SAND97-2795C
SAND--97-2795C

A MECHANICAL DIODE: COMPARING NUMERICAL AND EXPERIMENTAL CHARACTERIZATIONS

CONF-980515--

Todd Simmermacher
Post Doctoral Associate

Daniel Segalman
Member
Technical Staff

Mathias Sagartz
Member
Technical Staff

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0557

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 address. It is shown that the model predicts the experimental strains and compliance fairly well.

It will be seen that the joint behavior is a mechanical analogy to a diode. In compression, the joint is very stiff, acting almost as a rigid link, while in tension the joint is soft, acting as a soft spring.

Introduction

The predictive modeling of vibration of many structural systems is crippled by an inability to predictively model the mechanics of joints. The lack of understanding of joint dynamics is evidenced by the substantial uncertainty of joint compliances in our numerical models and by our 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 shift of energy to other frequencies. Inadequate understanding of the physics precludes reliable predictions.

This paper reports 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 focussed 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 demonstrated 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 regarding future work.

Test Article Description

A critical part of this project was the choice of joints. The joint had to be simple enough to give insight to 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.

Initial studies of the joint used in this study focused on static compliance. Such joints exhibit 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 was how nonlinear elastic response is affected by pre-load, joint material, bolt material, and friction. These parameters are generally believed to have 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 compres-

DISCLAIMER

sion and tension. 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.

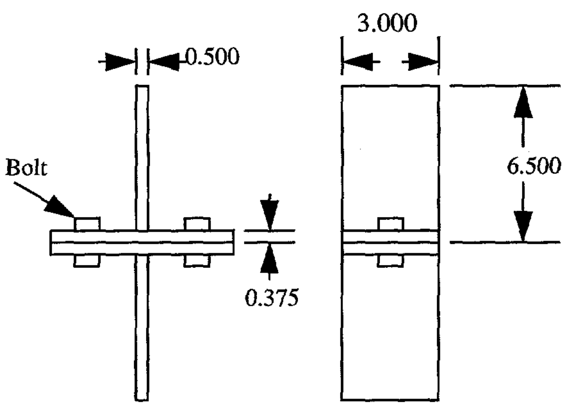

Figure 1. Dimensions of Bolted Flange Joint

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 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.

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 load that can be applied to the bolt. The maximum was around 2700 lb. A "lubed" surface is one that has had a light, low viscosity oil applied to the surface then wiped off. A "nascent surface" has a degreaser applied to remove any surface contaminants. The surface roughness is a standard roughness measure, typically determined from a profilameter. 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 disassembling and reassembling the joint and retesting it in the same configuration.

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 a load cell. The resulting load-displacement curve was 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

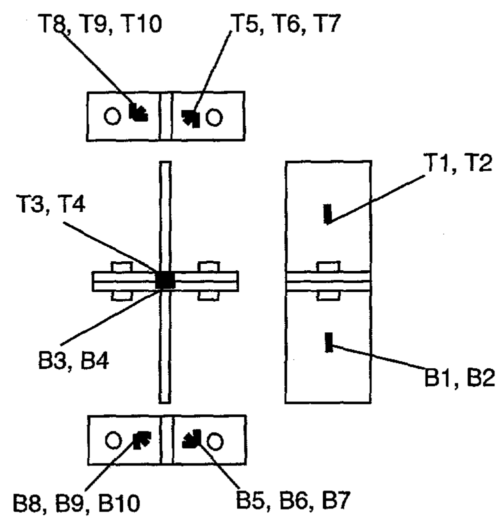

Figure 2. Location of the strain gauges

The test article was 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

The 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. The code 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.).

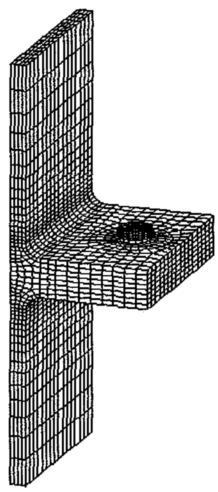

Figure 3. Mesh used for simulation

Results

The results of the calculations and the measurements 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.

For reasons that we do not yet 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 gripes. A possible explanation is that the compliance of the machine is affecting the measurements. In the remaining plots, compliance is measured relative to the difference between the displacement of the flanges. A Linear Voltage Differential Transducer (LDVT) mounted on the specimen was used for these measurements.

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. A new algorithm has been developed since these calculations were made that is expected to improve these issues.

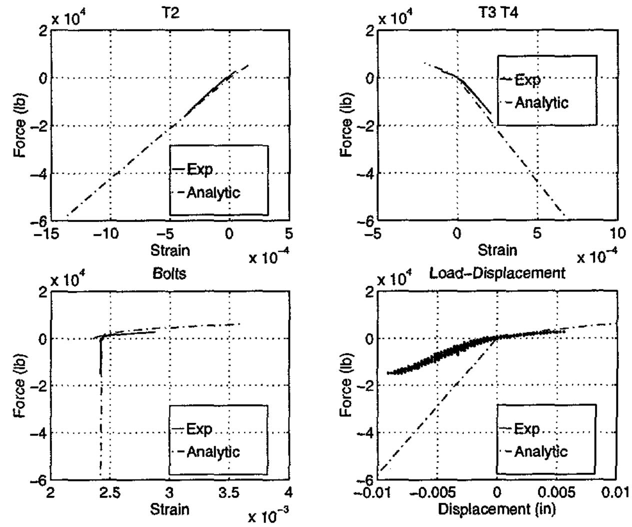

Figure 4. Comparison between experiment and analysis (Nominal Case)

Figure 5 is a plot of the force applied to the joint vs. the displacement between the faces of the flanges as described above (w20 and n20, "w"=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.

It is noted that the analytic results qualitatively represents the experimental data. The analytic results, as before, seem stiffer in both compression and tension than the experimental results show. In compression, the joint is basically a bar. The compression compliance calculated with the model is consistent with the stiffness for a bar of equal dimensions, verifying the calculation. The additional stiffness in both compression and tension may be due to the testing machine.

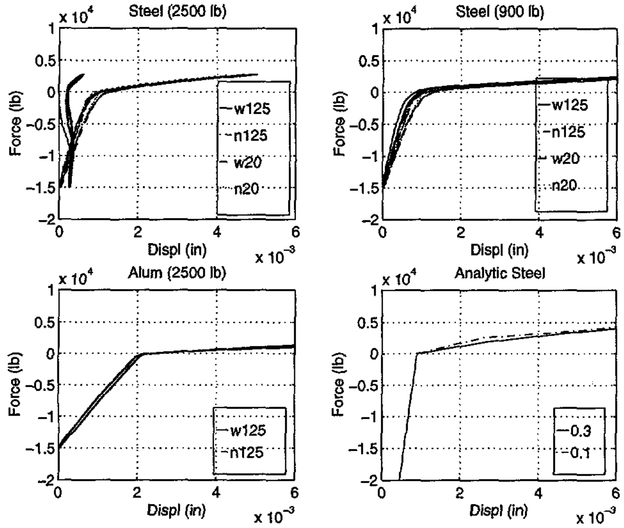

Figure 5. The effect of surface finish on static compliance

The steel joint seems unaffected by surface finish. There is an errant dataset that can be ignored in the steel joint with 2500 lb preload on the bolt. It is believed that the LVDT was improperly installed outside of its operating range. The remaining sets are fairly consistent. It appears that some of the experimental runs on the different joints have a slightly lower compliance. Figure 6 isolates the steel joint with a surface finish of 20 and a lubed surface. When the test involves moving from compression to tension, the force displacement curve lies above the corresponding curve for moving from tension to compression. In the aluminum, the effect is almost imperceptible, yet present as is seen in the narrow hysteresis loop for aluminum in Fig 5. The conventional wisdom is that this sort of behavior is associated with slippage in the test apparatus.

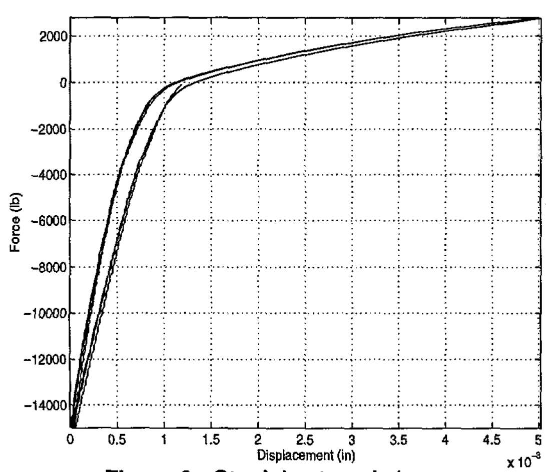

Figure 6. Steel hysteresis loop

Another parameter of interest was the preload on the bolt. Figure 7 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 bolt yield. As may be expected, the bolt with the higher preload has a higher stiffness. With the steel joint, once again the hysteresis loop is apparent. Qualitatively, the analysis mimics the experimental results.

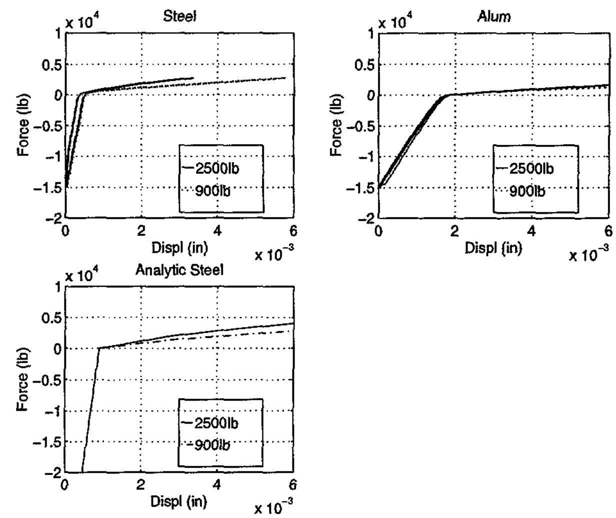

Figure 7. The effects of preload on static compliance

Finally, the responses are directly dependent on joint material. 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 artifact of the LDVT as discussed before. Analysis results for the aluminum joint are not available at this time for comparison.

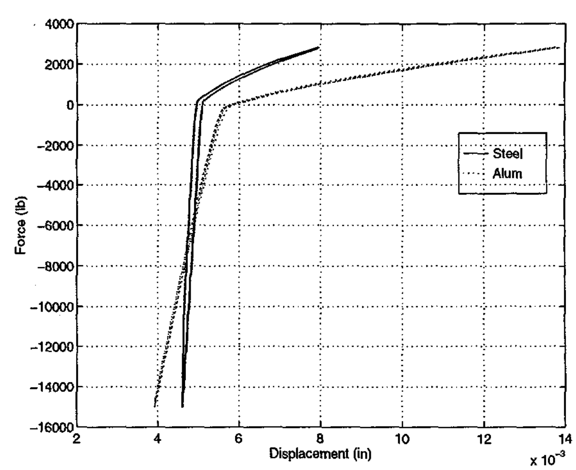

Figure 8. Comparison of different joint materials

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.

Conclusions

This work showed the results of a preliminary study on bolted interfaces. It was shown that the simulations predicted the strain fields, and qualitatively predicted the compliance. The deviations in the compliance are felt to be due to the testing machine used.

The most important conclusion that we made was that current state art in computational nonlinear quasistatics is inadequate to provide guidance on the subtle significance of such quantities as surface preload, surface roughness, surface waviness, or other surface treatment.

Acknowledgments

The authors wish to thank Martin Heinstein for his help with using the contact algorithm used in this work.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

References

Greene W. H., Knight, N. F, and Stockwell, A.E. (1988), "Structural Behavior of the Space Shuttle SRM Tang-Clevis Joint," *AIAA Journal of Propulsion*, Vol 4, No.4, pp 317-327.

Tsai, J-S, and Chou, Y-F, (1988),"The Identification of Dynamic Characteristics of a Single Bolt Joint," *Journal of Sound and Vibration*, Vol. 125, No. 3, pp 487-502.

Mangalgiri, P. D., Ramamurthy, T. S., Dattaguru, B., and Rao, A.K. (1987), "Elastic Analysis of Pin Joints in Plates Under Some Combined Pin and Plate Loads," *International Journal of Mechanical Science,* Vol 29, No 8, pp 577-585.

Kaplan, S. M., (1971), "Flexibility Coefficients for Structural Joint Assemblies," *AIAA Journal of Spacecraft*, Vol. 8, No. 1.

Blanford, M. (1997), *JAS3D: A Multi-Strategy, Iterative Code for Solid Mechanics Analysis*, Sandia National Laboratory Internal Memo.

CUBIT Mesh Generation Environment, Volume 1: Users Manual, Sandia National Laboratory, No. SAND94-1100.