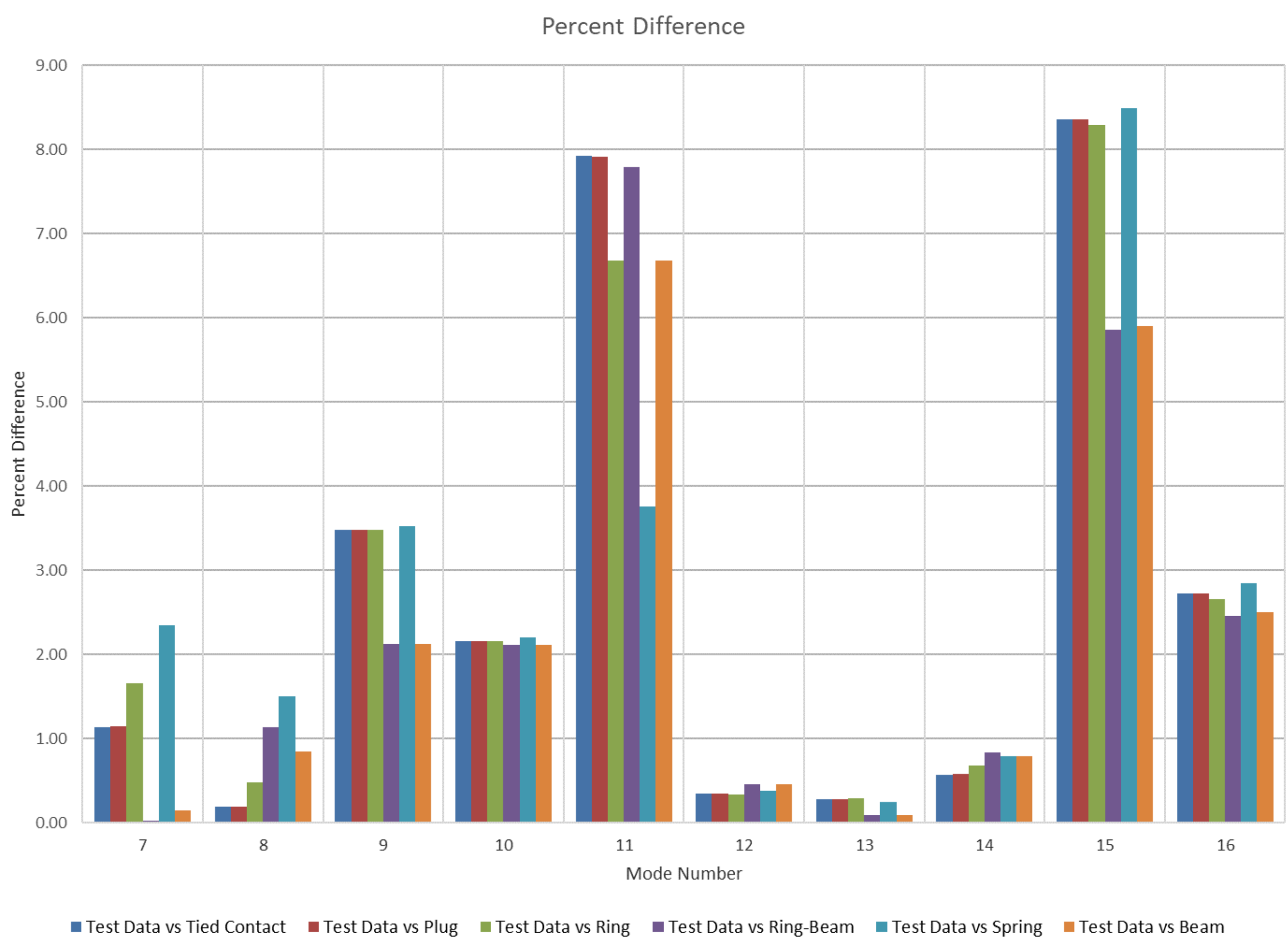
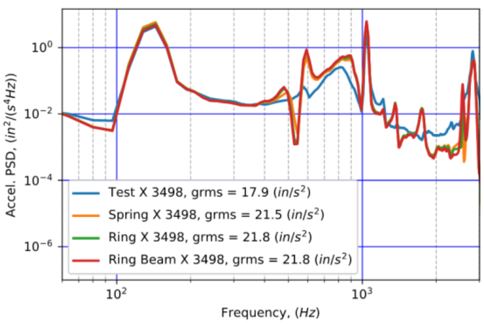


Fig. 13 Percent difference between test data and various methods for modal analysis

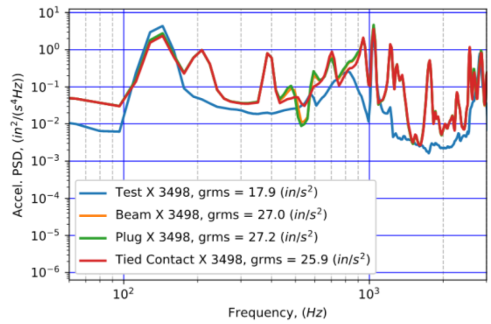
4.2 Random Vibration Comparisons

A typical study will require a random vibration analysis of the system for structural dynamics performance. In this regard, we compare accelerometer responses on two sides of the joint and see if there is any clear indication of a preferred modeling method for the fastener. The acceleration responses are noted in the auto-spectral densities shown in Fig. 14 - Fig. 17, where the X-direction is transverse and the Y-direction is axial. The responses were grouped into similar behaving responses with the *Beam*, the *Plug*, and the *Tied Contact* methods grouped together and shown in the right column of Fig. 14 - Fig. 17. This leaves the *Spring*, the *Ring,* and the *Ring-Beam* methods in the other group and shown in the left column of Fig. 14 - Fig. 17. In this particular experiment, the *Spring* and the *Ring* methods have responses that are similar and appear to be more accurate than the *Beam*, *Plug*, and *Tied Contact* methods. The *Spring* and *Ring* methods also lend themselves to easier implementation over the previous methods. Any of the methods, however, appear to be adequate and could benefit from furthering calibration.

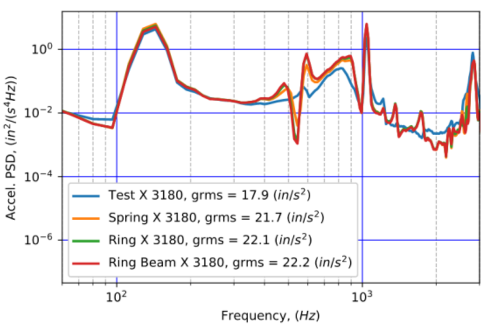
None of the methods do a particular good job of capturing the response at the forward center location, Fig. 17. This is an area of future study and probably due to nonlinear issues.



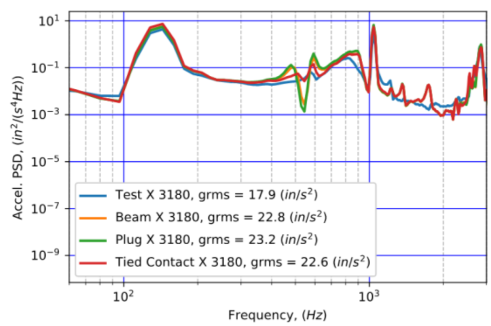
(A) Aft Center Fastener Set 1



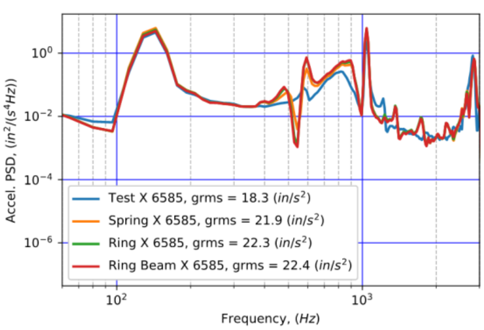
(B) Aft Center Fastener Set 2



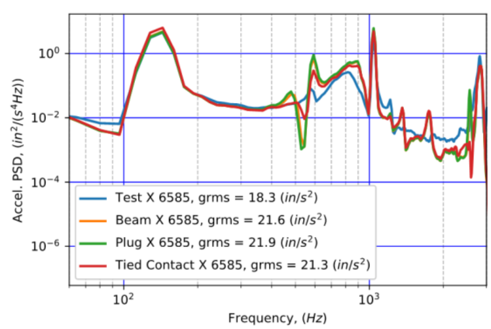
(C) Aft Left Fastener Set 1



(D) Aft Left Fastener Set 2

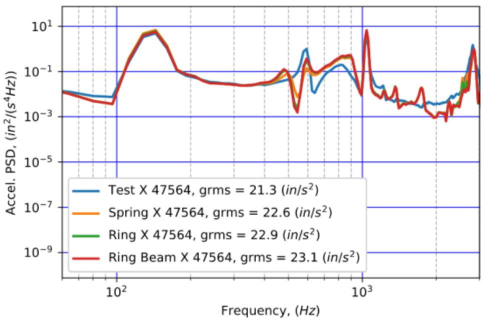


(E) Aft Right Fastener Set 1

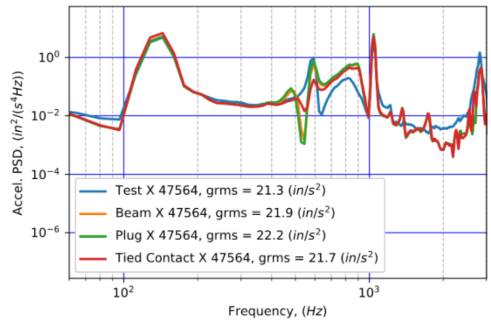


(F) Aft Right Fastener Set 2

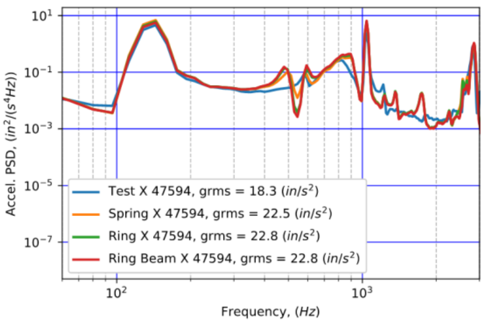
Fig. 14 X-direction responses aft of bolted joint compared to test



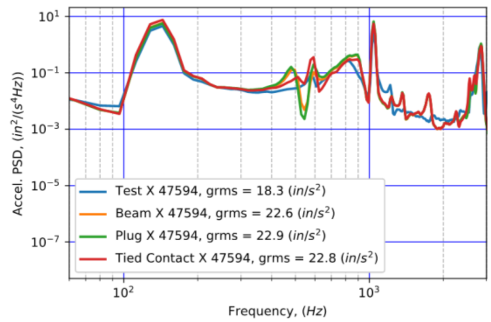
(A) Forward Left Fastener Set 1



(B) Forward Left Fastener Set 2

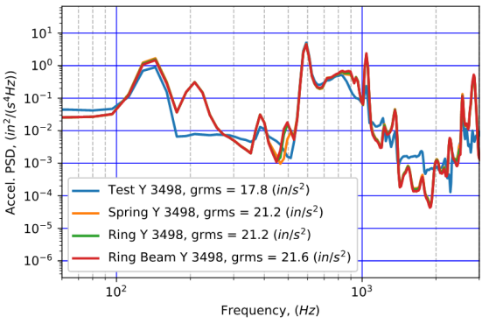


(C) Forward Center Fastener Set 1

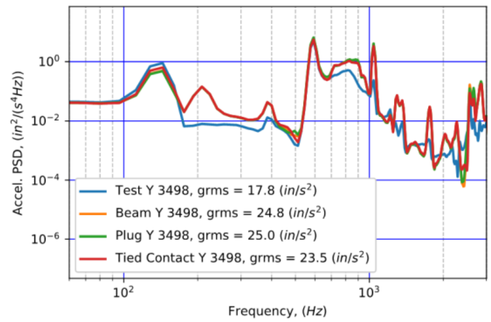


(D) Forward Center Fastener Set 2

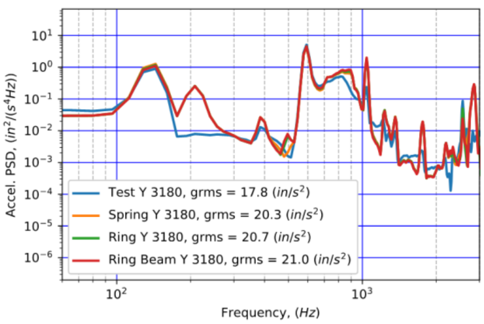
Fig. 15 X-direction responses forward of bolted joint compared to test



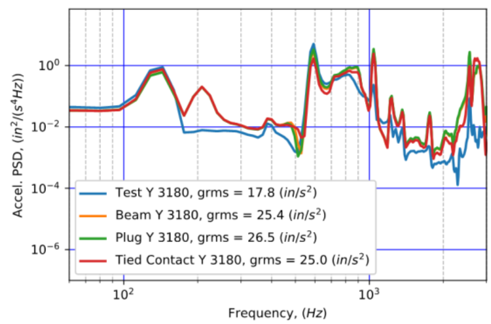
(A) Aft Center Fastener Set 1



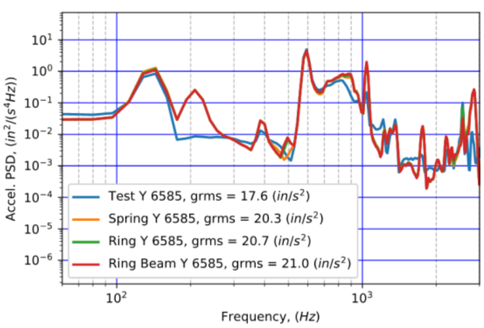
(B) Aft Center Fastener Set 2



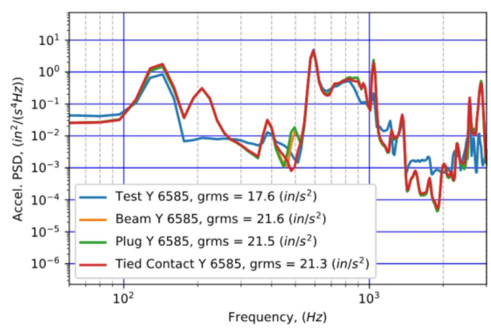
(C) Aft Left Fastener Set 1



(D) Aft Left Fastener Set 2

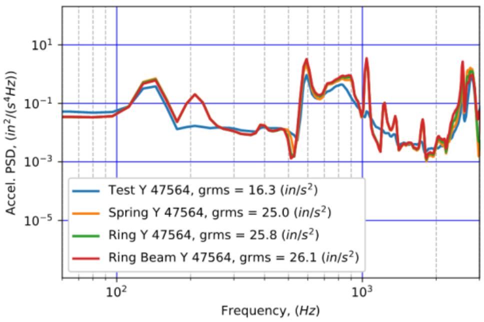


(E) Aft Right Fastener Set 1

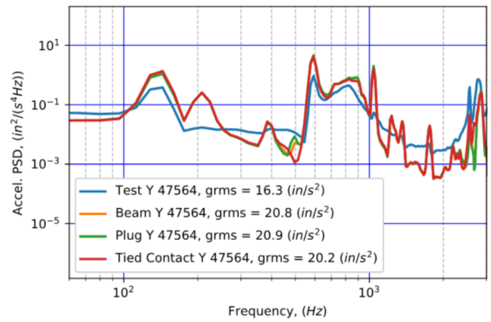


(F) Aft Right Fastener Set 2

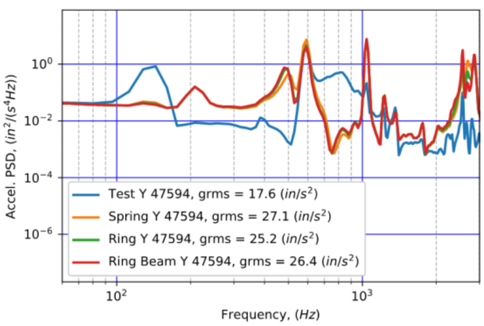
Fig. 16 Y-direction responses aft of bolted joint compared to test



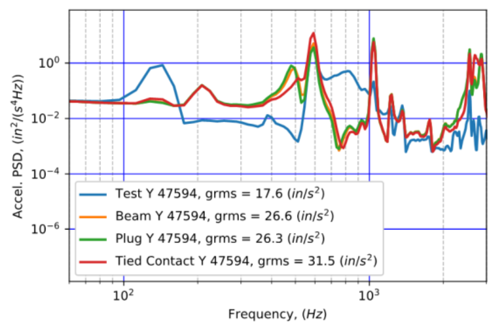
(A) Forward Left Fastener Set 1



(B) Forward Left Fastener Set 2



(C) Forward Center Fastener Set 1



(D) Forward Center Fastener Set 2

Fig. 17 Y-direction responses forward of bolted joint compared to test

5. CONCLUSIONS

This paper explores various methods of modeling fasteners. The hope is that it can provide the analyst with a method that is consistent with reporting stresses in the parts being joined and providing the fastener loads. Under this specific lap joint, it is recommended to use the *Ring Method*. It is suggested, however, to use the *Spring Method* if the structural integrity of the fastener is of interest. The *Ring-Beam Method* would be suitable if preload and stress near the fastener is of concern. It is beneficial that the *Ring,* the *Ring-Beam,* and the *Spring* methods are easily implemented. Any of the methods, however, appear adequate and could profit from furthering calibration.

Future work should explore additional joints as well as the response at the forward center fastener gage location where none of the methods did particularly well at matching that response.

ACKNOWLEDGEMENTS

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy National Nuclear Security Administration under contract DE-NA0003525.

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