An Enhanced Static Reduction Algorithm for Predictive Modeling of Bolted Joints

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1. Introduction

Bolted joints in assembled structures are responsible for much of the structure's damping and gives rise to nonlinear behavior. While a bolted joint can presumably be modeled in commercial FE codes, even quasi-static analysis is extremely expensive due to the level of detail required to capture micro-slip. This work explores the application of a new static reduction method to reduce the computation costs associated with analyzing built-up structure. This novel method applies a Gauss-Seidel algorithm to a model that has been statically reduced to retain only the DOF at the contact interface. To validate the approach, a simple contact problem was first considered that examined contact between a deformable block and a rigid surface. Coulomb friction was used at the interface and the results were verified by examining the load dependence of contact area and model nonlinearities. Subsequently, a contact problem between two deformable bodies in 2D was considered which modeled two beams in a sandwich configuration. In all cases it was found the static reduction method's resulted in dramatic computational savings while providing good accuracy as compared to simulations in commercial finite element software.

While most studies to date have presumed that a nonlinear transient analysis must be used to correctly account for friction in the interfaces between structures, Festjens et al. [1] recently proposed a model reduction technique in which a single quasi-static loading is applied to the structure and they showed how this can be used to predict the dynamic response for oscillations up to some maximum displacement. Their method spatially decomposes a structure into a linear domain away from the joint and a nonlinear domain near the joint. Then the inertial term in the joint domain is neglected and the joint is assumed to behave quasi-statically. Lacayo and Allen [2] later presented a variant on this method, known as Quasi-Static Modal Analysis, and applied it to structures where the joints were modeled as discrete Iwan elements. They that Quasi-Static Modal Analysis produces very accurate estimates of nonlinear behavior of the joint, especially the amplitude-dependent modal damping and natural frequency when the response is dominated by a single mode. In essence, Quasi-Static Modal Analysis (QSMA) is an extension of modal analysis to structures with weakly nonlinear joints in that one can estimate the amplitude dependent natural frequency and damping of a structure using a few nonlinear static simulations. The modes are assumed to remain uncoupled and any changes in the mode shapes are neglected.

This advancement prompted Jewell, Allen & Lacayo [3] to apply this technique to detailed finite element models that included nonlinear contact between the bolted interfaces using a commercial software package. While their results showed that such an analysis is feasible, they struggled to obtain accurate results and noted that, once the structure had been meshed with adequate fidelity to capture micro-slip, the computational cost was very significant even to perform a single static analysis. This work explores a more computationally efficient alternative that follows the work of Ahn and Barber [4, 5]. Specifically, static reduction is used to eliminate all of the DOF except those at the contact interface, and then a Gauss-Seidel algorithm is used to solve the nonlinear contact problem in Matlab. A variant on the Gauss-Seidel algorithm has been developed, based on the Block-

Gauss Seidel approach and will be elaborated in the presentation, that seems to improve the computational efficiency and the resulting algorithm is evaluated by comparing it with the commercial software package, Abaqus ®.

2. Sample Results

The proposed algorithm was tested by applying it to the structure shown in Fig. 1, which represents a very simple structure with a bolted joint. The normal load, *P*, represents the clamping load from a bolt and the lateral load, *Q*, provides a loading to the structure that induces micro-slip.

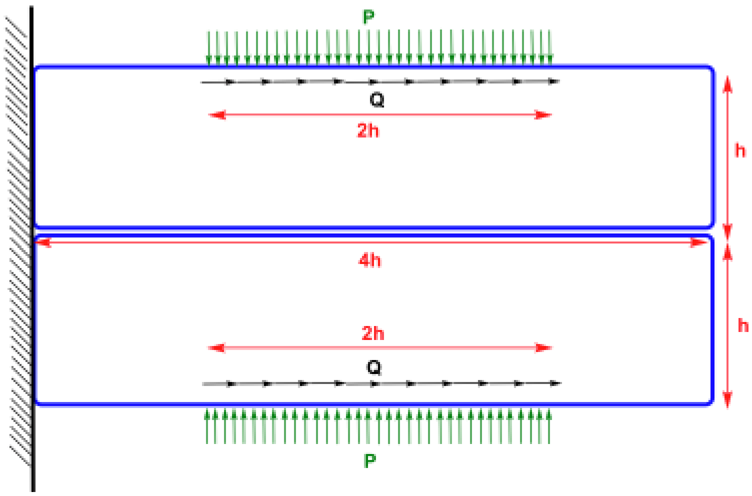

Figure 1. Beam structure with a clamping load representing a bolted joint and a shear load which exercises the joint.

A finite element model was created of this structure, with 300 nodes along the contact interface. Then the stiffness matrices for the top and bottom blocks was exported to Matlab and statically reduced using the approach in [5]. The proposed algorithm was then to find the contact forces at the interface, and they were compared to a solution of the full order FEM in Abaqus. The results were indistinguishable, and so only the result from the proposed algorithm is shown. The difference between the solutions, expressed as a percentage by dividing it by the largest force over the contact surface, was computed and is shown below. There are small differences at the edges of the contact, presumably due to a slightly different number of nodes being in contact in the two solutions, but the forces are within 1% of each other.

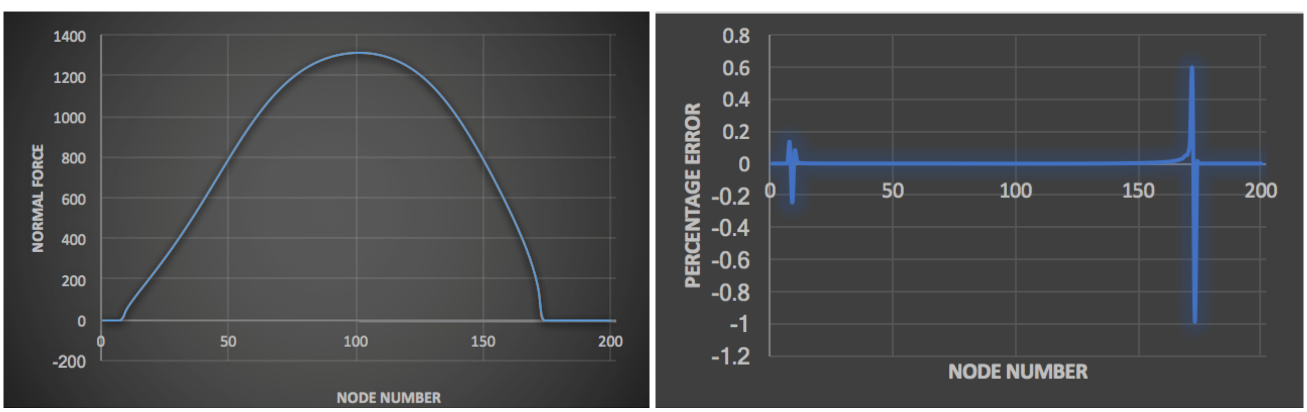

Figure 2. (left) Normal force at the contact of the beams as computed by the proposed algorithm. The result from Abaqus was visually indistiguishable. (right) Percent error in the result computed by the proposed algorithm, taking the result from Abaqus as the truth model.

While this simple model could be solved very quickly in Abaqus, the solution above took only 30 seconds, the proposed algorithm was even faster, solving in uncompiled code in less than 0.15 seconds. This difference is expected to be very important when going to three-dimensional models, where solve times have been in excess of 24 hours even for relatively simple models [3]. Furthermore, commercial contact algorithms are known to favor robustness over accuracy, which perhaps explains the challenges encountered in [3] in obtaining physically reasonable results using a commercial code. In the future this algorithm will be used to compare predictions of the stiffness and damping of joints to experimental measurements.

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