Influence of Interface Curvature in Nonlinear Model Correlation of S4 Beam with QSMA

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Abstract

Bolted joints are a significant source of damping and nonlinearity in many assembled structures. For decades researchers have sought to predict the damping and nonlinearity in bolted joints from first principles, but so far no method has succeeded although many methods are able to tune a model to correlate with experimental measurements. This work employs Quasi-Static Modal Analysis (QSMA) to seek to predict the nonlinearity observed in two modes of the S4 Beam (or C-Beam) benchmark structure. A prior effort showed that the contact pressure plays an important role in the dynamic behavior of the joints; surface topography on the order of a few microns can change the behavior significantly. This work explores two methods of accounting for this: smoothing the actual measured surface geometry and applying it to the FE Model and approximating the contact as spherical with a radius of curvature that approximates the measurements. Then we seek to determine whether the models are able to capture the changes in the linear natural frequencies with increasing preload. Additionally, the nonlinearity in the FEM is compared to measurements in terms of the change in the effective natural frequency and damping ratio as a function of vibration amplitude in Mode 2 (shear of the joints) and Mode 6 (torsion of the joints).

Keywords: Coulomb Friction, Quasi-Linear, Contact Mechanics, Nonlinear Modal Model

1 Introduction

Joints have long been known to be a major source of damping, nonlinearity and uncertainty in structural dynamics. While many studies have sought to predict the behavior of joints, and some commercial software packages give the impression that this can be readily done, no study has ever presented a thorough prediction of the behavior of an actual joint and validated it with measurements. Specifically, many structures with joints behave in a quasi-linear manner in which the response is well approximated as a superposition of modal responses although the nonlinear dissipation and stiffness of the joint causes the natural frequencies and damping ratios of the affected modes to change with amplitude [1, 2]. Hence, one would like to be able to predict the nonlinearity in the frequency and damping versus amplitude for the primary modes of a structure due to its joints.

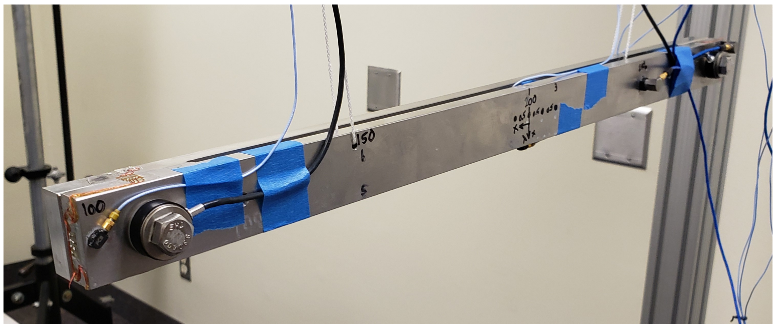
This work seeks to address two aspects of this problem: 1.) predicting the linear natural frequencies of a structure with bolted joints and 2.) predicting how the effective natural frequency and damping ratio of the structure vary as a function of vibration amplitude. The quasi-static modal analysis method (QSMA) [3] is applied to detailed finite element models of the S4 Beam, a benchmark structure with two joints that was first studied by Singh et al. [4], and the contact near the bolted joint is modeled in detail with a fine enough mesh to resolve micro-slip around the contact. This work builds on that of Jewell et al. [5], who were the first to apply QSMA to a detailed FE model of the S4 Beam. They studied the mesh and solver settings needed to obtain acceptable predictions of the stiffness and damping of the joints, and presented the first comparison between predictions and experimental measurements.

Jewell et al. [5] found that, in order to obtain agreement between the simulation and the experiments, the bolt preload had to be increased to twice the expected ultimate strength of the bolts, something that clearly is not possible. This suggested that more accurate modeling of the contact pressure in the joint was required. Brink et al. [6] studied an S4 Beam with more carefully machined surfaces and modeled the contact in detail and verified their predictions using static pressure film in both the simulations and experiments. They successfully predicted the shift in the linear (i.e. low amplitude) resonance frequencies of the structure as the preload was increased. Wall et al. [2] later did the same for the S4 Beam studied in [5].

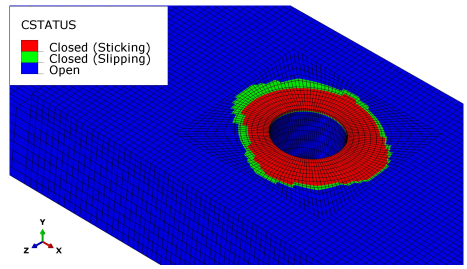
This research builds on those by studying the effect of surface curvature/topology on the nonlinear behavior of the joints. To explore the effect of surface curvature, several models with spherical contacting surfaces and various radii were considered, and QSMA was applied to see how the nonlinearity in two modes of interest changed due to the radius of curvature. Additionally, the actual topology of the surfaces was measured, smoothed and applied to the FE models. Comparing these results we can begin to understand what level of detail might be needed to model the interfaces of actual joints.

2 Methods

The configuration used to test the S4 Beam is shown in Figure 1a. The two load washers used to measure the preload in the bolts are visible, as well as the accelerometers. The bungees and cabling was kept as light as possible to avoid adding extraneous damping.



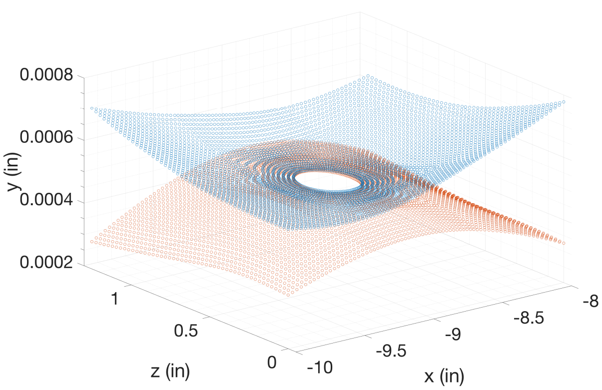
(a) Experimental setup used to perform impact testing on the S4 Beam.



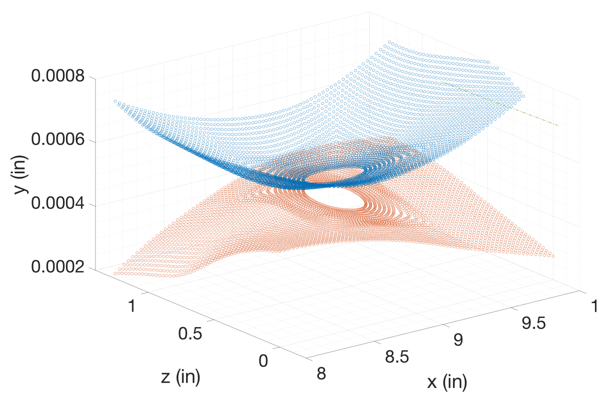
(b) Contact Status in FEM for Lowess-50 model, deflection=0.002 inches, $\mu = 0.6$

Figure 1: Experimental setup (a) and contact solution from FEA (b)

The topology at the contacting surfaces was measured using G2 Contoura coordinate measuring machine (CMM) with a stated accuracy from the manufacturer of $2\ \mu$m (79μ in). A grid of roughly $11,000$ points was measured on each interface. During the measurement, the beam was bolted flat onto the measurement table, and an epoxy plug was used to fill the bolt hole so the machine could easily cover the whole surface in a single measurement. The measurements were smoothed using the locally weighted smoothing method (Lowess in Matlab) to minimize noise and the resulting surfaces are shown in Fig. 2. The difference in height between the corners of the contact patch and the area near the bolt ranges from about 0.15 to 0.25 mil (3.81 to 6.35 microns) over the four surfaces. This would be most closely matched by a spherical surface with R=4000 in to 8000 in, although it would not be highly accurate to approximate any of these surfaces as spherical.



(a) B5B6 Beam - Left



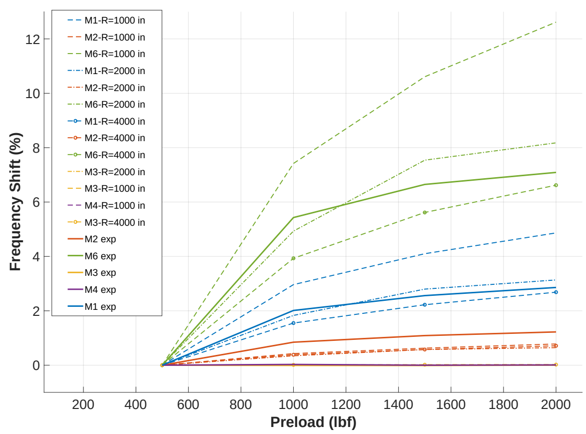
(b) B5B6 Beam - Right

Figure 2: Surface Topology for the B5B6 beam.

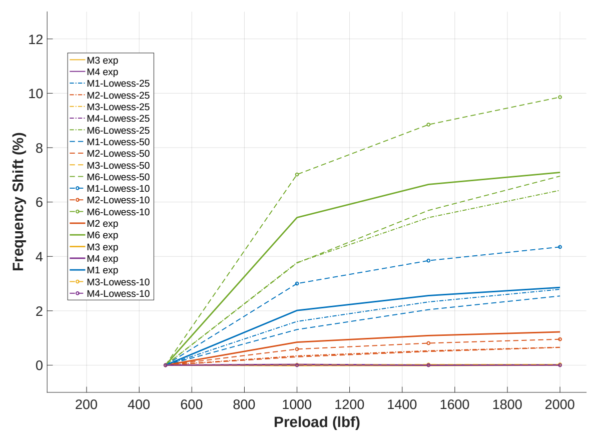
The topologies shown (and many others) were applied to the same FEM by taking the FEM for the nominal geometry and perturbing the nodes at the interface to align with the desired topology. For each model the bolt preload was applied and then Abaqus performed an eigen analysis about the preloaded state to estimate the natural frequencies. (When doing this, Abaqus welds together any nodes that are in contact and stuck during the nonlinear static preload step.) To illustrate the fidelity of the mesh used, Fig. 1b shows the stuck and slipping nodes from the Abaqus solution for a smoothed model, after applying preload and deflecting the beam 0.002 inches into Mode 2.

3 Results

Fig. 3a shows the shift in each linear natural frequency with increasing preload, taking the frequency at the 500-lb preload case as the baseline. The experimentally measured frequencies are compared with those predicted by the models with spherical curvature (left) and with the smoothed actual geometry (right). Note that while the first six natural frequencies are shown, only those for Modes 1, 2, and 6 changed significantly as the preload was increased from 500 lbs to 2000 lbs. The model with spherical curvature produces reasonable agreement with the measurements when the radius of curvature is between 2000 and 4000 inches. The actual surfaces agree well with the measurements when the Lowess smoothing is applied with a factor between 25 and 50%. In either case the model seems to be capable of predicting the desired behavior.



(a) Sphere Surfaces vs Experiment



(b) Lowess Surfaces vs Experiment

Figure 3: Linear frequency shift for Modes 1, 2, 3, 4 and 6 from the experiment and (a) the spheres surfaces, (b) the measured and smoothed (Lowess) surfaces)

4 Conclusion

The IMAC presentation will present further results including the natural frequency and damping ratio of Modes 2 and 6 versus vibration amplitude for the various models.

References

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