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Insights on the nonlinear modeling and characterization of bolted lap joint interface of beams

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ABSTRACT

This work explores explicit reduced-order modeling of the effects of nonlinear forces and linear joint stiffness of a free-free and cantilever bolted lap joint beam with a tip mass. Bolted joint interfaces are a significant source of uncertainties in assembled structures due to their inherent nonlinearities. These nonlinearities usually create linear and nonlinear softening effects for the system's response and they are known with the presence of nonlinear damping. In order to model the linear and nonlinear joint forces explicitly, linear and nonlinear springs and dampers are modeled at the bolted lap joint. The influences of the springs and dampers are implemented into the dynamics of the system by deriving the continuity relationships of the two beams at the joint using the Euler Bernoulli beam theory. Two different modeling methodologies for the bolted lap joint interface force are considered, namely, the concentrated force and the distributed force. In the concentrated force modeling, the bolted lap joint interface force is modeled as a combination of one spring and one damper. On the other hand, the distributed force is modeled in an integral form as an interface force. These two models will be evaluated and compared to each other with showing the limits of applicability of the concentrated force representation. Both free and forced vibrations results will be generated and compared with published experimental data. This work seeks to develop a bolted lap joint model which does not rely on experimental data for calibration in various scenarios to determine linear and nonlinear distributed forces.

Keywords: Bolted joint, distributed force, nonlinear dynamics

INTRODUCTION

Bolted joints are a significant source of energy dissipation and other nonlinearities in structures. Almost every assembled structure contains bolted joints, such as aircraft, spacecraft, buildings, and vehicles. Yet many frictional models that are implemented into finite element analysis software do not accurately model bolted joint interfaces or completely neglect them in analysis. The dynamics and modal behaviors of bolted-joint interface structures can be significantly different than an equivalent monolithic structure [1, 2]. The nonlinear inherent effects of bolted joints make them extremely complex to model accurately as compared to monolithic structures. The main sources of the nonlinearities and energy dissipation at the bolted joint interface is from friction and changes in the effective stiffness properties. Factors of friction include surface roughness, geometry, slippage, and multiple asperity contact. Slippage is the most important factor of energy dissipation for bolted joint models. There are models that consider the energy dissipation caused by bolts and therefore, the nonlinearities of jointed structures. The most common are the 4-parameter Iwan model. An Iwan model is composed of many Jenkins elements in parallel. A Jenkins element is a linear spring attached to a frictional slider. Each frictional slider has unique strength of φ, and each spring has a stiffness of k [3]. The Iwan model captures nonlinear damping of a bolted joint. The model considers the joint to be in one of two states, the micro-slip or the macro-slip regime. Overall, Iwan models are proficient at capturing nonlinear damping, softening as well as modal coupling if experimental data is available to tune the Iwan parameters. To address the issues with the Iwan model, this study proposes a reduced-order model with explicitly defining the linear and nonlinear forces at a joint interface. The structure in the work consists of two beams connected with a lap joint with one bolt in order to understand the effects of a joint on a beam structure before analyzing more complex configurations with multiple joints and bolts.

REDUCED-ORDER MODELING

In this study, the joint forces of a jointed structure connected are represented explicitly with springs to evaluate the linear and nonlinear characteristics of the system shown in Figure 1. Starting from the experimental measurements and reduced-order

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model used in [4], two different approaches for modeling the bolted lap joint interface force are considered, namely, the concentrated and distributed force. The concentrated force representation is used in [4] for a beam with a tip mass. Then, this model will be enhanced by including the distributed effects of the interface force at the joint which will be shown in the final presentation.

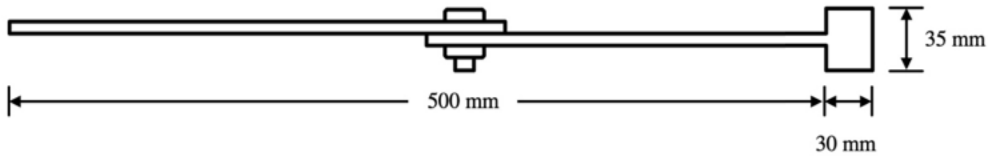

Fig 1. Lap joint beam under investigation.

To capture the transverse and angular movement at the joint, translational and torsional springs are considered for the concentrated force, as performed by Ahmadian and Jalali [4]. The linear translational spring, K_l, is used for modeling micro-vibro-impact of the interface and in some extreme scenarios, slapping of the joint. The linear torsional spring, K_θ, is considered to evaluate the difference in the angle of the two beams at the joint. Since the joint is modeled as a collection of springs, it is reduced to a localized/concentrated point instead of a section of the beam with a length and area. It should be mentioned that both linear and nonlinear damping effects will be considered at the joint location. Moreover, the translational and torsional springs will have nonlinear contributions to evaluate the joint's nonlinear dynamics with the joint interface. In this extended abstract, only the linear characteristics of the system shown in Figure 1 and the impacts of the linear translational and torsional stiffnesses at the joint on the natural frequencies and mode shapes of the system are investigated for the concentrated force model. It should be noted that the linear governing equations of motion and continuity equations considered for the concentrated force representation are similar to the ones developed in [4]. The improvement in the nonlinear modeling of the concentrated force compared to [4] and the introduction of the distributed force representation will be deeply discussed in the presentation.

PRELIMINARY RESULTS

Performing a linear analysis on the effects of the translational and torsional springs on the mode shapes of the system for different joints, the plotted curves in Figures 2 and 3 show the variations of the first three bending mode shape functions with varying K_l and K_θ terms with the joint located at half of the structure's length. When K_l and K_θ are 10^{20} (black curves), the bolted structure behaves as one continuous beam, but as the stiffness values decrease due to the softening effect at the bolted lap joint interface, the two beams begin to behave more independently. Specifically, as K_θ value is decreased, a sharp change in the angle at the joint location becomes more prevalent and the amplitude of the nodes located to the right of the joint decrease in modes 2 and 3, as indicated in Figure 2. The effects of K_θ at the joint location appear to be minute when the joint is near a node, which is not the case when K_l is decreased, see Figure 3. Furthermore, as the K_l value decreases, the distance between the two beams at the joint increases. This reduces the amount of contact at the interface and the amount of area that contributes to the overall stiffness of the structure, thus decreasing the natural frequencies of the system**.**

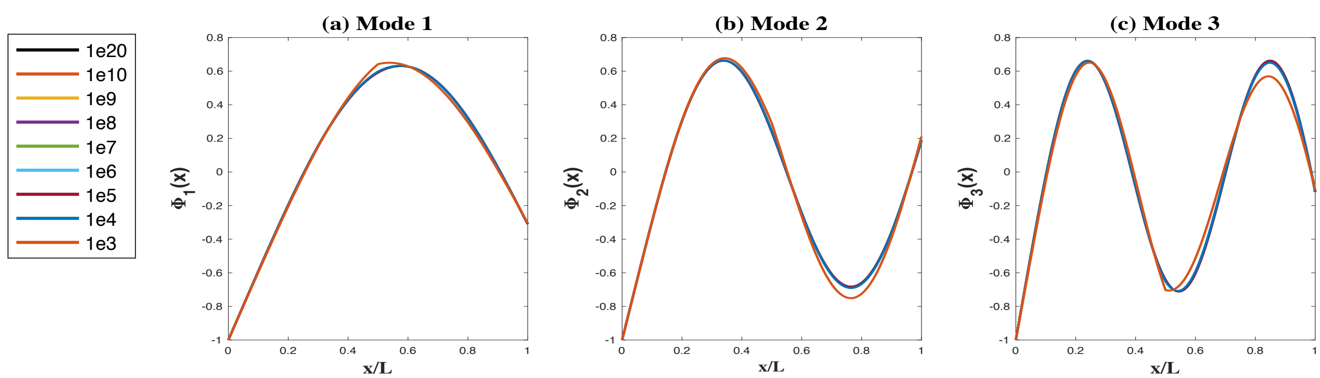

Fig 2. First three modes of vibration for the bolted lap joint beam with varying K_θ (N/rad).

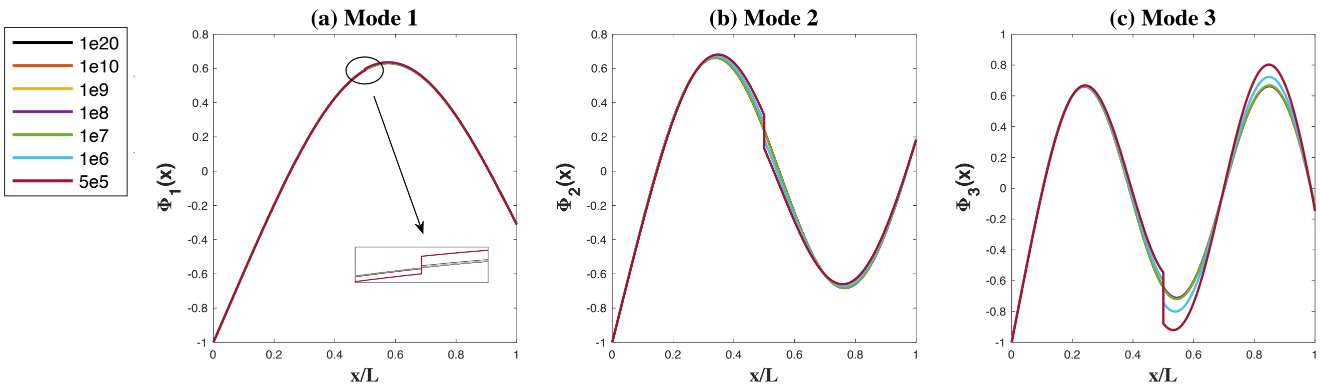

Fig 3. First three modes of vibration for the bolted lap joint beam with varying K_l (N/m).

In the final presentation, the effects of the location and type of boundary conditions on the linear and nonlinear characteristics of bolted lap joint beams will be deeply studied when considering both concentrated and distributed force representations with identifying the possible sources of nonlinearities for both stiffness and damping.

CONCLUSIONS

In this work, the dynamic effects of the linear properties of a bolted lap joint were examined by adjusting the values of translational and torsional springs It was found that the bolted structure behaves as a continuous beam when both the springs constants are higher than 10^{10}. When varying the stiffness values, the translational spring has a higher impact on the mode shapes than the torsional spring one. Additionally, if the joint is positioned at a node of a mode shape, high and low values of the torsional stiffness have very minimal effects on the mode shape variation. A deeper investigation to model the nonlinear and linear forces as area-dependent, with magnitudes varying at all locations of the joint interface, in contrast to the current constant localized/concentrated forces, will be presented. The area that the joint forces will reside will be dependent on the bolt preload and the frustum zone. Furthermore, the nonlinear softening and damping must be captured by implementing a nonlinear stiffness and damping representations in the bolted lap joint interface force.

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