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Static Strength Characteristics of Mechanically Fastened Composite Joints

(MSFC Center Director's Discretionary Fund Final Report, Project No. 95–07)

D.E. Fox and K.W. Swaim
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September 1999

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TECHNICAL MEMORANDUM

STATIC STRENGTH CHARACTERISTICS OF MECHANICALLY FASTENED COMPOSITE JOINTS
(MSFC Center Director's Discretionary Fund Final Report, Project No. 95–07)

1. INTRODUCTION

Composite materials used in spacecraft design offer many advantages in weight reduction, strength, and stiffness when compared to conventional materials. However, to utilize composites fully, a thorough understanding of the joint strength is required to prevent premature failure of a component at an interface. Analysis of bolted composite joints presents a great challenge to the structural analyst because of the large number of parameters, which will affect the strength. These parameters include edge distance, width, bolt diameter, laminate thickness, ply orientation, ply-stacking sequence, and bolt torque. Since the strength characteristic of a composite joint is unique due to the influence of these parameters, strength data derived from structural testing is required to allow for a thorough assessment.

The purpose of this research project is to evaluate the influence of various hole parameters on the structural strength characteristics of mechanically fastened composite joints. Testing is performed to determine the strength characteristics. Testing is followed by analysis and test data correlation. The successful correlation of test and analytical data will increase confidence in analysis methods, allow formulation of a coherent analysis methodology, and permit development of further analytical techniques. Also, the research will improve the understanding of testing composite joints and associated failure modes.

2. COUPON TEST CONFIGURATION

The composite coupons used for testing were fabricated from IM6/3501 graphite epoxy 32-ply quasi-isotropic laminate. This material system is selected because the extensive A-basis material database available. The quasi-isotropic laminate is selected because it is a typical design in structural applications. Eighteen different coupon configurations were designed with the following hole parameters:

Diameter:	d = 0.164, 0.194, 0.25 in.
Edge Ratios:	e/d = 1.5, 2.0, 3.0
Width Ratios:	w/d = 2.0, 2.5
Torque:	Q = 0.0 in.-lb

The general coupon design is shown in figure 1 and table 1.

Table 1. Test coupon design matrix.

Test Phase	d (in.)	e/d	e (in.)	w/d	w (in.)	No. of Coupons
A	0.164	1.50	0.246	2.50	0.410	7
B	0.164	2.00	0.328	2.50	0.410	7
C	0.164	3.00	0.492	2.50	0.410	7
D	0.164	1.50	0.246	4.00	0.656	7
E	0.164	2.00	0.328	4.00	0.656	7
F	0.164	3.00	0.492	4.00	0.656	7
G	0.190	1.50	0.285	2.50	0.475	7
H	0.190	2.00	0.380	2.50	0.475	7
I	0.190	3.00	0.570	2.50	0.475	7
J	0.190	1.50	0.285	4.00	0.760	7
K	0.190	2.00	0.380	4.00	0.760	7
L	0.190	3.00	0.570	4.00	0.760	7
M	0.250	1.50	0.375	2.50	0.625	7
N	0.250	2.00	0.500	2.50	0.625	7
O	0.250	3.00	0.750	2.50	0.625	7
P	0.250	1.50	0.375	4.00	1.000	7
Q	0.250	2.00	0.500	4.00	1.000	7
R	0.250	3.00	0.750	4.00	1.000	7

3. TEST CONFIGURATION

Coupon testing was performed using a double-lap shear test fixture. A shear pin was used to secure the coupon to the test fixture since torque from a fastener would add friction thus increasing the strength capability of the joint. A 5,000-lb tensile test machine was utilized to test the coupons. Testing followed the methodology specified in ASTM E 238–84, *Standard Test Method for Pin-Type Bearing Test of Metallic Materials*[1] and MIL–HDBK–17B, *Polymer Matrix Composites*.[2] All testing was performed using displacement or stroke control.[1]

4. COUPON TEST RESULTS

Seven coupons were tested for each coupon configuration. The test data for each coupon test phase was plotted and reduced. Many of the plots exhibited a slight lag at the beginning of the load application, which represented the looseness or "slop" in the test setup. This "slop" was removed from the data and the coupon test data for each test phase was combined into a single plot. Numerical analysis was performed on the data utilizing the Chauvenet's Criterion, thus eliminating dubious data points.[3] Figures 2–19 show the coupon test data for each test configuration.

Based on the data reduction, an initial failure load was calculated. This failure load is defined to be the first hump in the curve, the point where the laminate could not sustain any more loading without significant displacement at the bolthole. The majority of the coupons tested in each test phase exhibited similar load and displacement characteristics up to the defined initial failure load. Ultimate failure is defined as the complete failure of the composite coupon. Not all test coupons were tested to ultimate failure, and components would never be designed to this ultimate failure load. Definitions for ultimate failure load, initial failure load, and first-ply failure are shown in figure 20.

5. POSTTEST CORRELATION ANALYSIS

Posttest analysis of the data was performed using finite element modeling techniques, FORTRAN programs, and closed-form methods. The finite element method and FORTRAN programs only looked at predictions of first-ply failure and did not consider any type of nonlinear effect or progressive failure. The closed-form method which is a modified equation to the bolthole bearing stress calculation was used in an attempt to match the initial failure load (previously defined) from the test data.

5.1 Finite Element Modeling

NASTRAN v70 finite element models, along with PATRAN, were used to perform analysis on the Phase P coupons. Models were built to gain understanding of the stress distributions on the various plies of the laminate. Loads were applied to the hole using cosine load distributions and the end of the coupon was fixed. Results of the analysis showed first-ply failure of the laminate to occur at loads >50 percent of the initial failure load. This was expected since the transverse strength of a single ply is significantly lower than the fiber direction. However, even after the predicted first-ply failure, the laminate still exhibited significant strength. Figure 21 presents the first-ply failure loads relative to initial failure load, and figure 22 shows the NASTRAN finite element model.

5.2 Bolted Joint Stress Field Model FORTRAN Code

The Bolted Joint Stress Field Model (BJSFM) FORTRAN code was also used to determine the stress distributions around the hole of the composite.[4] It was found that the results from the BJSFM model were very similar to the NASTRAN model. The BJSFM calculates the bolthole load that corresponds to the first-ply failure of the laminate. For the Phase P coupon, the failure was calculated on the 90-degree ply in its transverse direction (reference fig. 21).

5.3 Analytical Methods

In an attempt to analytically predict the initial failure load as defined above, a modified bolthole bearing stress calculation was performed. The calculation is based on the bolthole diameter, the laminate thickness, and the calculated laminate strength at first-ply failure:

$$Fb = S * T * D \tag{1}$$

where:

S = calculated laminate compression strength (psi)
(based on Tsai Hill Failure Theory)
T = thickness (in.)
D = hole diameter (in.)
Fb = predicted failure load (lb).

Table 2 compares the test measured initial failure load and the predicted failure load using the above relationship.

Table 2. Test coupon measured and predicted failure loads.

Test Phase	Dia.(in.)	e/d Ratio	w/d Ration	Measured Failure (lb)	Predicted Failure (lb)
A	0.164	1.5	2.5	1277	1279
B	0.164	2.0	2.5	1318	1279
C	0.164	3.0	2.5	1139	1279
D	0.164	1.5	4.0	1388	1279
E	0.164	2.0	4.0	1302	1279
F	0.164	3.0	4.0	1256	1279
G	0.190	1.5	2.5	1454	1481
H	0.190	2.0	2.5	1438	1481
I	0.190	3.0	2.5	1410	1481
J	0.190	1.5	4.0	1424	1481
K	0.190	2.0	4.0	1395	1481
L	0.190	3.0	4.0	1371	1481
M	0.250	1.5	2.5	2203	1949
N	0.250	2.0	2.5	2191	1949
O	0.250	3.0	2.5	2055	1949
P	0.250	1.5	4.0	2157	1949
Q	0.250	2.0	4.0	2099	1949
R	0.250	3.0	4.0	1971	1949

6. DISCUSSION

As previously mentioned, the first-ply failure occurs at a load much lower than the initial failure load. All failures after first-ply failure are progressive-type failures where serious matrix damage, delamination, and fiber breakage is occurring and the stiffness is changing. Attempts were made during modeling to remove plies from the laminate after predicted failure to adjust stiffness and to determine new stress levels; however, no trend was found to match the test data. This method to model the progressive failure of the laminate was found inadequate.

As shown in table 2, the modified bolthole bearing stress calculation correlated well with the test data. This method is based only on a pin-type connection; however, a preloaded connection would only increase load-carrying capability.

7. CONCLUSION

The purpose of this research project was to evaluate the influence of various hole parameters on the structural strength characteristics of mechanically fastened composite joints. The purpose was not to develop failure theory codes that would be capable of evaluating different failure mechanisms in the composite-bolted connection for a given load.

The test data revealed that even after first-ply failure, the bolted connection (tested) still maintained considerable strength capability. The research performed for the configurations tested showed that if the BJSFM FORTRAN code or finite element models are used to predict bolthole failures based on ply properties, the actual bolthole capability is higher. The modified bolthole-bearing calculation agreed well with the initial failure load obtained from tests for the configurations tested.

The methods discussed here should not be substituted for testing of an actual configuration. This type of analysis offers a tool or methodology to the designer/analyst for preliminary design predictions to be made on the structural strength characteristics of mechanically fastened composite joints.

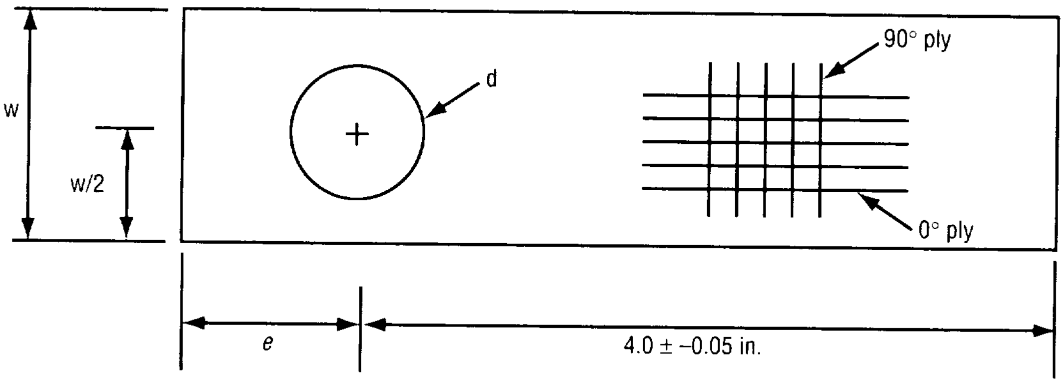

Figure 1. Coupon design.

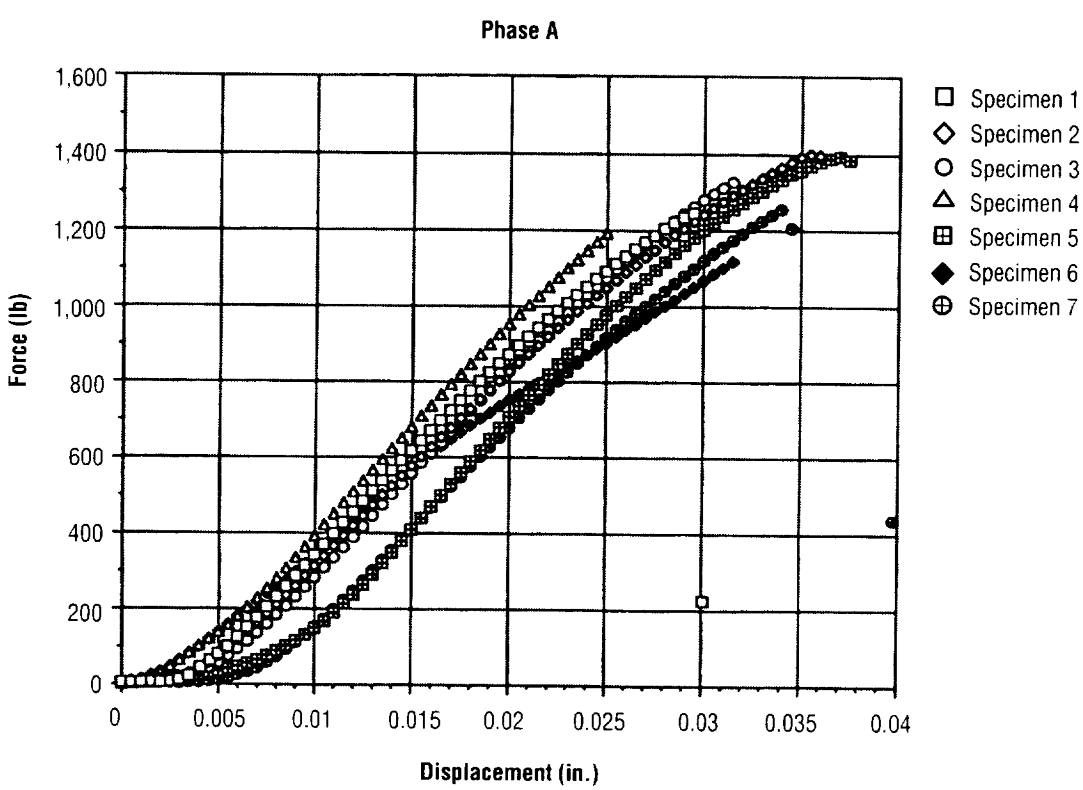

Figure 2. Phase A test data.

Phase B

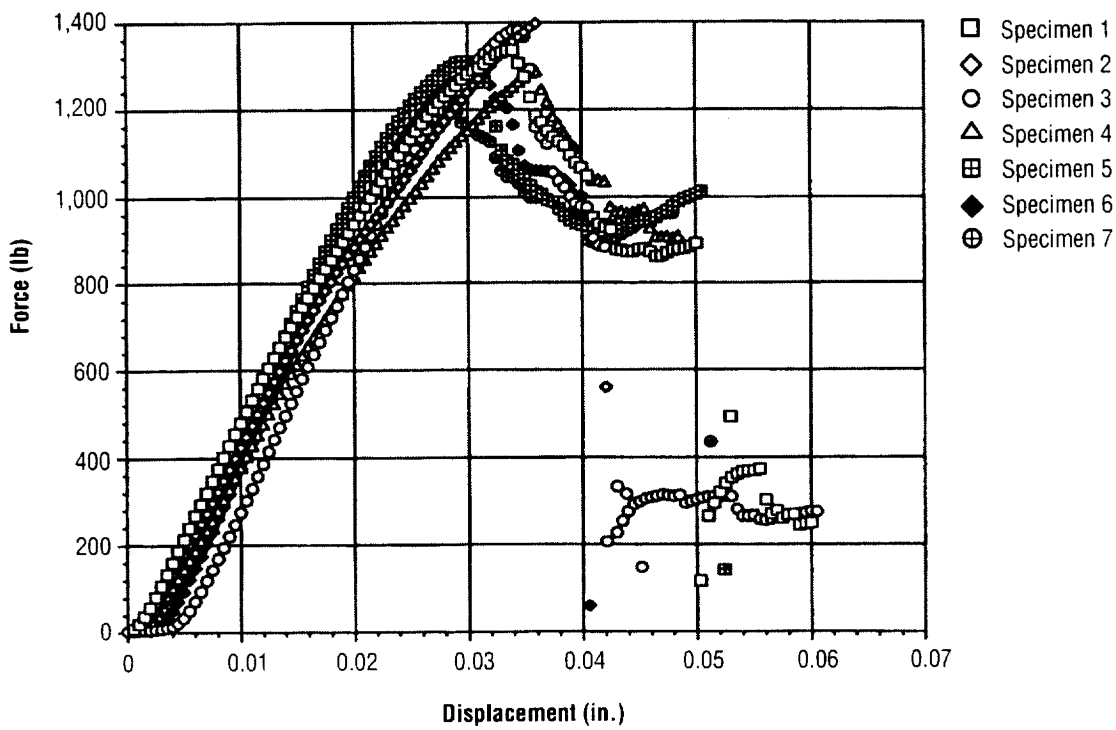

Figure 3. Phase B test data.

Phase C

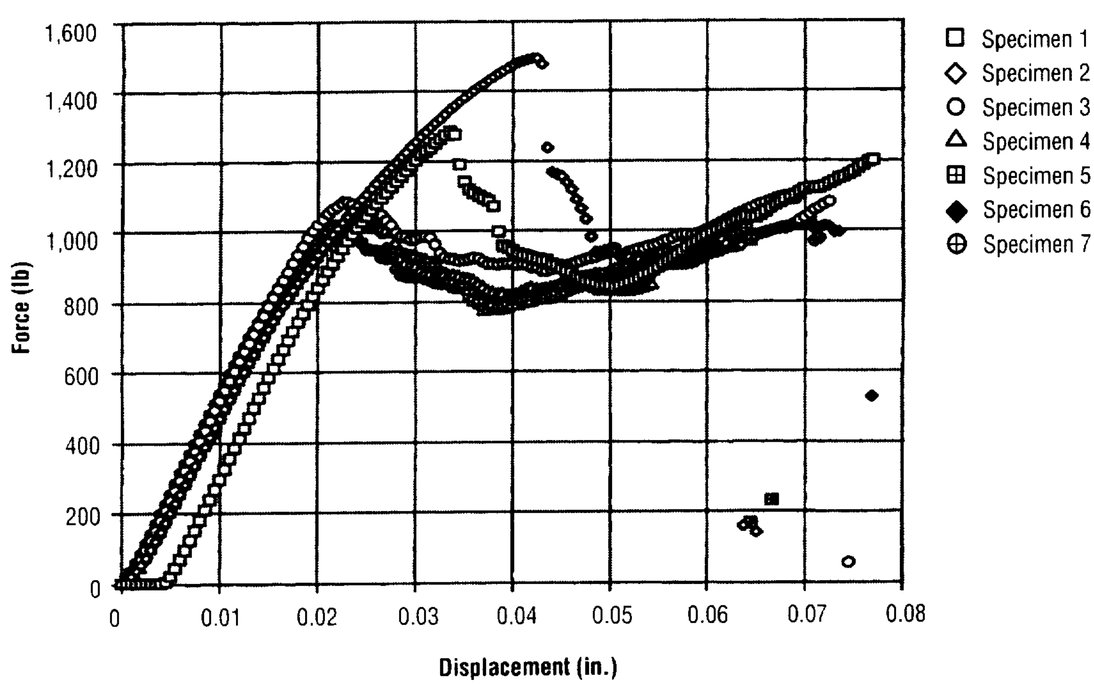

Figure 4. Phase C test data.

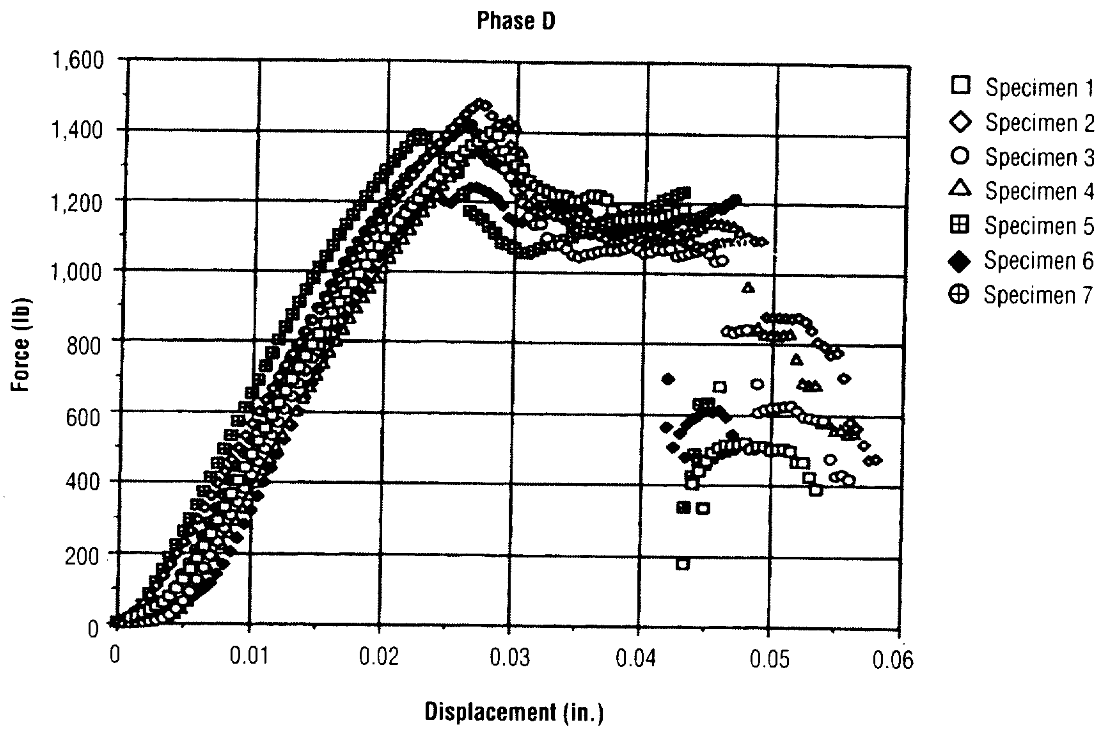

Figure 5. Phase D test data.

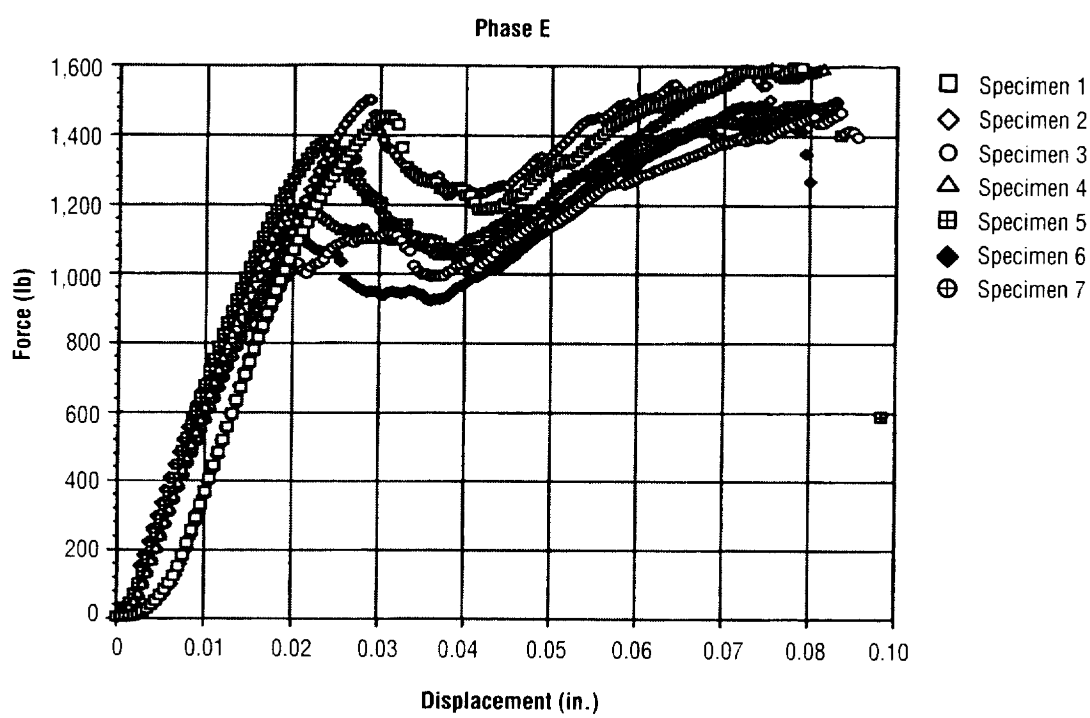

Figure 6. Phase E test data.

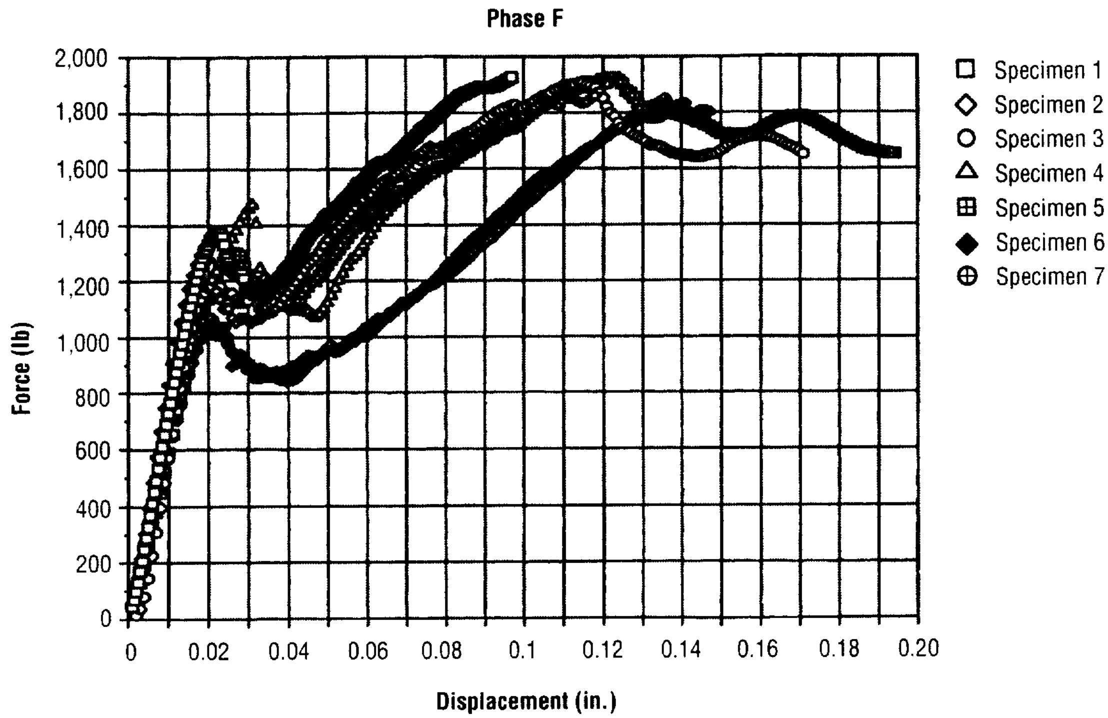

Figure 7. Phase F test data.

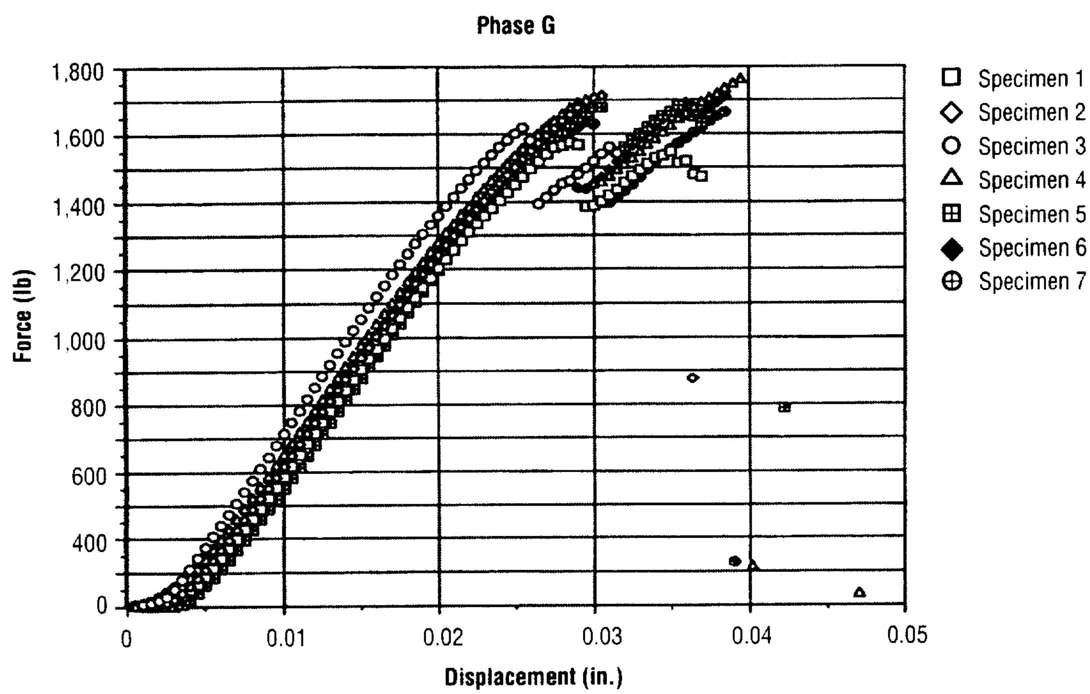

Figure 8. Phase G test data.

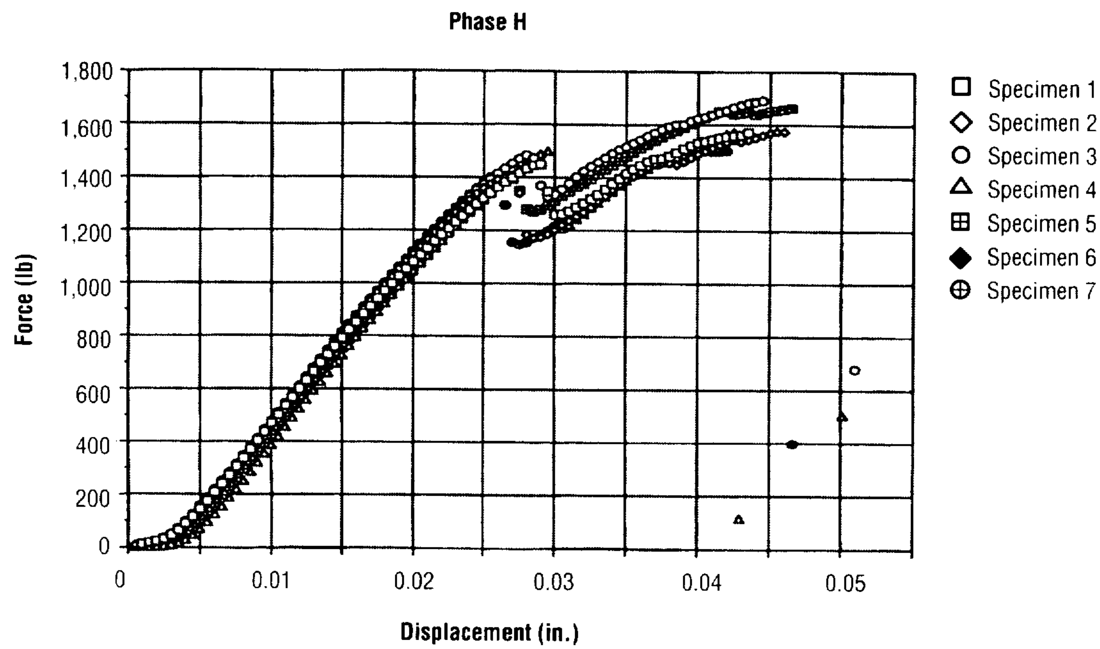

Figure 9. Phase H test data.

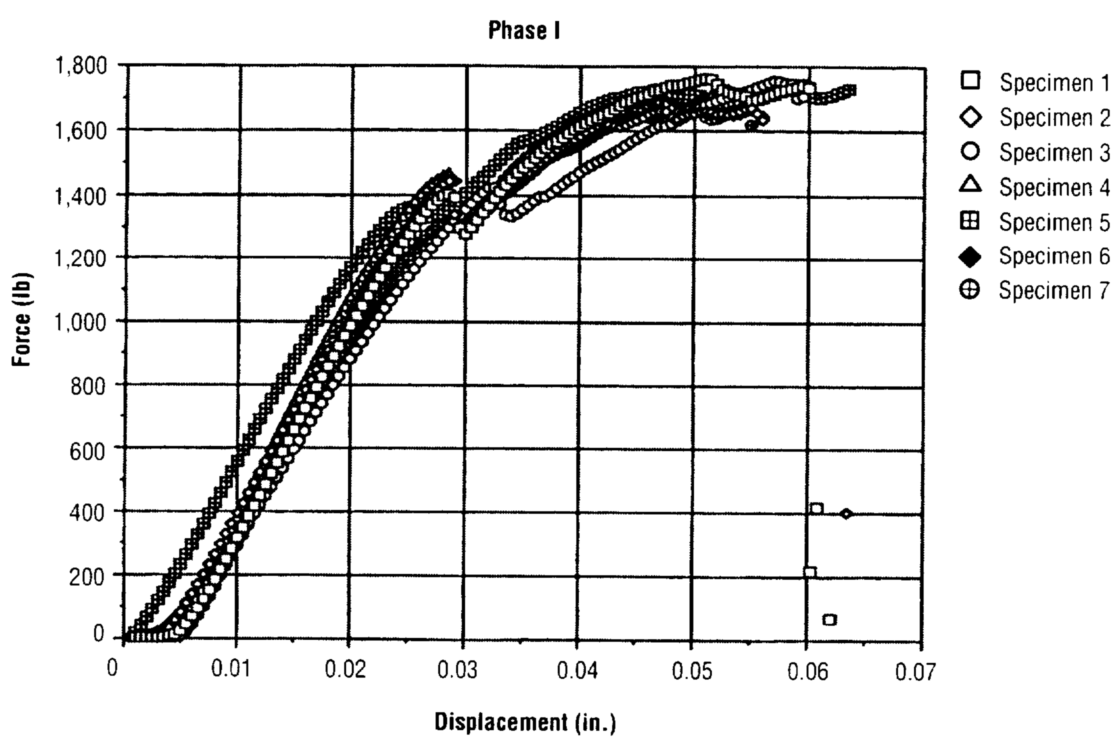

Figure 10. Phase I test data.

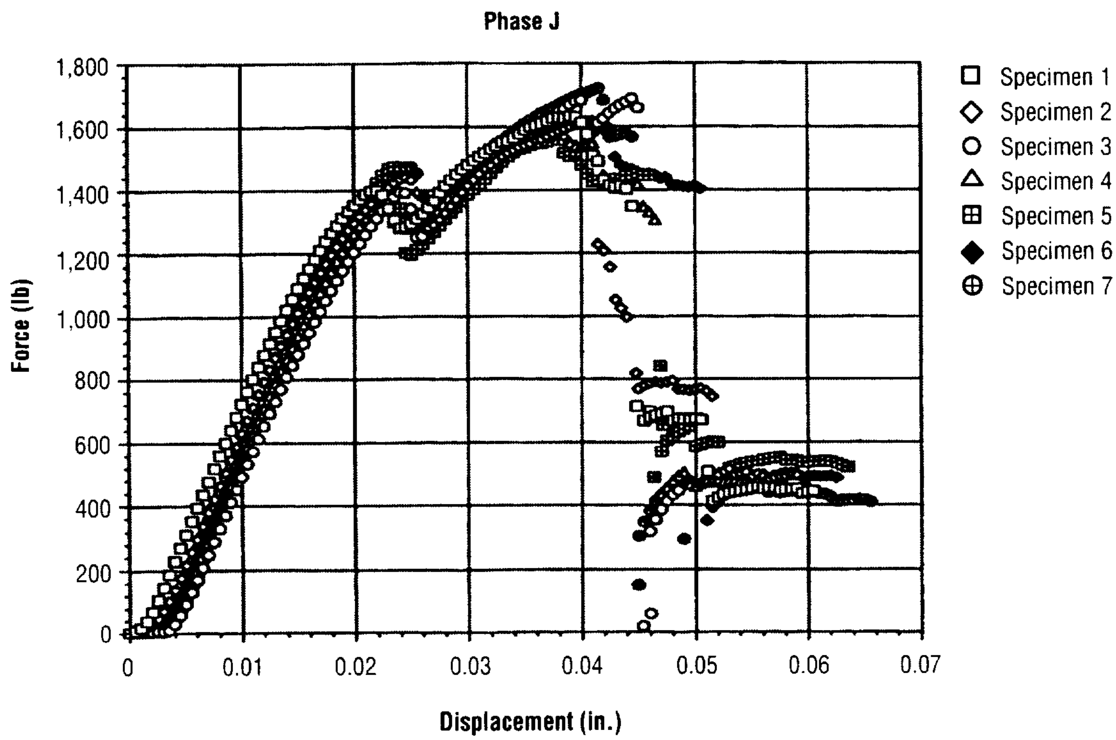

Figure 11. Phase J test data.

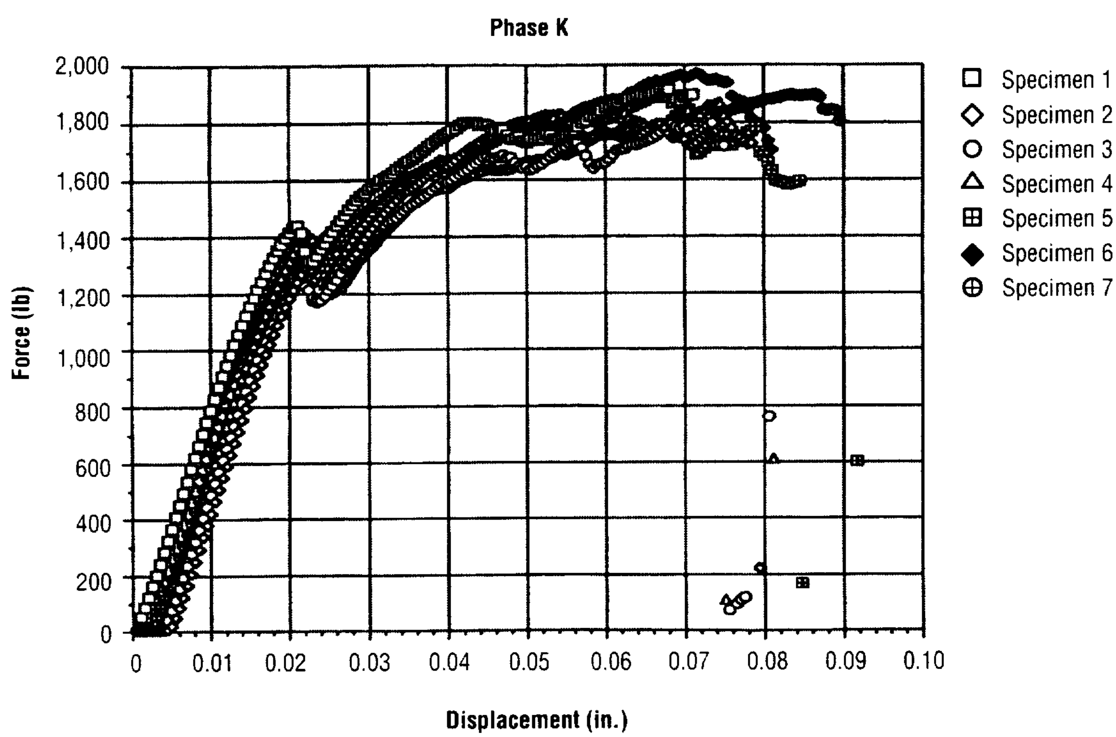

Figure 12. Phase K test data.

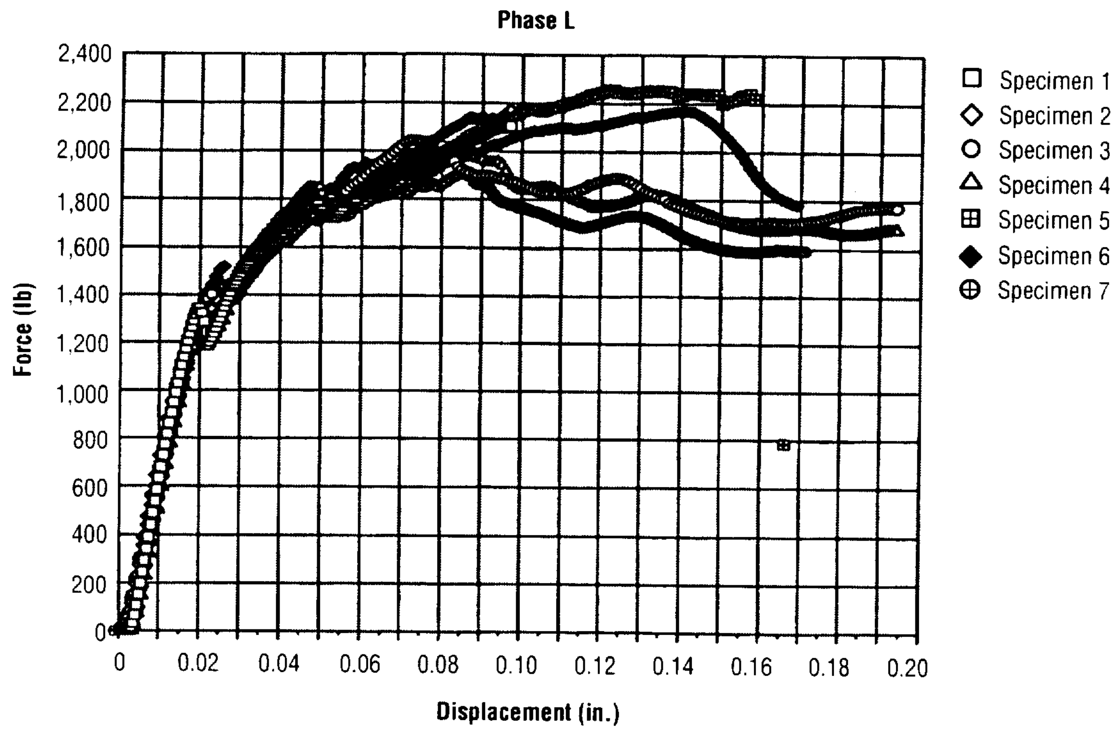

Figure 13. Phase L test data.

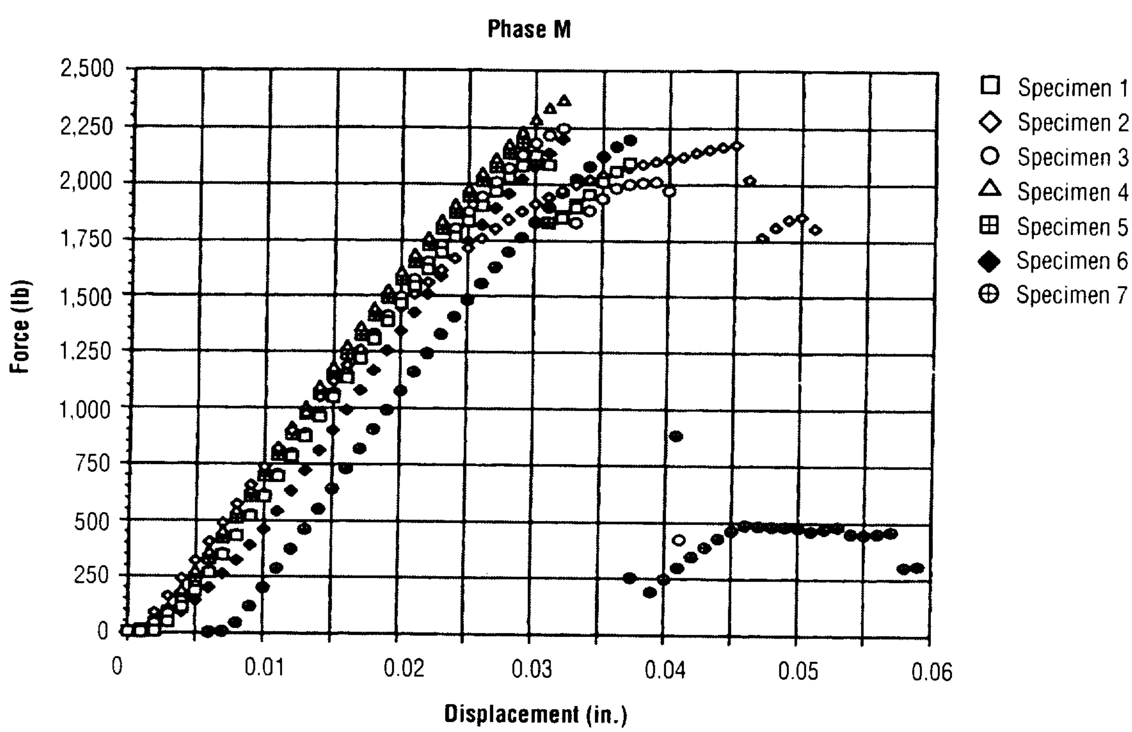

Figure 14. Phase M test data.

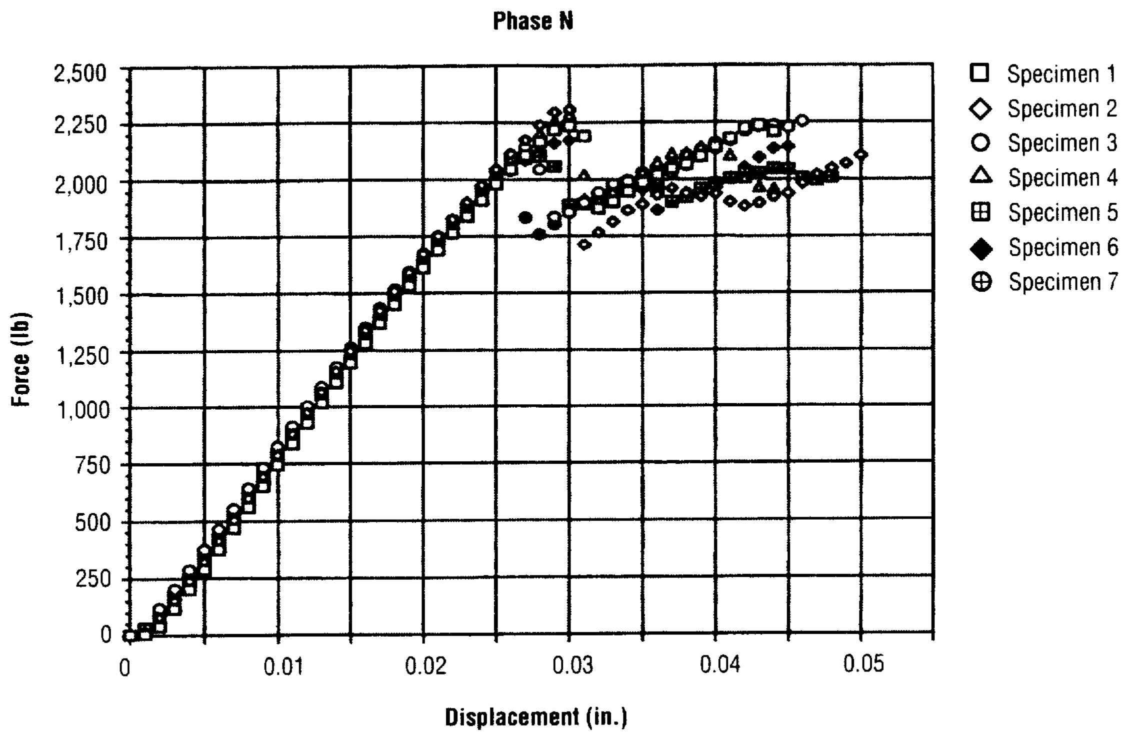

Figure 15. Phase N test data.

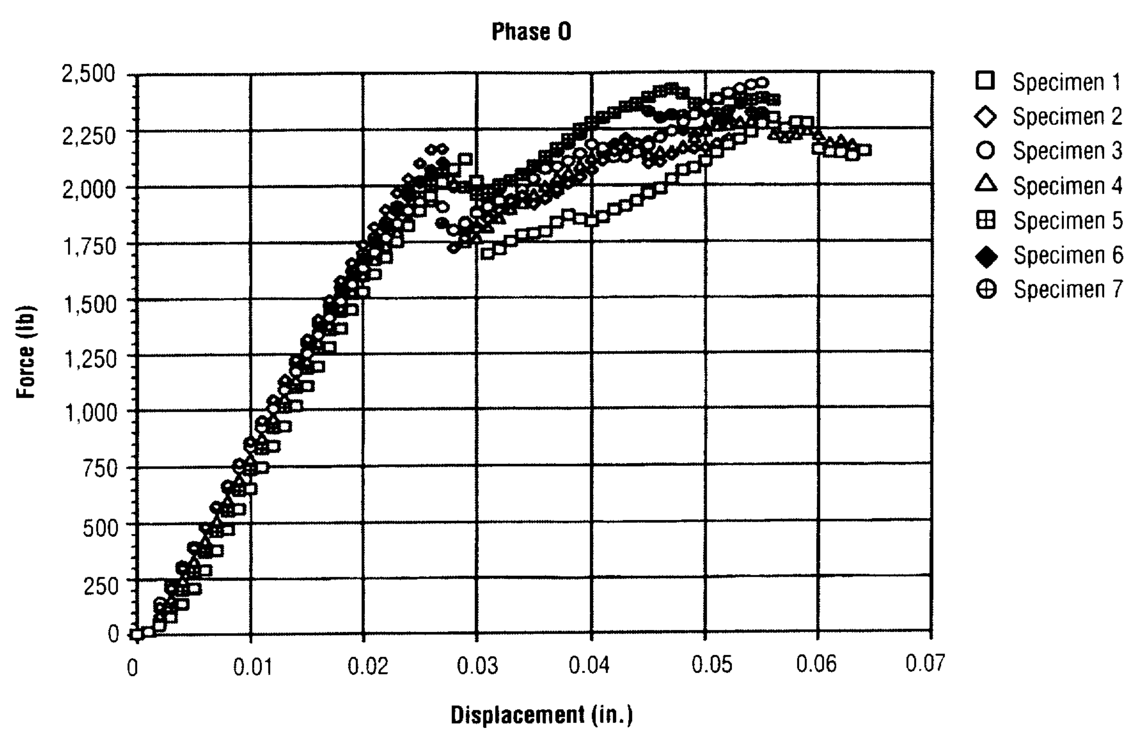

Figure 16. Phase O test data.

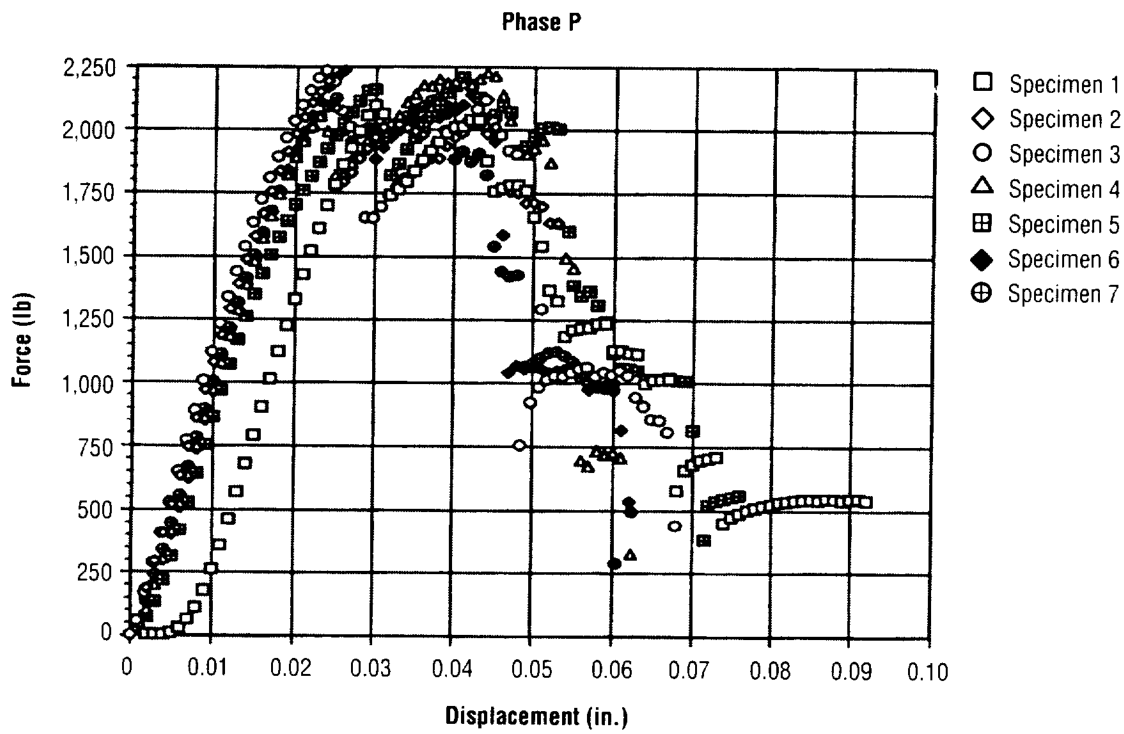

Figure 17. Phase P test data.

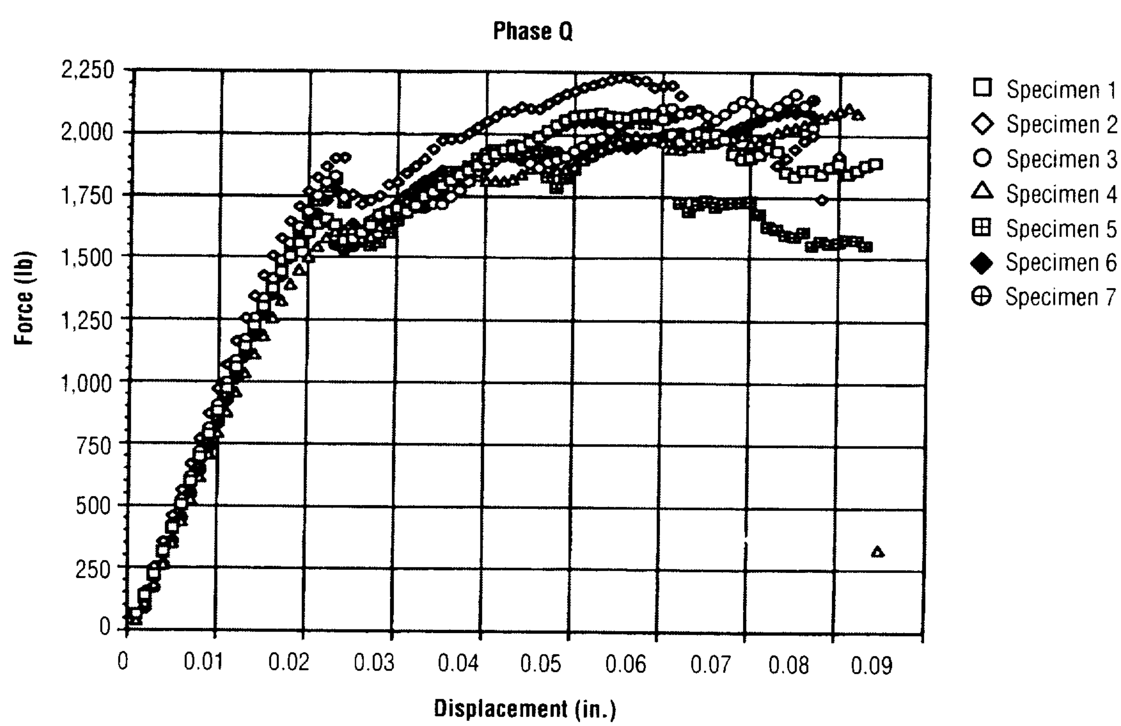

Figure 18. Phase Q test data.

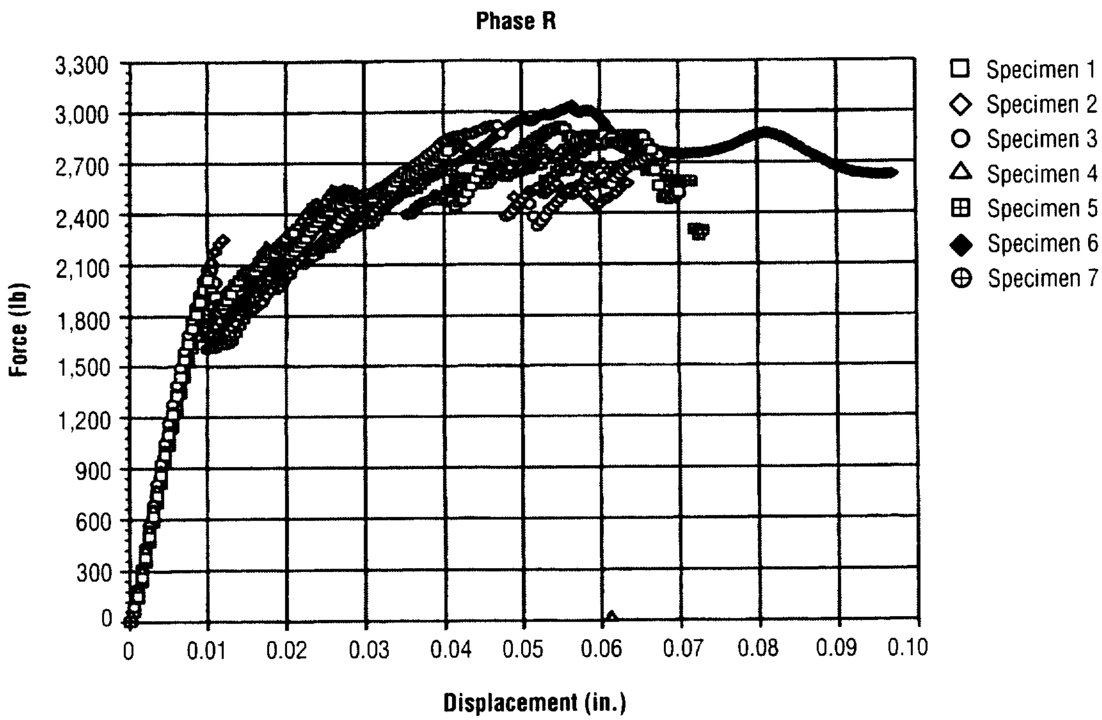

Figure 19. Phase R test data.

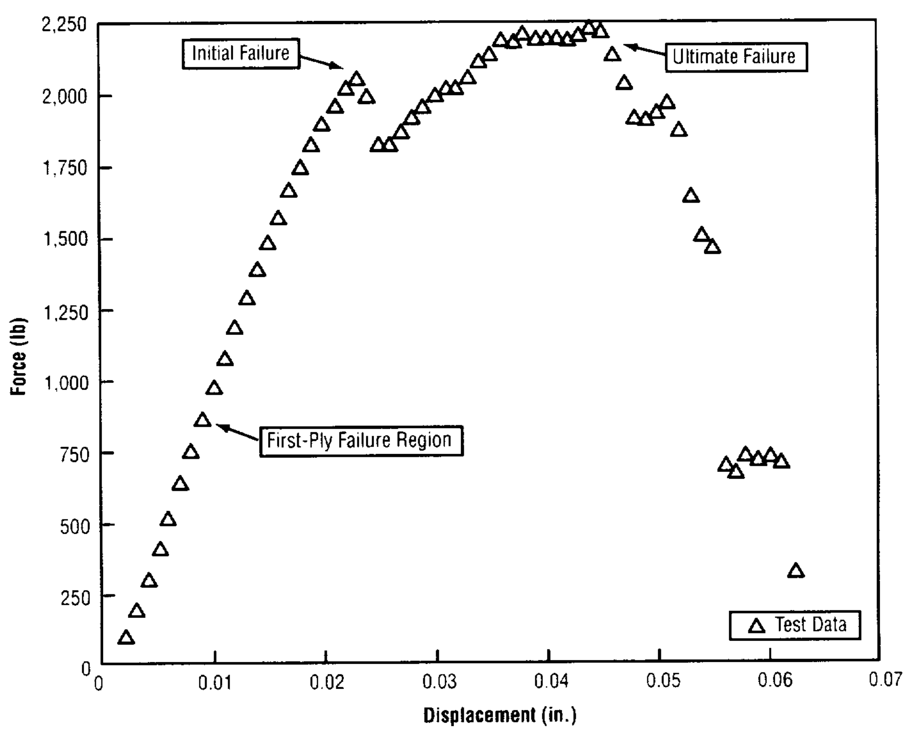

Figure 20. Failure Definition.

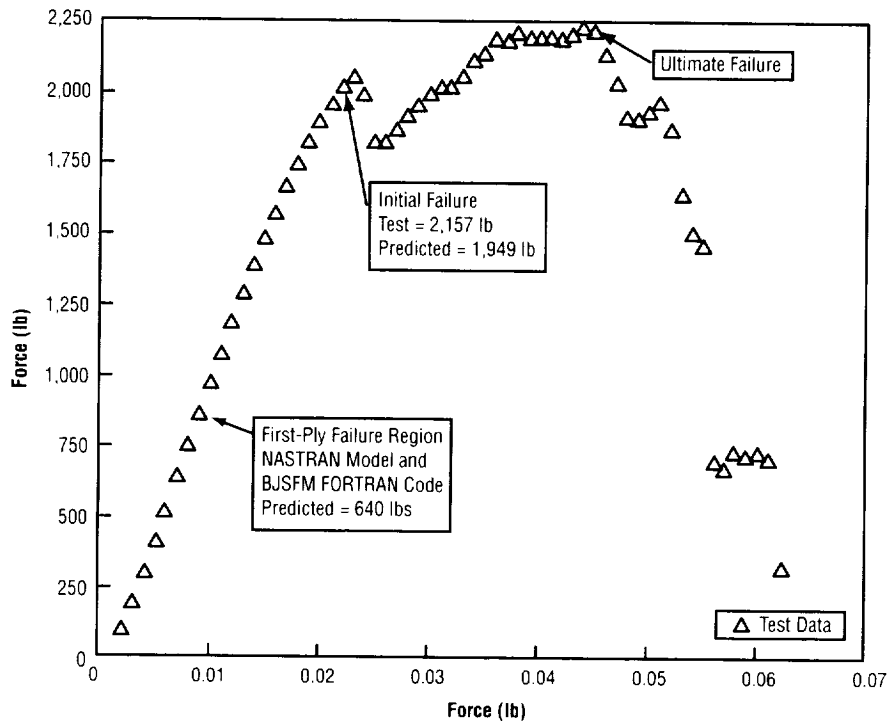

Figure 21. Phase P coupon 4 test data.

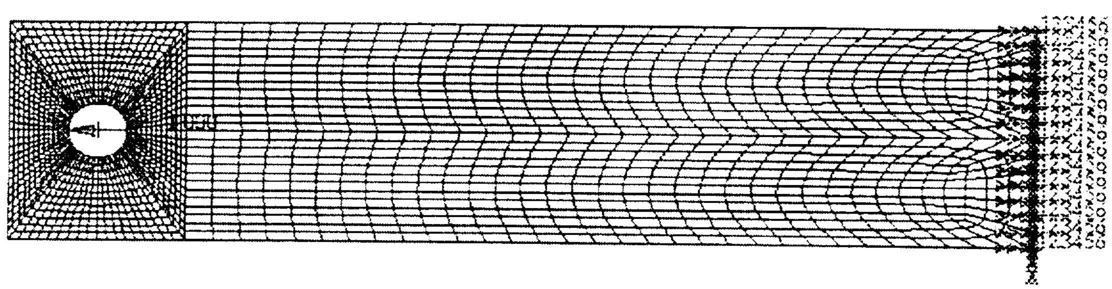

Figure 22. Phase P test coupon finite element model.

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3. Holman, J.P.: *Experimental Methods for Engines*, 4th Ed., McGraw Hill Book Co., 1984.

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13. ABSTRACT *(Maximum 200 words)*

The analysis of mechanically fastened composite joints presents a great challenge to structural analysts because of the large number of parameters that influence strength. These parameters include edge distance, width, bolt diameter, laminate thickness, ply orientation, and bolt torque. The research presented in this report investigates the influence of some of these parameters through testing and analysis. A methodology is presented for estimating the strength of the bolthole based on classical lamination theory using the Tsai-Hill failure criteria and typical bolthole bearing analytical methods.

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