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A Mechanical Diode: Comparing Numerical and Experimental Characterizations

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Abstract

In this introductory work, joint compliance is studied in both a numerical and experimental setting. A simple bolted interface is used as the test article and compliance is measured for the joint in both compression and in tension. This simple interface is shown to exhibit a strong non-linearity near the transition from compression to tension (or vice-versa). Modeling issues pertaining to numerically solving for the compliance are addressed. It is shown that the model predictions, in spite of convergence being very sensitive to numerical artifacts of the interface model, are in good agreement with experimentally measured strains and joint compliances.

The joint behavior is a mechanical analogy to a diode, i.e., in compression, the joint is very stiff, acting almost as a rigid link, while in tension the joint is relatively soft, acting as a spring.

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The authors wish to thank Martin Heinstein for his help with using the contact algorithm used in this work. Support for the analytic portion of this research was funded by the ASCI (Accelerated Strategic Computing Initiative) program. Support for the experimental portion was provided by MAVEN (Model Accreditation Via Experimental Sciences for Nuclear Weapons).

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Introduction

The predictive modeling of shock and vibration in many structural systems is crippled by an inability to model the mechanics of joints. A lack of understanding of joint dynamics is evidenced by the substantial uncertainty of joint compliances in numerical models and by a complete inability to predict joint damping. The lore is that at low amplitudes, joint mechanics are associated with Coulomb friction and stick-slip phenomena and that at high amplitudes, impact processes result in dissipation as well as a shift of energy to other frequencies. Inadequate understanding of the physics precludes reliable predictions.

This report presents the work performed on a quasistatic joint study done as a first step in a research program aimed at understanding the dynamic behavior of joints. An experimental program on a bolted joint was accompanied by corresponding calculations using a state-of the art nonlinear quasistatics finite element code. This coupled study had the additional benefit of providing some measure of the capability of such codes to capture the relevant physics of this simpler geometry.

A lot of previous work has focused on joints and bolted interfaces. A large part of the research has utilized the Force-State mapping technique developed by Crawley and Aubert, 1986. This method determines the compliance through a measure of the quasistatic force vs. velocity and displacement. The effects of inertia on the response is removed from the data. Other studies of note include Greene, et al. (1988), Tsai and Chou, (1988), Mangalgiri, et al., (1987), and Kaplan, (1970).

Although there have been many other studies performed on bolted joints, the variety of joint geometries has led to large variations in behavior. This study is an attempt to quantify the behavior of typical joints found in today's weapon systems. These systems consist of many different interfaces to hold the various components in place. The important simulations pertain to the harsh environment the system sees during delivery. It is here that the joints get rigorously exercised and knowing how the entire system behaves is critical.

This paper starts with a description of the joint that was tested and some details on the tests performed. Next, the model is briefly described. Finally the results of the experiments and analysis are compared and conclusions are drawn.

Test Article Description

A critical part of this project was the choice of a specific joint. The joint had to be simple enough to give insight into the relevant physics and yet realistic enough to be representative of joints seen on current weapon systems. An additional requirement was that it had to have response characteristics that would allow testing without specialized equipment. For the above reasons, a bolted flange joint design was selected.

Initially, analytical studies of the joint were focused on static compliance. The analysis for the joint predicted different stiffnesses in compression and in tension and it seemed that an understanding of joint dynamics should begin with an understanding of the nonlinear static behavior. Further, understanding of the static compliances could be used to plan future tests. Among the parameters of this problem were how nonlinear elastic response is affected by pre-load, joint material, bolt material, and friction. These parameters are generally believed to have a considerable effect on the compliance of the joint.

The bolted flange joint chosen for our study is shown in Figure 1. This joint is characterized by the large contact surface in the flange. The relatively long span between bolts is a major factor in the change of joint stiffness between compression and tension. Bolt holes in the flanges were 0.035 inches larger in diameter than the bolt shank so there was a limited amount of shifting possible between the bolt head and the top surface of the flange. The non-linear behavior exhibited by this joint is believed to be consistent with many other types of joints that are present in weapon systems.

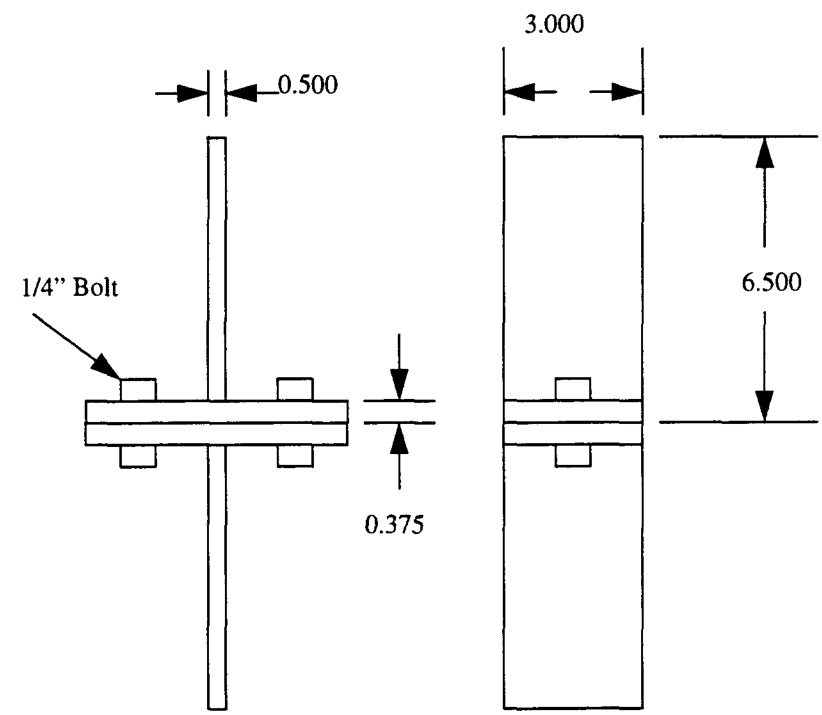

Figure 1. Dimensions of bolted flange joint

The joint was sized to manifest large displacement within the load range available on the hydraulic testing machine (20,000 lbf).

Beyond sizing, parameters that were felt to be important in the joint behavior were chosen based upon experience. These parameters were joint material, bolt material, bolt pre-load, and interface surface treatment. It was felt that of the four, the interface surface treatment would have the least effect on the joint compliance. Table 1 is a matrix summarizing the tests.

All testing was done on an MTS hydraulic testing machine. Jaws on the loading heads gripped the upper and lower ends of the specimens so that the clear distance between heads was about nine inches. The same procedure was used for all testing. A specimen with the bolts loosened was set in the machine, aligned with the lower jaw and then gripped with that jaw. Next, the top and bottom halves of the specimen were carefully aligned and the top jaw grip was tightened on the top half. Finally, a slight compression was applied and the bolts were tensioned to the appropriate preload. Each specimen was taken through three loading cycles, each of which consisted of slowly increasing the compression to 15000 lbs, holding at maximum compression for a moment, a slow release to 0 load, holding, tensioning to 2800 lbs, holding, and finally, a slow release to 0 load.

Table 1: Test Matrix for Joint

Joint Material	Bolt Preload	Bolt material	Surface Condition	Surface Roughness
Steel/Steel	2500 lb	Steel	lubed	125/125
Steel/Steel	2500 lb	Steel	nascent	125/125
Steel/Steel	900 lb	Steel	lubed	125/125
Steel/Steel	900 lb	Steel	nascent	125/125
Steel/Steel	2500 lb	Steel	lubed	20/20
Steel/Steel	2500 lb	Steel	nascent	20/20
Steel/Steel	900 lb	Steel	lubed	20/20
Steel/Steel	900 lb	Steel	nascent	20/20
Alum/Alum	2500 lb	Steel	lubed	125/125
Alum/Alum	2500 lb	Steel	nascent	125/125
Alum/Alum	900 lb	Steel	lubed	125/125

In the test matrix, the bolt preload that was used as nominal was approximately 2500 lb which is about 90% of the maximum working load that can be applied to the bolt. A "lubed" surface is one that has had a light, low viscosity oil applied to the surface. A "nascent" surface has a degreaser applied to remove any surface contaminants. The surface roughness is a standard roughness surface finish callout on machinist drawings, 125 being a rough machined finish and 20 being a very smooth machined finish. In Table 1, the surface roughness is specified for both surfaces of the joint. In addition to the above tests, repeatability tests were performed by removing the specimen from the test machine, disassembling, and reassembling the joint and retesting it in the same configuration. Also, some tests were repeated after rotating one half of the test specimen 180 degrees with respect to the other half.

Experimental Setup

Several types of instrumentation were used to measure the response of the bolted joint to a force input. A Linear Variable Differential Transducer (LVDT) internal to the testing machine provided a measure of the displacement of the jaws which gripped the test article. Input force was provided by the testing machine's internal load cell. The resulting load-displacement curve were used to characterize the joint and to assess the predictive ability of the simulation model.

Strain gauges were applied to the joint in the locations specified in Fig. 2. The strain gauges were located in positions where the simulations and intuition predicted significant strains. The information provided by the strain gauges allowed further verification of the simulation model

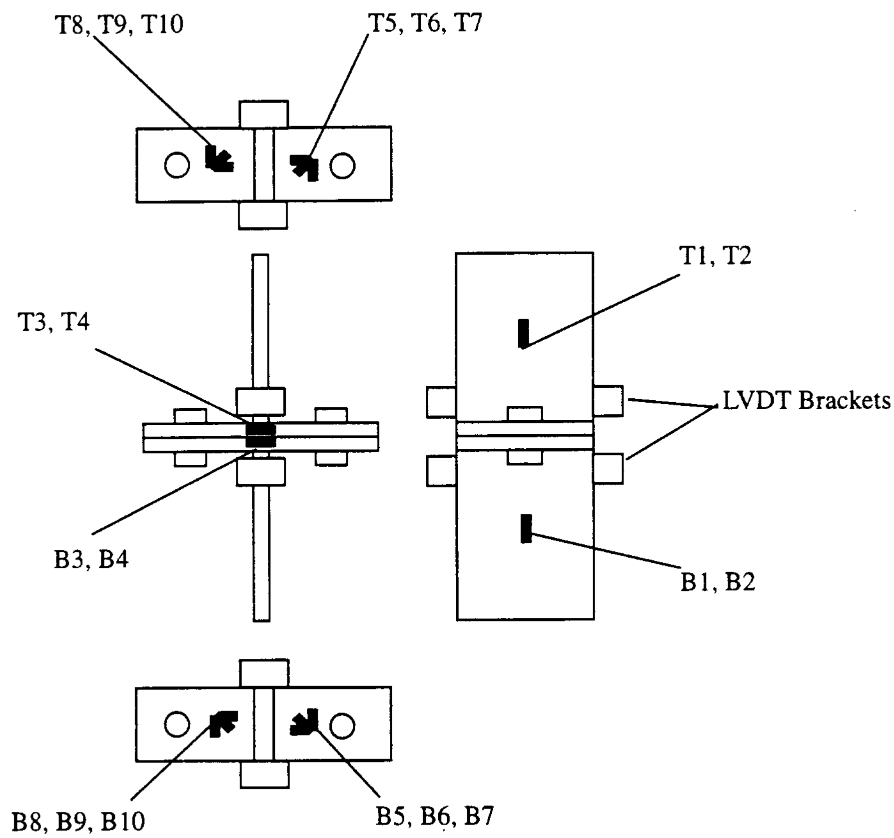

Figure 2. Location of the strain gauges

Initial testing showed a problem with using the testing machine's displacement measurements so all specimens used in subsequent testing were also instrumented with a displacement sensor that measured the relative localized displacement at the center of the joint.

Special bolts with built-in strain gauges were used so that the load in the bolts could be continuously monitored. This load in the bolt provided insight into the participation of the bolts in the response of the joint. This permitted the initial preload to be determined accurately and also showed when the preload was overcome by the displacement of the joint.

Description of the Model

Simulations of the static tests were performed using the analysis code JAS3D version 1.4-E. The code was developed for quasi-static analysis of non-linear structural systems. It has an advanced contact algorithm which was necessary to simulate the important responses of the joint. Initial difficulty in producing an accurate solution was traced to an inappropriate choice of parameters defining the contact surface. The procedure for choosing the parameters has been somewhat automated in the current contact algorithm although it was not available when the simulations were performed. This phenomenon will be explained in more detail in the next section.

The mesh of the joint was developed using the Cubit mesh generating tool developed at Sandia. A solid geometry is developed in Cubit then meshed, typically using domain decomposition to facilitate the production of a reasonable mesh. The final mesh exploited some of the symmetry of the model and consisted of about 8000 nodes (Fig 3.) It should be noted that the model has only an interface friction coefficient but no provision for incorporating surface roughness. Preload was modeled by applying a pseudo-temperature decrease to the bolt.

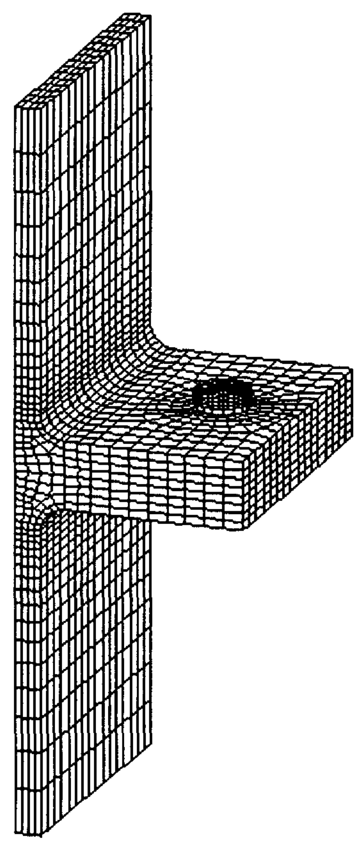

Figure 3. Mesh used for simulation

Results

The results of the calculations and the measurements on the first test specimen are shown in Figure 4. Very good agreement is found in the force/strain plots at each of the locations shown in the figure (see Fig 2 for strain gauge locations). This set of data was taken from the first set of experiments. These experiments were used as "practice" runs to get a feel for the behavior of the joint and the test equipment. A mild steel specimen with a coarse surface finish was used for the test. Mild steel has poor shape stability for machining and the specimen demonstrated this, having one of the mating surfaces showing a significant concave bow. Based on this test, we switched to a dimensionally stable stainless steel for all specimens used in subsequent tests.

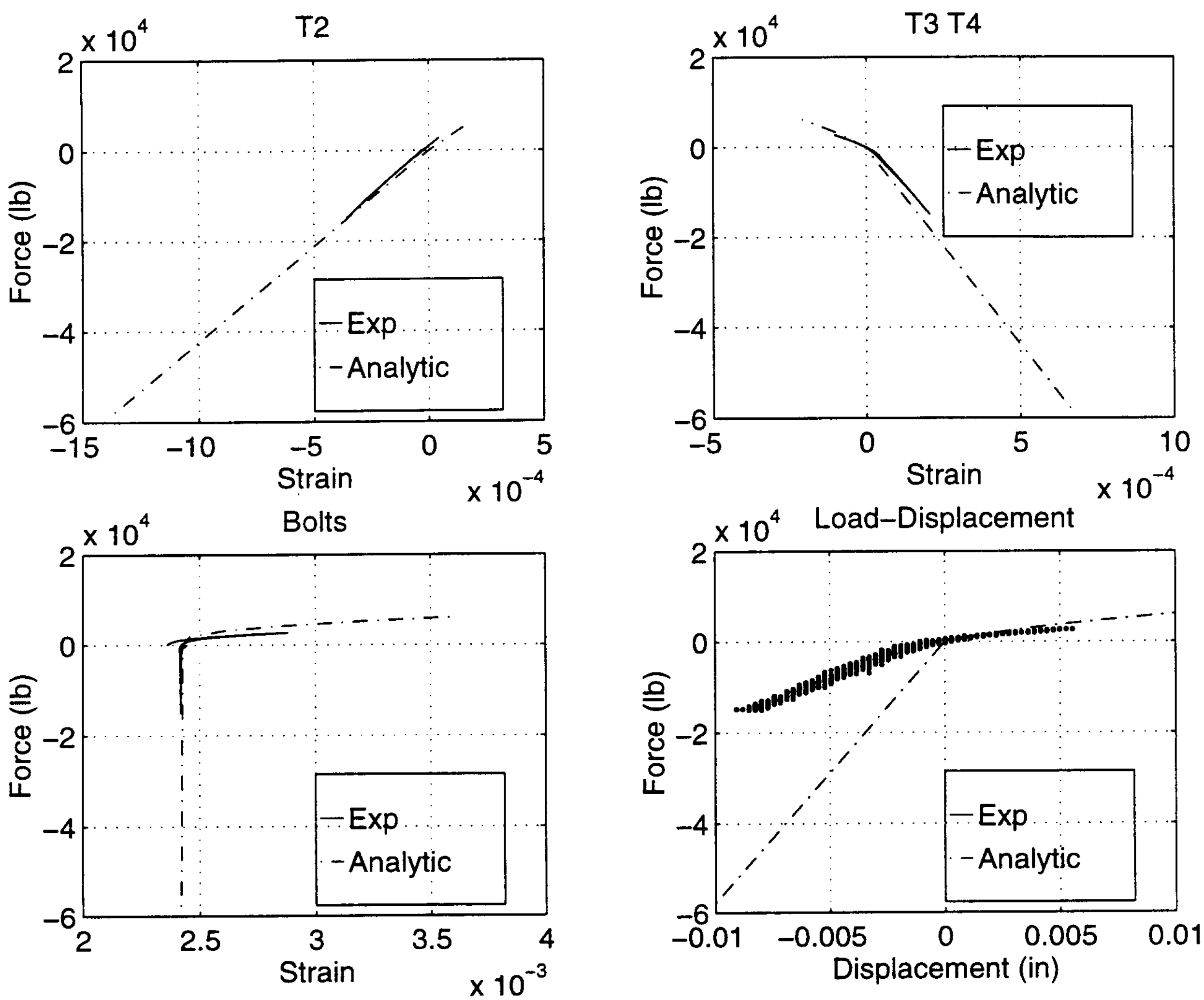

Figure 4. Comparison between experiment and analysis
(Nominal Case)

For reasons that we do not yet fully understand, there is substantial disagreement between the simulated and experimental force-displacement curve. The displacement measurement was made by the machine and shows the displacement between its grips. A possible explanation is that the compliance of the machine is affecting the measurements. For the remaining tests, compliance was measured relative to the difference between the displacement of the flanges. A Linear Voltage Differential Transducer (LVDT) mounted on the specimen was used for these measurements (see Fig. 2).

A very interesting feature of the numerical calculations was that the code would not converge for small increments in imposed load. Each calculation had to be done as a single-step large deformation from rest. This is believed to be due to the contact algorithm that was used in the code. The algorithm requires two interacting parameters, a distance tolerance and a force tolerance, to be specified for each contacting surface. The distance tolerance specifies how close two surfaces have to be to be considered in contact. The force tolerance describes the "stickiness" of the surfaces. Both parameters are numerical artifacts that are adjusted to influence the convergence of the problem. The nature of the contact in this simulation made these parameters vary over different solution regions as well as over the contact surface itself. Since these calculations were made, a new algorithm has been developed that is expected to improve these issues.

Figure 5 shows plots of the force applied to the joint vs. the displacement between the back faces of the flanges as described above (125=coarse finish, 20=smooth finish, L=lubed, N=nascent). The joints were disassembled many times between runs to change the surface condition of the mating surfaces and to test repeatability. All of the experimental results were shifted such that the smallest displacement was zero. The analytic results were also shifted to allow for easy comparison with the experimental results. The analytic results had the "knee" at zero force and zero displacement.

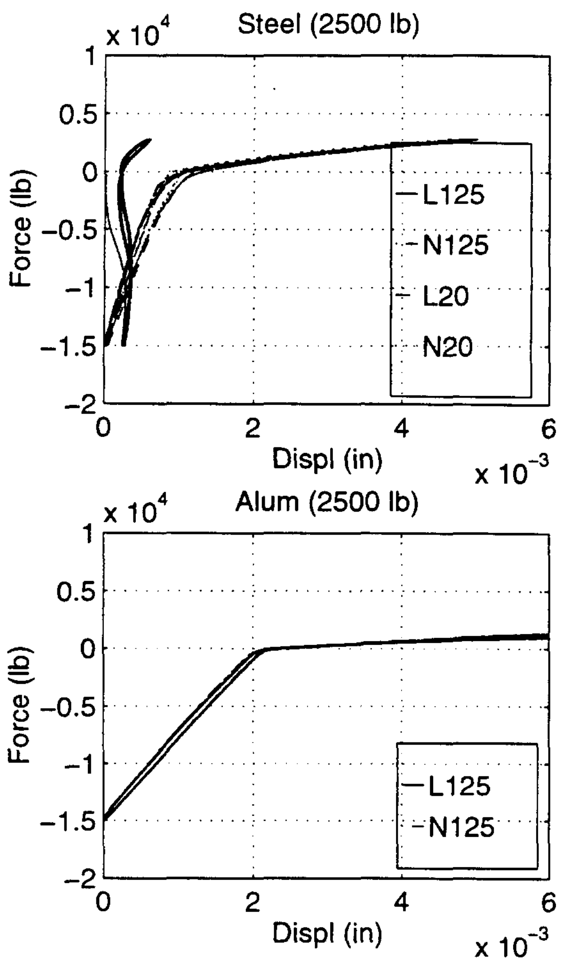

Figure 5. The effect of surface finish on static compliance

The steel joint seems unaffected by both surface finish and lubrication. There is an errant dataset that can be ignored in the steel joint with 2500 lb preload on the bolt. In that case, the LVDT was improperly installed outside of its operating range. The remaining sets are fairly consistent, especially in tension.

With the LVDT gauges mounted on the specimens, the agreement between the analytical results and the experiments is much improved. Figure 6 shows a typical comparison between theory and experiment (steel specimen, coarse interface, 2500 lbs bolt load, lubricated interface). Note that the compliance (slope of the curves) in both tension and compression shows good agreement. For this plot the reading of the LVDT gauge at 0 load was taken to be 0 displacement so all displacements are given relative to this datum. The offset that appears in the compression part of the curve is assumed to be an artifact of imperfect flatness of the mating surfaces. As expected and as predicted by the analysis, in compression the specimens behaved essentially like bars with the cross-section of the top or "stem" parts of the specimen.

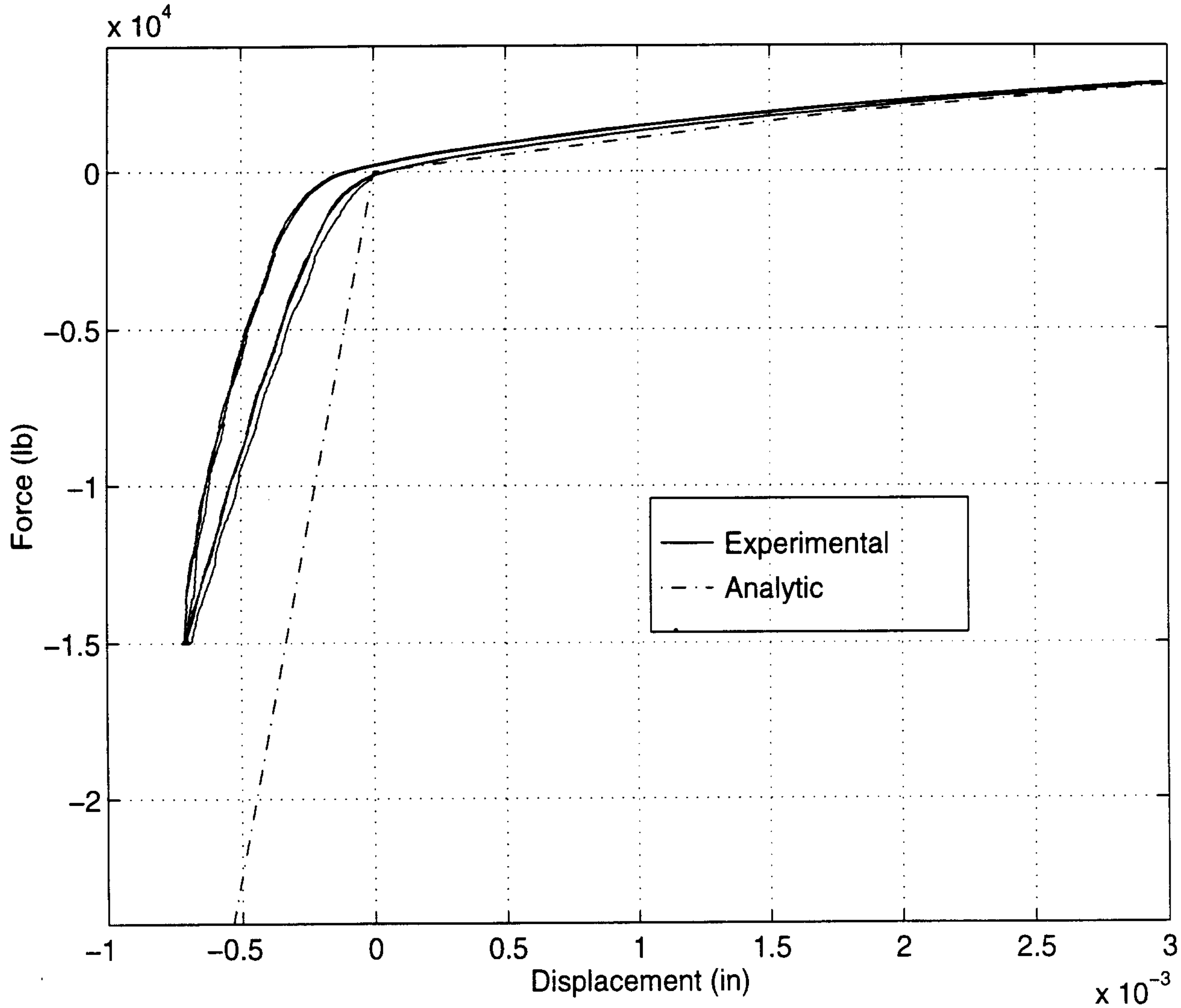

Figure 6. Typical comparison between experimental and analytic compliance

While there was some test-to-test variation, the experiments did not show any significant dependencies on surface roughness or lubrication. This is also not surprising since the symmetry of the specimens would tend to minimize relative motion between the mating surfaces. In accordance with analytical predictions, the stiffness of the specimens in tension was slightly less with the 900 lb bolt tension than with the 2500 lb tension.

In all of the tests a significant hysteresis was observed. Figure 7 shows a typical set of results from a steel specimen with a lubricated coarse interface and 2500 lb bolt tension. The part of the force-displacement curve going from maximum compression to maximum tension lies above the remainder of the curve that loads up in compression and loads down in tension. The divergence in the loading and unloading paths varied noticeably from test to test but hysteresis was always present. In the aluminum, the effect is less obvious, yet present, as is seen in the narrow hysteresis loop for aluminum in Fig 5. At present we have no good explanation for the cause of the hysteresis or explanation for an mechanism that may be absorbing energy at the joint.

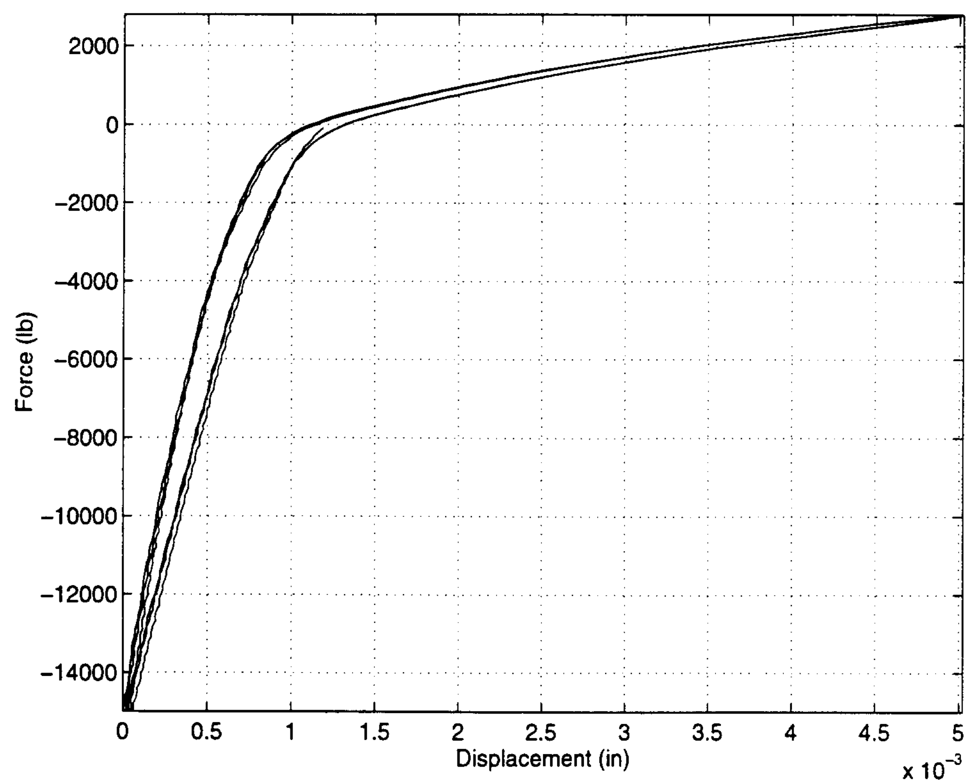

Figure 7. Steel hysteresis loop

Another parameter of interest was the preload on the bolt. Figure 8 shows the experimental and analytic studies of the bolt preload. The bolt was preloaded with either 2500 or 900 lbs of force. This represents about 90% and 30% respectively, of the recommended working load limit. As may be expected, the bolt with the higher preload has a higher stiffness. Qualitatively, the analysis mimics the experimental results.

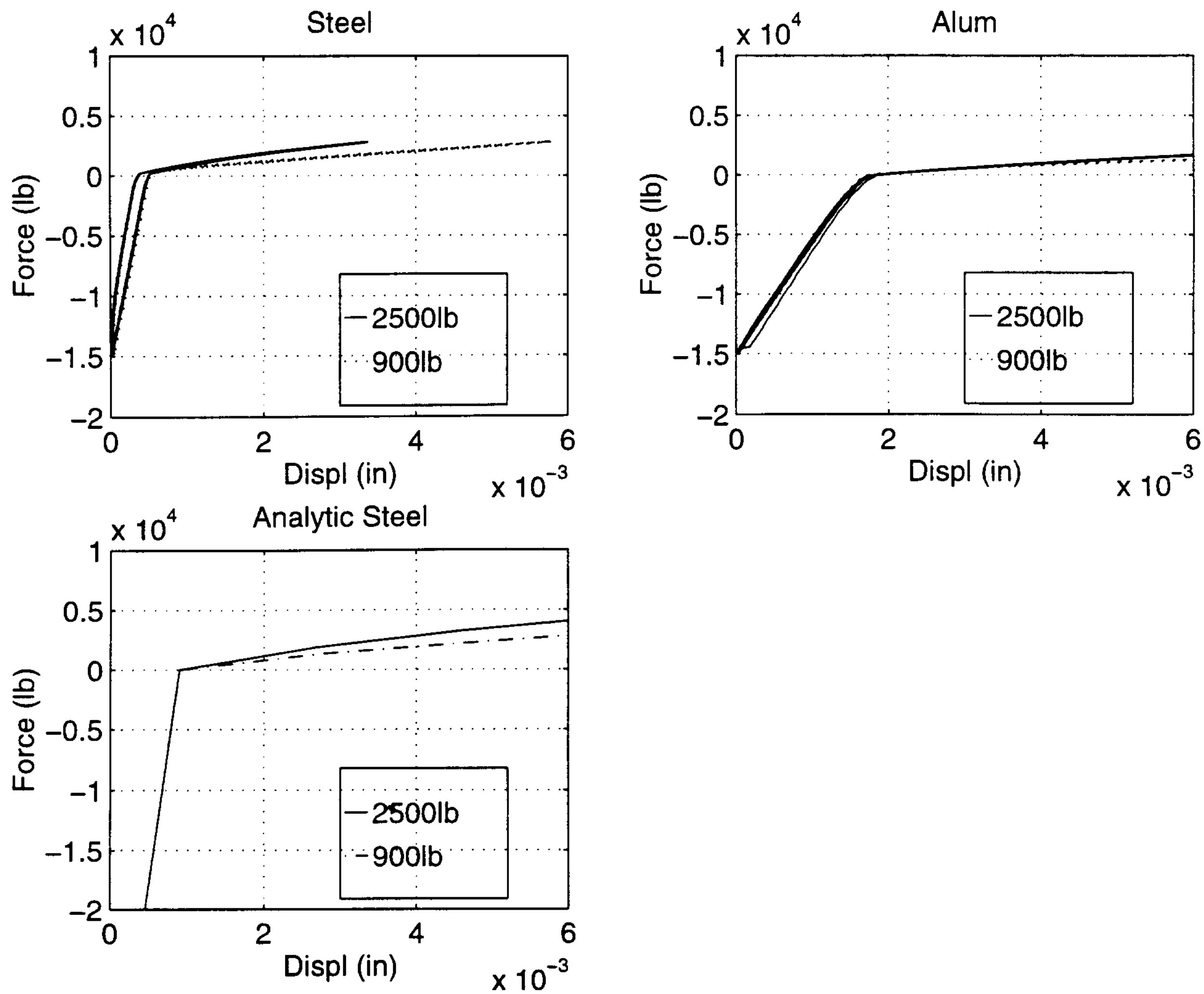

Figure 8. The effects of preload on static compliance

For all tests, the bolt tension appeared to "ratchet" down during the three cycles of the load history. As typical examples, Figure 9 shows the bolt tension for steel specimens with the smooth interface. At present we have no explanation for this phenomenon, but we believe it to be related to shifting of the bolt and it's washers with respect to the flange holes. The bolt tension curves show that, as expected, the 2500 lb pretension was almost sufficient to keep the bolt tension constant while the 900 lb pretension was quickly overcome.

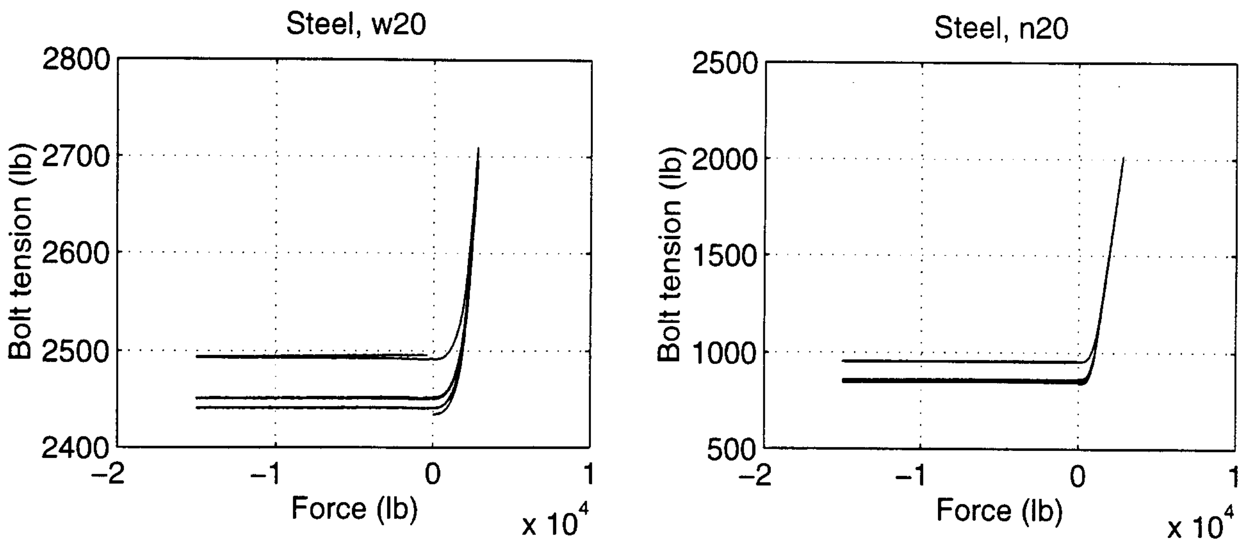

Figure 9. Bolt tension histories

Finally, the responses are directly dependent on joint material (Fig. 10). The difference in stiffness between the two materials is quite apparent. The aluminum, as expected, is softer in both compression and tension. The hysteresis loop can be seen in both compression and tension. These plots have not been corrected for the offset caused by the LVDT which was not consistently set up at the same point in its operating range.

The computational tool used, like most nonlinear large deformation finite element codes, is capable of predicting the gross nonlinear processes, but is unable to capture the effects of small changes. The figures presented in this work show a fairly large range of displacements. It was difficult to obtain a solution at regions around the "knee" of the compliance curves (i.e., the transition from tension to compression). This appears to be a discretization artifact in the contact algorithm; as the mesh is refined one anticipates that the code will be more sensitive to smaller changes. On the other hand, mesh refinement results in substantially slower convergence. It is felt that more work needs to be done in algorithm development to improve this situation.

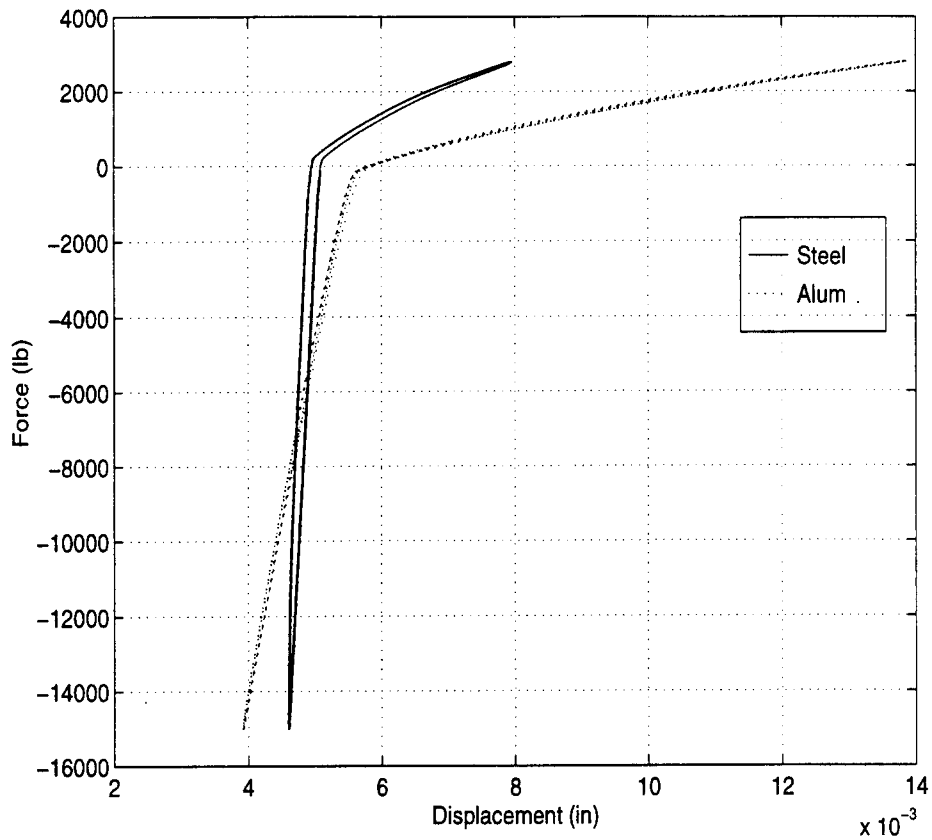

Figure 10. Comparison of different joint materials

Conclusions

The experimental program provided data on the static behavior of a simple bolted joint. The surface related parameters that were varied in the program, lubrication and roughness, showed very little effect on the results. However, this was expected since the symmetry of the loading precluded much relative motion of the mating surfaces. The bolt tension had a minor effect on joint stiffness, but it was small compared with the dramatic effect due to the joint geometry itself. The flexing in the joint pieces between the bolt holes caused the system to be much softer in tension than in compression. A problem with this type of testing is that the displacement at the joint is usually small. This causes difficulty in making an accurate compliance measurement for the joint, especially in compression.

Two unexpected results were observed, the hysteresis in the load displacement curve during cyclic loading and the cyclic reduction of the bolt preload. At present we have no definitive explanations for either phenomenon. The hysteresis, especially, is an interesting phenomenon since it appears to represent energy dissipation in the system. However, at this time we are not sufficiently confident of our testing technique to make definite statements about energy loss.

Model calculations of the joint behavior and of the strains in the specimens showed good agreement with test results. However the surface interactions proved challenging to model and performing the analyses was far from a trivial exercise. Our conclusion is that the current state of the art in computational nonlinear quasistatics is that it is not sufficiently mature to provide guidance on the subtle significance of surface parameters such as preload, roughness, waviness, or lubrication.

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