

13:52:51

OCA PAD AMENDMENT - PROJECT HEADER INFORMATION

12/19/96

Active

Project #: E-18-X33
Center #: 10/24-6-R8575-0A0

Cost share #:
Center shr #:

Rev #: 4
OCA file #:
Work type : RES
Document : PO
Contract entity: GTRC

Contract#: RQ11806
Prime #: NAS1-20220

Mod #: 07

Subprojects ? : N
Main project #:

CFDA: NA
PE #: NA

Project unit: MSE Unit code: 02.010.112
Project director(s): JOHNSON W S MSE (404)894-3013

Sponsor/division names: LOCKHEED AERONAUT SYS CO-GA /
Sponsor/division codes: 261 / 007

Award period: 950301 to 961230 (performance) 961230 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	99,993.00
Funded	39,365.00	99,993.00
Cost sharing amount		0.00

Does subcontracting plan apply?: N

Title: CREEP BEARING BEHAVIOR IN HIGHLY LOADED BOLTED JOINTS

PROJECT ADMINISTRATION DATA

OCA contact: William F. Brown 894-4820

Sponsor technical contact	Sponsor issuing office
STEVE BECK, D/81-8A (000)000-0000	LAURIE DYSERT, D/52-35, Z/0510 (404)494-8359

LOCKHEED AERONAUTICAL SYSTEMS CO. 86 SOUTH COBB DRIVE MARIETTA, GEORGIA 30063	LOCKHEED AERONAUTICAL SYSTEMS CO. 86 SOUTH COBB DRIVE MARIETTA, GEORGIA 30063
---	---

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : NA NA supplemental sheet
Equipment title vests with: Sponsor X GIT

Administrative comments -
MOD. 07 ADDS FINAL INCREMENT OF FUNDS TO FULLY FUND THE PROJECT.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

U

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/24/97

Project No. E-18-X33_____ Center No. 10/24-6-R8575-0A0_

Project Director JOHNSON W S_____ School/Lab MSE_____

Sponsor LOCKHEED AERONAUT SYS CO-GA/_____

Contract/Grant No. RQ11806_____ Contract Entity GTRC

Prime Contract No. NAS1-20220_____

Title CREEP BEARING BEHAVIOR IN HIGHLY LOADED BOLTED JOINTS_____

Effective Completion Date 961230 (Performance) 961230 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	_____
Final Report of Inventions and/or Subcontracts	Y	_____
Government Property Inventory & Related Certificate	Y	_____
Classified Material Certificate	N	_____
Release and Assignment	N	_____
Other _____	N	_____
Comments_____		

Subproject Under Main Project No. _____

Continues Project No. _____

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Management	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other _____	N
_____	N

NOTE: Final Patent Questionnaire sent to PDPI.

E-18-x33

#1,2,3,4

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Report No. 5
October 1995

Prepared For
Lockheed Martin Corporation

Prepared By:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview: Preparations for bearing creep tests are nearly complete. The second oven, which is designed for use on the creep frames, has been mated with its controller and is currently burning out its insulation. The first creep test will be for 250 hours at 177°C (350°F) with a sustained load of 4000 lbs. The machine shop which made an error in the construction of the original grips has machined new grips to replace the originals. Insulation for the third oven has been acquired and the casing has been completed.

Progress:

Bearing Creep Tests- The first bearing creep test should begin in the first week of November. This first test will be run at 177°C (350°F) with a titanium bolt loaded to 4000 lbs. This test will serve as a starting point for the determination of bearing creep limits for this material.

Ultimate Bearing Strength Tests- Ultimate bearing strength tests are still on hold while the setup for these tests is being modified. Currently, the approach being pursued is one suggested by the proposed ASTM bolt bearing standard where two independently movable plates are used to get a zero clearance fit with the specimen. This equipment will be machined while the first bearing creep tests begin.

Second oven- The second of three test ovens is complete and has been running at full power to burn out the binder in its insulation. From experience with the first oven, it was possible to better insulate the second oven so that it has been able to reach a maximum temperature of 248°C (480°F) (compared to 223°C (450°F) for the first oven) with identical 420 watt heating elements. All three of the test ovens are stainless steel casings with 2.5cm (1") thick Thermal Ceramics Kaowool M Board for insulation. The ovens are intended for experiments at temperatures up to 400°F, and can maintain any temperature from RT to 204°C (400°F) within 1°C.

Third Oven- The casing for the third testing oven has been completed. Fitting of the insulation, mounting brackets, motor, fan, and controller should be completed by the end of November. This oven is identical to the second oven and is will allow two bearing creep tests to be run concurrently, while the first oven will still be available for ultimate bearing strength testing.

Grips- To rectify an error made in manufacturing the original grips which allowed specimens to slide out of the grips at high temperatures, the machine shop has machined new grips and left their faces smooth. The new grips were then sent to Surfalloy, in Troy, Michigan, to have a finish similar to the finish they apply to the "Composite" grips MTS sells. The finish is made of tungsten carbide sprayed onto the surface using a plasma arc. The finish for these grips was made to have features .01524 cm (.006") high. Currently, a test is being run to find the maximum grip strength of the new grips.

Concerns: The creep tests may reveal that the material does not exhibit creep behavior in the load range the titanium bolts are capable of reaching without bending (6000 lbs.) If this is the case, there may be some delay while the setup is modified to allow greater loads to be placed on the bolt without causing deformation.

Plans: The third test oven should be completed by the end of November and be ready for service. The bearing creep tests will continue throughtout November (two tests) and should be able to increase in tempo soon afterwards as the second oven becomes available for testing. A new clevis for the ultimate bearing strength tests should be completed in November so that these tests can be successfully performed. This new adjustable clevis will also be usable for high load bearing creep tests.

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Report No. 6
November 1995

Prepared For
Lockheed Martin Corporation

Prepared By:

R. J. Wright
R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson
W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview: The first bolt bearing creep test (250 hrs. at 177C (350F) has been successfully completed and has revealed no time dependent behavior at this load and temperature. The second bolt bearing creep test has begun at a load of 5000 lbs. at 177C (350F). A third oven is under construction and should be ready in time for the third and fourth bolt bearing creep tests, which will be run concurrently.

Progress:

Bearing Creep Tests- The first bearing creep test has been completed. This first test was run at 177°C (350°F) with a titanium bolt loaded to 4000 lbs. This test had to be started twice after the extensometer's blade slipped on the clevis' mounting pin 20 hours into the test. The problem was resolved and the test restarted. The specimen then went for an additional total of 269 hours under load. During this time, no time dependent behavior occurred, and the specimen recovered elastically to its original dimensions when the test was finished. However, the specimen did show imprints from the two washers on either side when it was taken out early on. At the completion of the test, the slight indentions had not increased. Deformation in the thickness direction will be monitored as a function of clamp-up force in future tests.

To prevent a recurrence of the extensometer slipping on the mounting pin it is clipped to, a series of small notches has been cut into the pin for the clip gauge blade to fit into. This setup will still allow the clip gauge to slide off in the unlikely event of catastrophic failure, but will otherwise securely hold the extensometer blade in place. The third and fourth tests should start around the second week of December.

Ultimate Bearing Strength Tests- Ultimate bearing strength tests are still on hold while the setup for these tests is being modified. Currently, the approach being pursued is one suggested by the proposed ASTM bolt bearing standard where two plates separated by a spacer the width of a specimen and clamped in a large grip are used to get a zero clearance fit with the specimen. Our version, however, will have both plates freely supported by a pin going through them instead of being mounted in a grip with a spacer as in the ASTM version. This modification will allow for

measurement of clamp-up force on the specimen independent of Poisson effects in the clevis and the bolt.

Second oven- The second of three test ovens is complete and has been used in the first experiment. The unit ran reliably at the 177°C temperature it was set for the 12 day duration of the test.

Third Oven- Brackets for the Third oven have been machined and we expect to be able to use it for the next iterations of tests. (to simplify recording and maintenance, we are planning to run the creep tests in concurrent pairs). This oven is identical to the second oven.

Grips- The new grips have demonstrated ability to hold on to specimens at loads up to 15,700 lbs. at 177°C (350°F). It is expected that this gripping strength will be sufficient to produce permanent damage in ultimate bearing strength testing.

Concerns: Nothing is known about what is happening to the clamp-up forces on the specimen under load. The presence of indentions on the specimen suggests that the high clamp-up loads may be causing a time dependent phenomenon around the bolt hole.

Plans: The bearing creep tests will continue into the Winter break period. After the second test is completed, the third and fourth tests will include a test at higher loads, and one at higher temperature. At the same time, the annual report will be prepared. At this time, the plan is to include photographs and diagrams of the test equipment in the report. The modified device for the ultimate bearing strength tests should be completed. The current plan is to acquire two and possible three of the new clevises so that bolt clamp-up forces can be measured during creep tests.

Creep Bearing Behavior of Highly Loaded
Composite Joints

Monthly Progress Report No. 7
December 1995

Prepared For
Lockheed Martin Corporation

Prepared By:

RJ

R. J. Wright
Experimental Investigator

Approved By:

W

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview: The second bolt bearing creep test has been run at a load of 5000 lbs. (38.1 ksi) at 177°C (350°F). This test revealed no permanent elongation of the bolt hole after 272 hours. The third test has been started at a load of 9000 lbs. (68.6 ksi) at 177°C (350°F).

Progress:

Bearing Creep Tests- The second creep test was successfully run at a load level of 5000 lbs. (38.1 ksi) at 177°C (350°F) for a total of 272 hours. The bolt hole showed no permanent elongation. However, the washer marks first noted in the 4000 lb. (30 ksi) test are more pronounced on the 5000 lb. (38.1 ksi) load specimen. Strain gauges have been ordered to convert the bushings in the test clevises into load cell so that stresses in the thickness direction can be measured. Based on estimates for the maximum continuous load, the third bearing creep test has been started at 9000 lbs. (68.6 ksi). The loads for the fourth test will be decided based on the results of the third test.

Ultimate Bearing Strength Tests- Ultimate bearing strength tests are still on hold while the setup for these tests is being modified. The design for the new clevis for this test has been finalized, and steel for the devices has been procured. Machining for the new clevises should be done in January.

Annual Report- The annual report was finished early this month. It includes labeled photographs and diagrams of the test equipment.

Concerns: The high loads of the third creep test require a steel bolt and notched specimen (so that the bolt has not lost rigidity due to having a slot cut in it). This version of the specimen geometry may affect the clamp-up behavior of the specimen.

Plans: The first aged specimen material (5000 hrs.) will come out of the aging oven on January 20. Coupons will be cut for comparison testing with the unaged material at that time. Bearing creep tests will continue throughout the next month. At the same time, ultimate bearing strength tests with the new clevis will begin at the end of the month, and should quickly map out the ultimate strength of the material. The exposure chamber capable of -45.5°C (-50°F) has arrived and will be available for ultimate bearing strength tests.

Creep Bearing Behavior of Highly Loaded
Composite Joints

Purchase Order #: RQ11806

Annual Progress Report
1995

Prepared For
Lockheed Martin Corporation

Prepared By:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

1.0 Summary

The goal of this activity is to produce an accurate prediction of the behavior of highly loaded bolted joints at elevated temperatures over long periods of time for the High Speed Civil Transport. The results of this program will include data on observed bearing and creep behavior, the effects of aging the material at high temperatures, and recommendations for accelerated testing of future materials.

In the past eight months, the researchers at Georgia Tech have designed and built clevises, grips, and ovens to test the joint at temperatures up to 204°C (400°F). Material has been put into aging ovens at 177°C (350°F) and 204°C (400°F) for aging times of 5,000 and 10,000 hours. Tests have shown the joint to have an ultimate strength in the neighborhood of 130 ksi and to be unsusceptible to time dependent hole elongation at stresses up to 38.1 ksi.

2.0 Equipment

The experimental test setup for the bolt bearing tests consists of a clevis with a bushing in it to apply clamp-up force to the coupon. The coupon is held at the other end by a bolted grip with fine tungsten carbide teeth. Elongation of the bolt hole is measured with an extensometer mounted on a stainless steel wire with its other end clipped to a post on the clevis (See Appendix).

2.1 Clevises

Two clevises were designed and built for bolt bearing and bearing creep tests at loads up to 12,000 lbs. (92 ksi). At the time, it was believed that this would easily produce damage in the joint, since early estimates were that the ultimate load carrying capacity would be 10500 lbs. (80 ksi). In testing, it was revealed that although the safety factor of two the clevises had been designed with allowed them to handle the actual loads the material failed at (18,000 lbs., or stresses of 137 ksi), the bolts specified for the experiment could not. As a result, the original clevises are being used for creep tests while zero clearance clevises are constructed.

2.2 Grips:

Two sets of grips were constructed to be used with the two clevises in bolt bearing tests. Early on, the grips suffered from two manufacturing errors by the machine shop which made them. The shop's first attempt to resolve the error left the grip faces too slippery to hold on to the specimens at the loads our tests had encountered. To raise the coefficient of friction on the grip faces, carborundum sanding screen was placed between the faces and the specimens. At room temperature, this procedure solved the slippage problem. However, at the elevated temperature of 177°C (350°F), the screens degraded and lost their abrasive qualities. To make up for the mistake, the machine shop is made new grips which with their faces left smooth. The new grips had a rough tungsten carbide finish applied to them by *Surfalloy* of Troy, MI (*Surfalloy* applies this same finish to MTS's "Composite" grip faces). The new grip faces have performed satisfactorily.

2.3 Test Ovens

Three ovens for testing the bolted joints were built. Two are optimized for use on creep frames while the other is dimensioned for use on hydraulic and screw driven machines. The ovens contain an experimental testing compartment 25.4cm (10") wide, 17.8cm (7") deep, and 55.9cm (22") high. At the top and bottom of the oven there are 6" diameter cutouts to allow clearance for test equipment. The oven consists of a 16 gauge stainless steel casing with an inch of Thermal Ceramics kaowool 'M' board insulation inside. A removable partition divides the main compartment into the testing chamber and a (6" X 7") duct which contains a 420 watt heater tape heating element and a stainless steel squirrel cage type blower. The heating element is wrapped around a stainless steel frame made from 1/8" welding rod attached to the side of the duct. Airflow in the duct is from bottom to top with the squirrel cage fan at the top blowing heated air into the main compartment at low speeds and removing cooler air from the bottom to be reheated.

The blower motor is protected from thermal damage by being mounted on top of the with an isolation mount. The motor's shaft goes through the insulation to the fan inside. The motor is controlled by a solid state variable speed switch mounted in a common control box on the back of the oven. The heating element is controlled by an

electronic relay temperature controller which reads temperatures in the testing compartment with a thermocouple mounted near the test specimen.

In trials the ovens have achieved and maintained temperatures in excess of 232°C (450°F). In tests with an oven reading 204°C (400°F) in the center of the experimental compartment at steady state, the temperature at a point 7" above the middle along the centerline was 209°C (408°F) and the temperature 7" below along the centerline was 201°C (394°F). This 8°C (14°F) variation well exceeded the developmental requirement for a thermal gradient of 17°C (30°F) or less across the testing area. The expected temperature ranges for the ultimate strength and bearing creep tests is from 163°C (325°F) and 190°C (375°F).

3.0 Experimental Results

3.1 Ultimate Bearing Strength Tests

These tests are conducted in a screw driven machine under displacement control. In the first room temperature bolt bearing ultimate strength test, the material showed a sudden loss of stiffness at a load of 17,862 lbs., or a bearing stress of 129.56 kpsi where it then dropped to a load level of 12,363 lbs. and a bearing stress of 89.67 kpsi. As material accumulated in the constraint of the clevis, the load picked up again to a maximum of 19,169 lbs. and a bearing stress of 139.04 kpsi. However, at this point the bolt in the specimen had deformed significantly. This test will be repeated upon completion of a zero gap clearance clevis designed to prevent bolt bending. The specimen showed heavy remote bearing damage and some delamination of the outer 45° plies. The .9525cm (.375") diameter bolt hole became a slot approximately 1.8cm (0.7") long during the test. Although the bolt bending contaminated the data track (since the clevis is the reference), this test did provide data on what the ultimate strength of the joint is and what failure mode it would exhibit at room temperature. Further ultimate bearing strength tests showed that the high strength steel bolts were failing at approximately 14,000 lbs. (107 ksi); before the specimen experienced permanent damage.

3.2 Bearing Creep Tests

Bearing Creep tests are performed in a creep frame within the creep testing oven. The first bearing creep test was run at 177°C (350°F) with a titanium bolt loaded to 4000 lbs. The specimen then went for a total of 269 hours under load. During this time, no time dependent behavior occurred, and the specimen recovered elastically to its original dimensions when the test was finished. However, the specimen did show imprints from the two washers on either side when it was taken out. Deformation in the thickness direction will be monitored as a function of clamp-up force in future tests.

To prevent the extensometer from slipping on the mounting pin it is clipped to, a series of small notches was cut into the pin for the clip gauge blade to fit into. This setup still allows the clip gauge to slide off in the unlikely event of catastrophic failure, but will otherwise securely hold the extensometer blade in place.

The second creep test was run at a load level of 5000 lbs. (38.1 ksi) at 177°C (350°F) for a total of 272 hours. The bolt hole showed no permanent elongation at the end of the test. However, the washer marks first noted in the 4000 lb. (30 ksi) test were more pronounced on the 5000 lb. (38.1 ksi) load specimen. Strain gauges have been ordered to convert the bushings in the test clevises into load cell so that stresses in the thickness direction can be measured. Based on estimates for the maximum continuous load, the third bearing creep test has been started at 9000 lbs. (68.6 ksi). The loads for future tests will be decided based on the results of the third test.

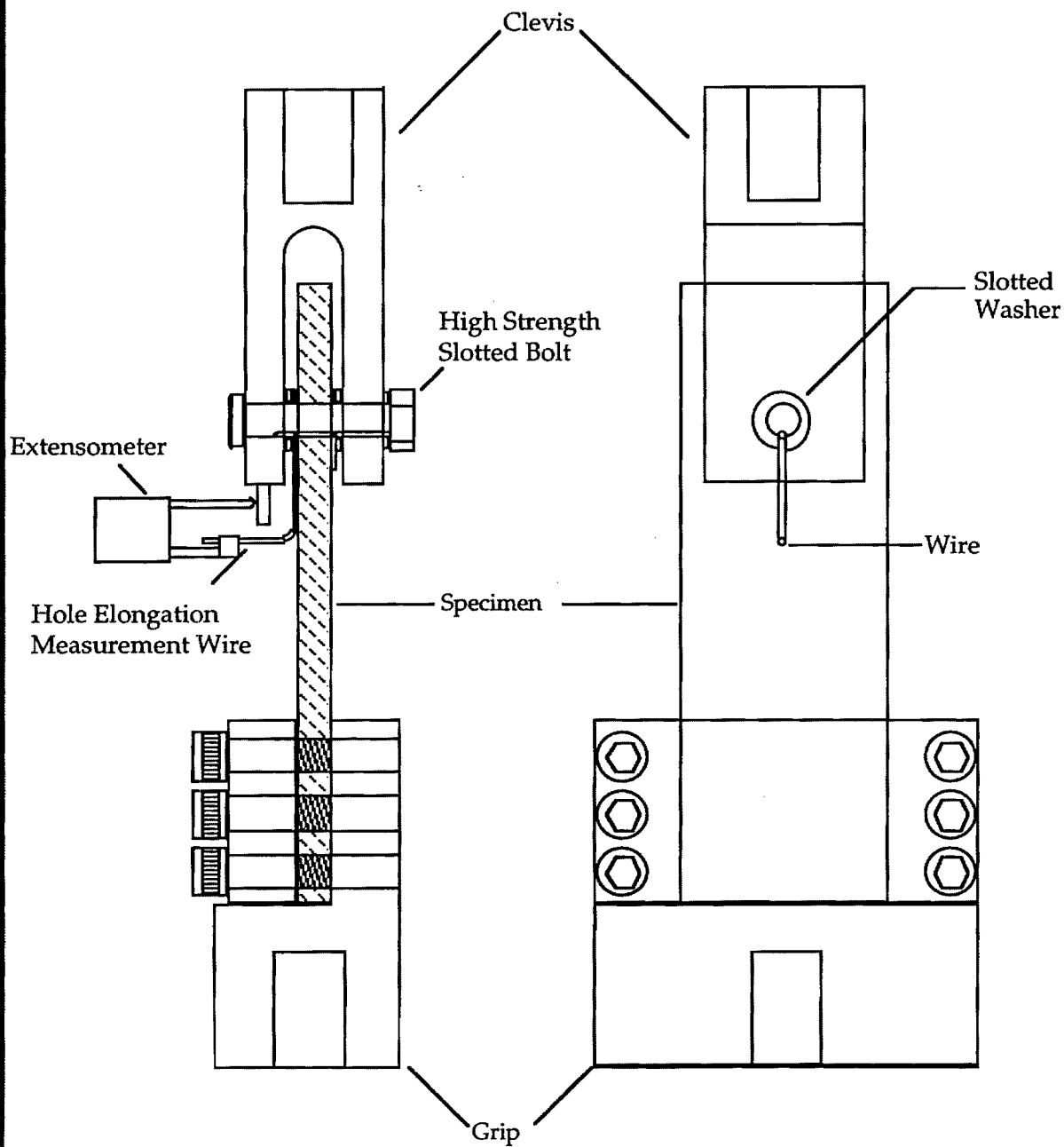
4.0 Conclusions

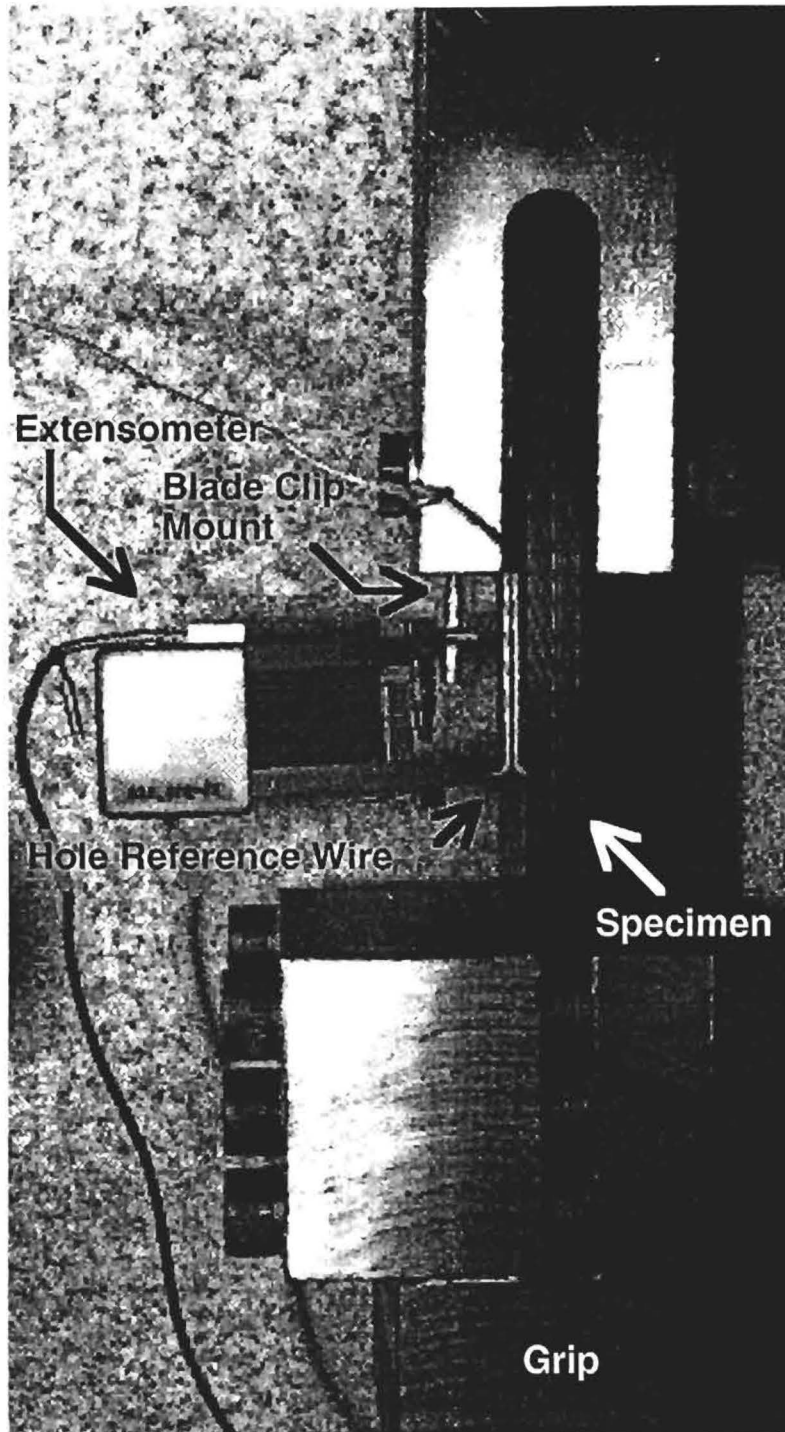
Work thus far has resulted in a robust experimental setup and identification of several key aspects of this joint's behavior. Early testing has pointed to clamp-up force as the source of the most obvious change in coupons at temperature. Ultimate bearing strength tests have shown the joint will not show permanent damage at loads up to 14,000 lbs. (107 ksi). Future creep and ultimate strength tests will be able to map out the performance regime of the IM7/K3B bolted joints.

APPENDIX

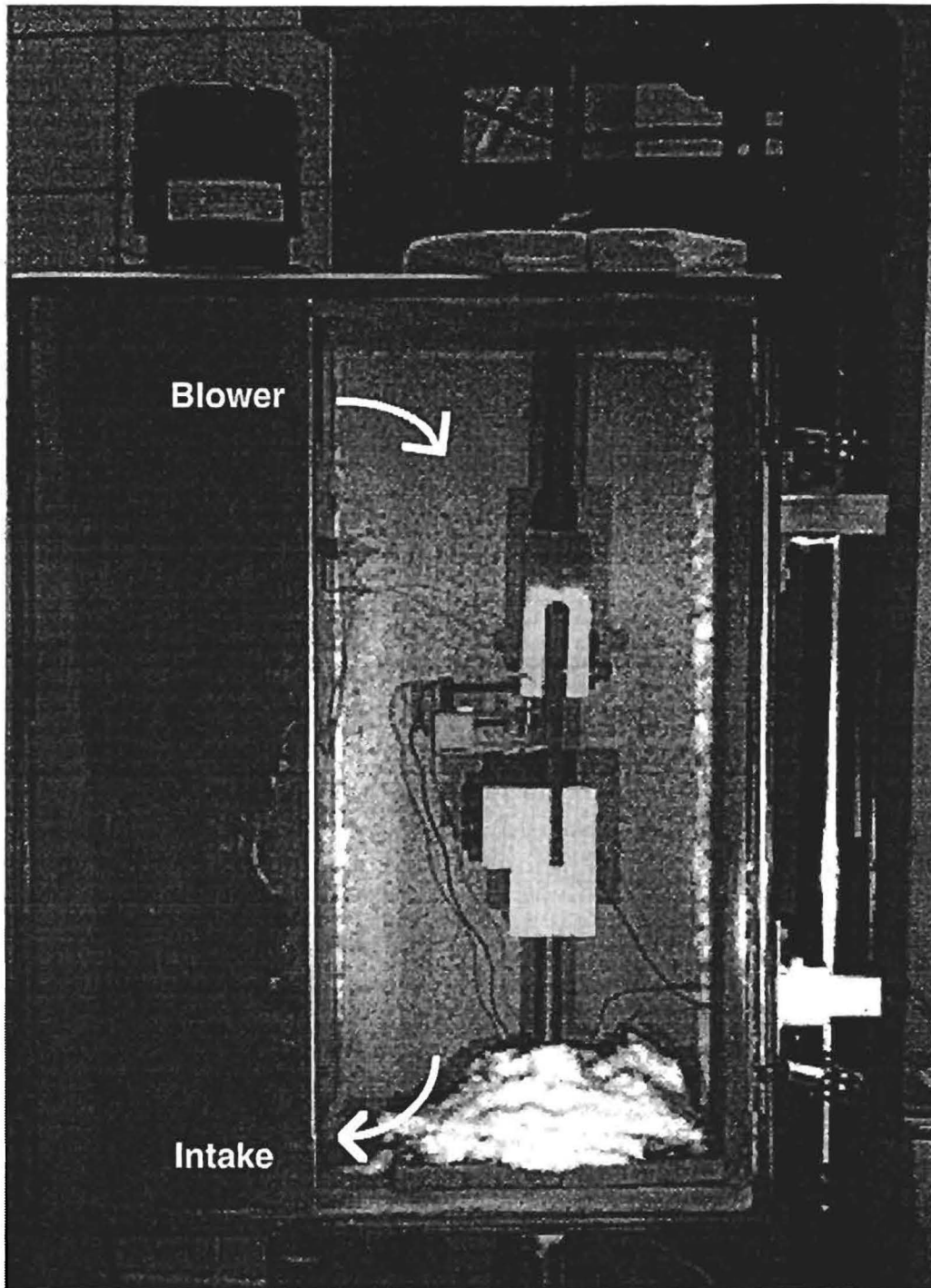
Photographs and Diagrams of Equipment For
Bolt Bearing Testing at Elevated Temperatures

Bolt Bearing Testing Setup

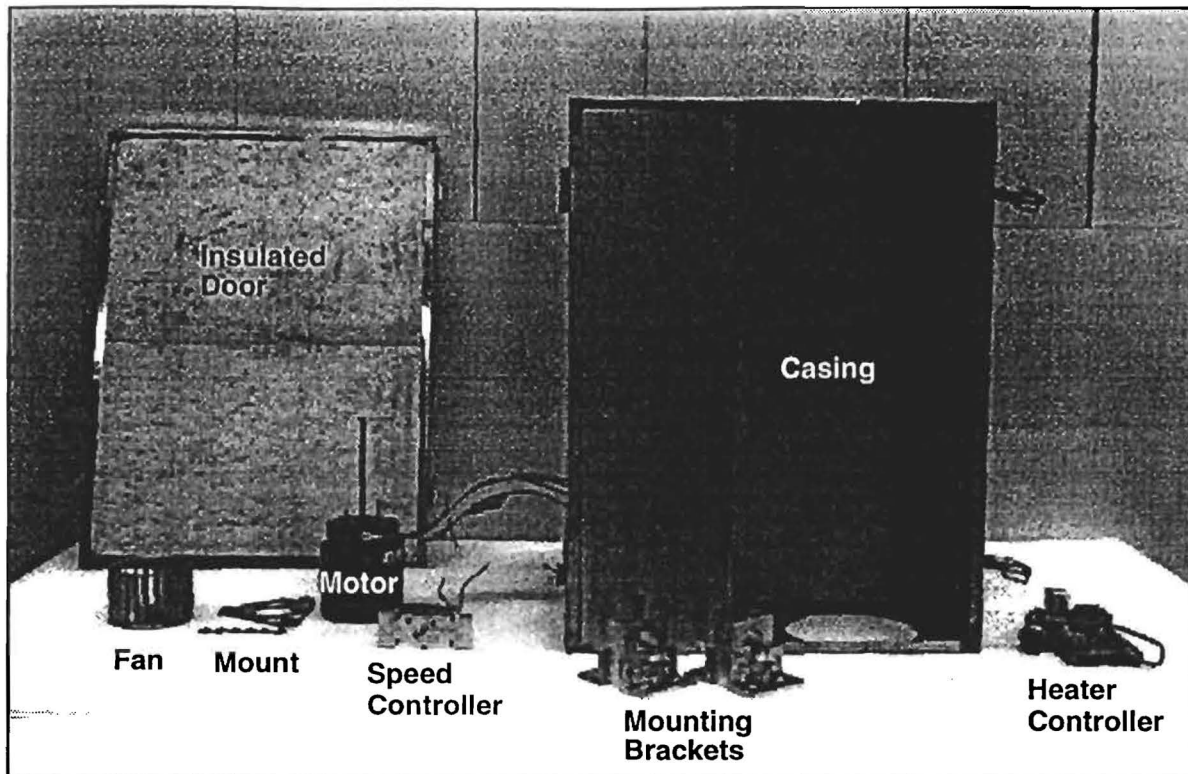




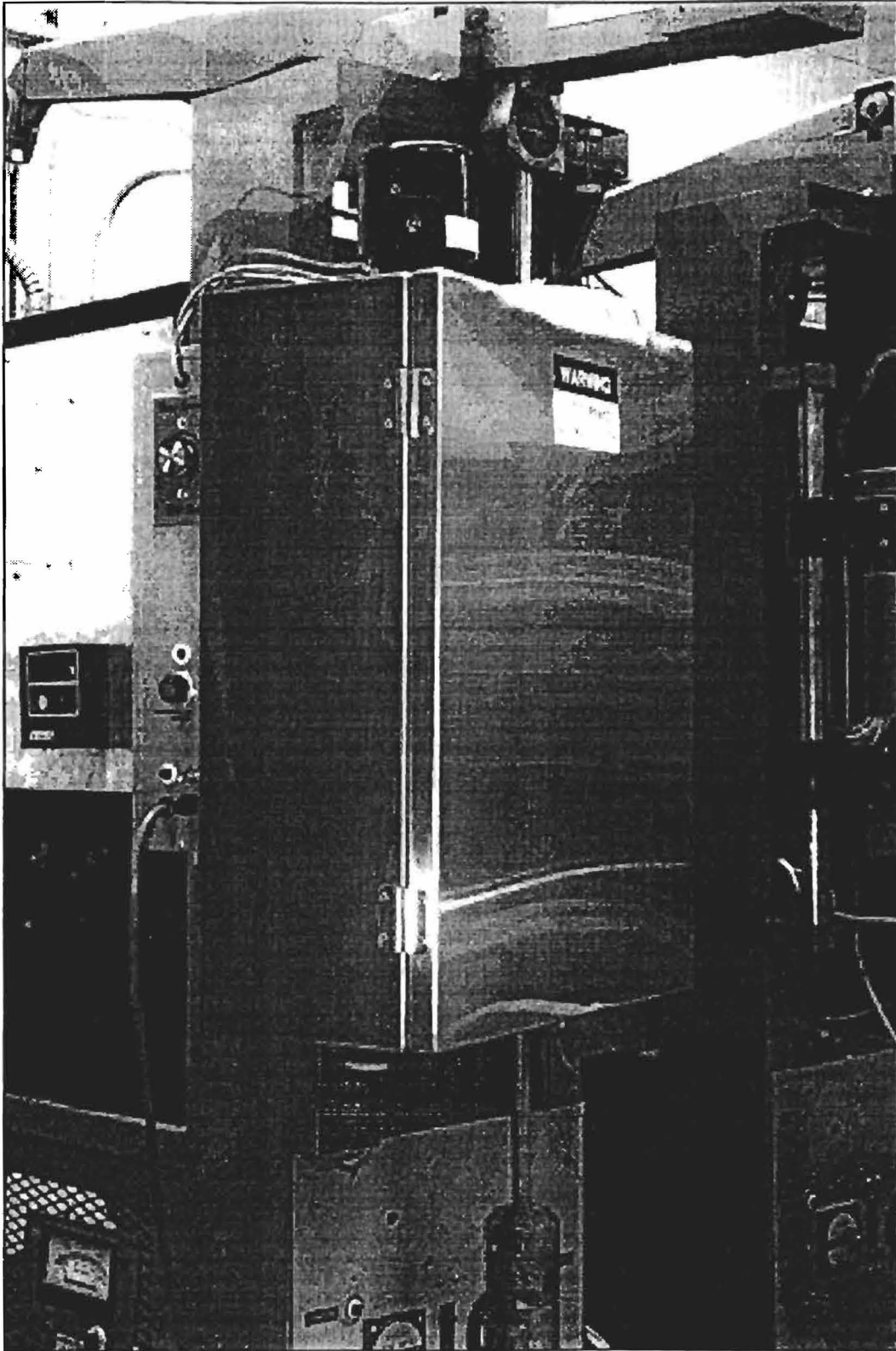
Test setup in the bearing creep oven.



Bearing creep oven mounted on the creep frame. Arrows indicate direction of air circulation.



Test oven components before assembly. The Oven door was manufactured with the insulation in it. The Brackets were machined by the experimental investigator.



Completed test oven mounted on the creep frame. The housing on the back contains the fan speed and oven temperature controllers.

E-18-X33


5

Creep Bearing Behavior of Highly Loaded Composite Joints


Monthly Progress Report No. 8
January 1996

Prepared For
Lockheed Martin Corporation

Prepared By:


R. J. Wright
Experimental Investigator

Approved By:


W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview: The fifth bolt bearing creep test (8000lbs. for 250 hrs. at 177C (350F) in pin bearing) resulted in immediate bearing failure of the joint. The sixth test is being started at a load of 5000 lbs. at 177C (350F). Additional weights have been ordered to allow simultaneous testing.

Progress:

Bearing Creep Tests- The Third bearing creep test was run at a load of 9000lbs. for 250 hours at 177C (350F). This test resulted in no elongation of the bolt hole, although the marks from the washers on the sides of the hole are more pronounced than in the previous test (5000lb. load). For the next test, it was decided to try loading the specimen without clamp-up force or other constraint to get data on this boundary condition to compare with clamped-up specimens. It was hoped that this loading method would result in bearing force concentrations sufficient to produce time dependent behavior, if any such behavior were possible at this load and temperature. However, when the test was run, the joint experienced bearing failure after supporting the 9000lbs. load for approximately 90 seconds. This test specimen shows significant brooming on either side of the bolt hole along with delaminations at every 90 degree ply throughout its thickness.

Because the 9000lbs. specimen had supported the applied load for a short period of time before failing, it was decided to try the next test at a load of 8000lbs. for 250 hours at 177C (350F). Mr. Brian Cornell and Dr. Hafiz Ahmad from Lockheed were present to observe the start of this test and confer with the experimental investigator on plans for further testing. After loading, the specimen failed in the same manner as the one used in the previous test; after supporting the full load for a short period of time. Damage to this specimen was in the same form as the damage to the 9000 lb. load specimen in the previous pin bearing test. This specimen is being cut and polished at Lockheed for microscopic examination of the damage present and better quantification of the observed failure mode.

After witnessing the results of this test, the plan for further testing was modified to perform the sixth bearing creep test at 5000lbs. for 250 hours at 177C (350F). It is hoped that this lower load level will not produce bearing failure, and will serve as a starting point for quantifying time dependent behavior of the material.

Material Aging- The 5000 hour mark for 64 ply IM-7/K3B specimens being aged at 177C (350F) and 204C (400F) in Georgia Tech's aging ovens was reached of January 20th. The aged material includes cut specimens and uncut panels at both temperatures. Panels are being cut into specimens at Lockheed. This approach makes it possible to isolate air exposure effects in the bolt hole from exposure effects on a sealed bolt hole. These specimens will be used in repetitions of tests on new material for paired comparison of aged and unaged properties.

Ultimate Bearing Strength Tests- The design of the new fixture has been finalized. It is being machined at the Georgia Tech Mechanical Engineering department's machine shop.

Concerns: The delamination and failure of the specimens in pin bearing may mean that it is not possible to do pin bearing tests at loads sufficient to produce time dependent behavior in a situation where clamp-up forces are not affecting the material properties.

Plans: The 5000lb. test began on the last day of the month. When additional weights for the creep frames arrive, it will be possible to run these high load tests more quickly. At this time, we are planning to map out creep behavior in a variety of clamp-up and loading conditions. The major objective of testing at this time is to produce time dependency data from a pin bearing specimen, however.

E 18-X33


#8

Creep Bearing Behavior of Highly Loaded Composite Joints

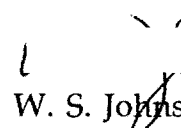
Monthly Progress Summary No. 2
April 1996

Prepared For
Lockheed Martin Corporation

Prepared By:


R. J. Wright
Experimental Investigator

Approved By:


W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Monthly summary for April, 1996.

The series of pin bearing tests has continued to complete a boundary condition for time dependent bearing behavior. This month, aged specimens were tested for the first time. Preliminary results show that there is degradation of the composite's properties after 5000 hours at 177°C (350°F). Unaged specimens withstood a load of 6500lbs. 250 hours at 177°C (350°F) without showing any hole elongation, while a specimen aged 5000 hours at 177°C (350°F) only lasted for four minutes under those conditions. A follow-up test currently in progress with a load of 6000lbs. at 177°C (350°F) with a specimen aged 5000 hours at 177°C (350°F) has shown no time dependent deformation after 180 hours under load. Load cells which will make it possible to measure clampup forces in real time are being manufactured, and should be ready to use by the time the current series of pin bearing tests is finished. Tests to be completed in the current series include tests on specimens aged 5000 hours at 204°C (400°F) as well as repeats of tests where time dependent deformation has been observed.

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Summary No. 3
May 1996

Prepared For
Lockheed Martin Corporation

Prepared By:

^ /

R. J. Wright
Experimental Investigator

Approved By:

-

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview:

The series of pin bearing tests has continued to complete a boundary condition for time dependent bearing behavior. Aged specimens tested this month have shown some variability in aging effects. Thus far, results show degradation of the composite's properties after 5000 hours at 177°C (350°F). Unaged specimens withstood a load of 6500lbs. 250 hours at 177°C (350°F) without showing any hole elongation, while a specimen aged 5000 hours at 177°C (350°F) loaded to 6000lbs. apparently elongated and then arrested before reaching the constraint of the clevis during its 250 hour run. A follow-up duplicate of this test is currently in progress. A coupon which had been aged at 204°C (400°F) for 5000 hours withstood a 6000 lb. load for 250 hours without showing evidence of time dependent deformation. All of the bodies for the testing load cells have been finished, and work is proceeding to instrument them with strain gauges. The variable clampup and high load capacity test fixture has been completed and is ready for testing. Repeats of the test of the specimen aged at 204°C (400°F) and the unaged specimens which showed time dependent deformation will be completed before clampup measurement tests begin.

E-18-X33
#11

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Summary No. 4
July 1996

Prepared For
Lockheed Martin Corporation

Prepared by:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview:

The series of pin bearing tests has continued to complete a boundary condition for time dependent bearing behavior. Aged specimens tested this month have shown striking variability in aging effects at different temperatures. Thus far, results show degradation of the composite's properties after 5000 hours at 177°C (350°F). A specimen aged 5000 hours at 177°C (350°F) loaded to 5700lbs. showed time dependent deformation which eventually arrested during its 250 hour run (Damage is similar to specimens aged at this temperature which were loaded to 6000 lbs.). A coupon which had been aged at 204°C (400°F) for 5000 hours withstood a 6500 lb. load for 250 hours without showing evidence of time dependent deformation; this performance meets the highest load achieved by an unaged specimen without time dependent deformation. New tests are ongoing to find the point where no time dependent behavior occurs in specimens aged at 177°C (350°F), as well as determinations of ultimate bearing strength using the zero clearance high strength clevis for the completed joint for comparison with computer analysis.

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Summary No. 5
August 1996

Prepared For
Lockheed Martin Corporation

Prepared by:

Handwritten signature

R. J. Wright
Experimental Investigator

Approved By:

Handwritten signature
W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Monthly summary for August, 1996.

The series of pin bearing tests has continued to complete a boundary condition for time dependent bearing behavior. A specimen aged 5000 hours at 177°C (350°F) loaded to 5500lbs. showed time dependent deformation which eventually arrested during its 250 hour run after reaching .02% of the hole diameter, which is far short of the 4% permanent hole elongation failure criterion. (Damage is similar to specimens aged at this temperature which were loaded to 6000 lbs. and 5700lbs., but with less brooming on either side of the bolt hole). Computer analysis of the clamped and unclamped bolted joints was conducted using Lockheed Martin's DIAL code with models analogous to ones previously used by Lockheed Martin for bearing bypass simulation. Stress states calculated with these models will be used to examine correlations between separately measured neat resin properties and bolted joint performance.

E-15-V32
214

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Summary No. 6
October 1996

Prepared For
Lockheed Martin Corporation

Prepared by:

R. J. Wright
R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson
W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Monthly summary for October, 1996.

(1) The bolt load cells are completed and have been calibrated.

(A)The devices have been shown to give linear outputs at loads over 1600lbs., which is twice the clamp up loading delivered by the standard clamp-up torque of 50 in-lb (780 lbs. Calculated, 760 lbs. experimentally measured), and remain so at the experimental temperature of 177°C (350°F)

(B)The load cells have demonstrated the capability of resolving load changes of 2 lbs. while under a static load of 1000lbs.

2. Clamped bearing creep testing has been started with unaged material.

The first tests are set to the highest loads survived by unclamped unaged material, 6500 lbs. This data will then be compared to behavior at 9000 lbs. (150% of the design ultimate load for the joint), where the joint has been shown previously not to show time dependent deformation while under load.

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Summary No. 7
November 1996

Prepared For
Lockheed Martin Corporation

Prepared By:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Monthly summary for November, 1996.

Testing of clamped up joints with a load cell placed on the bolt to read out clamp-up forces has showed a time dependent drop in clamp up force as a function of time after loading the joint at temperature (177°C (350°F)). In the first test, 6500lb. load with a clamp-up torque of 50 in-lb, the clamp up force was seen to drop by a quarter of its original by the time it had asymptotically leveled off. At the same time, unclamped bearing creep testing of material aged for 10,000 hours at 177°C (350°F) and 204°C (400°F) has shown somewhat different behavior from material aged 5000 hours. Most significantly, loads of 6000 lbs. do not appear to be causing outer ply delamination in material aged at 177°C (350°F) for 10,000 hours while material aged at the same temperature for 5000 hours showed outer ply delamination around the bolt hole in previous testing. Testing of the 10,000 hour aged material is continuing at this time.

E-18-X33
#16

Creep Bearing Behavior of Highly Loaded Composite Joints

Monthly Progress Summary No. 8
December 1996

Prepared For
Lockheed Martin Corporation

Prepared By:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Progress Summary for December 1996:

Testing of material aged 10,000 hours has continued to complete a picture of the changes in the material as it ages at 177°C (350°F) and 204°C (400°F). Unclamped bearing testing has shown that material aged at 177°C (350°F) for 10,000 hours is able to withstand loads of 6500 lbs., the highest load sustained by unaged material, without damage in unclamped loading. In contrast, unclamped loading to 6500 lbs. on material aged at 177°C (350°F) for 5000 hours produced bearing failure, and even though the material was able to withstand loads of 6000 lbs., this loading caused delamination and buckling of the outer plies. Material aged at 204°C (400°F) for 10,000 hours withstood loading to 6500 lbs. in unclamped bearing.

Given the apparent recovery by the material aged at 177°C (350°F), it was decided to repeat the 7000lb. load unclamped test which previously showed time dependant deformation leading to bearing failure in unaged material. When performed on material aged at 177°C (350°F) for 10,000 hours, the material withstood the 7000lb. load for 2.86 hours before undergoing bearing failure. In contrast, material aged for 10,000 hours at 204°C (400°F) suffered bearing failure after 52.25 hours, which even surpassed the performance of unaged material, which failed after 38.4 hours in duplicate tests. This test is currently being duplicated on material aged at 204°C (400°F) for 5000 hours for comparison.

Creep Bearing Behavior of Highly Loaded Composite Joints

1996 First Quarter Report
March 1996

Prepared For
Lockheed Martin Corporation

Prepared By:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview:

Bearing creep tests have continued, and have nearly completed mapping out the bolted joint performance envelope where the composite is not constrained by clampup forces. The next phase of testing will explore the effect of clampup on joint performance, the buildup of clampup forces on a joint under load, and the effect of constraint to a joint after deformation has begun.

Progress:

Bearing Creep Tests- The Third bearing creep test was run at a load of 9000lbs. for 250 hours at 177C (350F). This test resulted in no elongation of the bolt hole, although the marks from the washers on the sides of the hole are more pronounced than in the previous test (5000lb. load). For the next test, it was decided to try loading the specimen without clamp-up force or other constraint to get data on this boundary condition to compare with clamped-up specimens. It was hoped that this loading method would result in bearing force concentrations sufficient to produce time dependent behavior, if any such behavior were possible at this load and temperature. However, when the fourth test was run, the joint experienced bearing failure after supporting the 9000lbs. load for approximately 90 seconds. This test specimen shows significant brooming on either side of the bolt hole along with delaminations at every 90 degree ply throughout its thickness.

Because the 9000lbs. specimen with no clampup had supported the applied load for a short period of time before failing, it was decided to try the fifth test at a load of 8000lbs. for 250 hours at 177C (350F). Mr. Brian Cornell and Dr. Hafiz Ahmad from Lockheed were present to observe the start of this test and confer with the experimental investigator on plans for further testing. After loading, the specimen failed in the same manner as the one used in the previous test; after supporting the full load for a short period of time. Damage to this specimen was in the same form as the damage to the 9000 lb. load specimen in the previous pin bearing test. This

specimen has been cut to reveal a cross section of the bearing area and will be polished for microscopic examination. This analysis of the damage present should offer better quantification of the failure mode observed in all tests so far.

After witnessing the results of this test, the plan for further testing was modified to perform the sixth bearing creep test at 5000lbs. for 250 hours at 177°C (350°F). This test resulted in no elongation of the bolt hole, although a slight ridge is present on the resin rich smooth side (however, it should be noted that this feature is far less noticeable than the washer marks present in the clamped-up tests). The seventh test was then run at a load level of 6000 lbs. for 250hrs. at 177°C (350°F). The specimen used for the 6000 lb. test showed no time dependent deformation of the hole, and marks on the specimen were identical in form and size to those on the 5000 lb. specimen. This bearing load was especially significant since it failed to produce time dependent behavior at a load very close to the predicted in flight loading even without clamp-up force.

The eighth bearing creep test was run at 7000 lbs. with no clampup at 177°C (350°F) for 250 hours. In this test, the joint demonstrated time dependent deformation that ultimately appeared as joint failure. Examination of the specimen reveals that it had expanded until it reached the sides of the clevis (this was after the hole had deformed approximately .1").

The eighth bearing creep test has been started at 6500 lbs. with no clampup at 177°C (350°F) for 250 hours. This test is expected to finish the preliminary mapping of the joint's strength under sustained load at temperature. Both this and the 7000 lb. tests will be repeated.

Testing Program- The remaining bolt bearing creep testing matrix will consist of three basic test types:

1. Measured variable clampup force tests. In these tests, clampup forces will be monitored at different load levels with the aid of a load cell.
2. Near- constraint bearing tests. In these tests, the effect of small gaps in the joint will be monitored by spacing the constraining washers away from the specimen by a very short distance.
3. Comparison of aged to unaged properties. In addition to the 5000 hr. specimens, 10,000 hr. specimens will be available for testing in August.

In addition to these tests, a few other tests will be done if time is still available. These supplementary tests would include comparisons between K3B matrix composites and PETI-5 matrix lay-ups.

The 5000 hour mark for 64 ply IM-7/K3B specimens being aged at 177C (350F) and 204C (400F) in Georgia Tech's aging ovens was reached of January 20th. The aged material includes cut specimens and uncut panels at both temperatures. Panels are being cut into specimens at Lockheed. This approach makes it possible to isolate air exposure effects in the bolt hole from exposure effects on a sealed bolt hole. These specimens will be used in repetitions of tests on new material for paired comparison of aged and unaged properties. These specimens will be used for comparison with tests of unaged material in critical loading regimes, based on the same tests done on unaged material.

Ultimate Bearing Strength Tests- The design of the new fixture has been finalized. It is being machined at the Georgia Tech Mechanical Engineering department's machine shop. In addition to this device, a small load cell for use on the setup will be used to measure clampup forces as the joint is loaded.

Concerns:

The material behavior seems to have been very consistent for the current run of experiments. We expect the bolt bearing performance envelope can be completed without complications.

Plans:

In the next quarter, pin bearing testing will be completed. Bearing creep testing with measurement of clampup forces should provide a picture of what the relationship between constraint and bearing force is. At the same time, testing will begin with the aged specimens to determine if aging is significantly altering bearing creep characteristics.

Tests in Primary Matrix Completed Previously

Load lbs.	Time	Test Temp.	Age Temp.	Age. Time	Clamp-up	Result
4000	272 hrs.	350 F	-	0 hrs.	50 in-lb	No Creep
5000	269 hrs.	350 F	-	0 hrs.	50 in-lb	No Creep
9000	250 hrs.	350 F	-	0 hrs.	50 in-lb	No Creep
5000	250 hrs.	350 F	-	0 hrs.	0 in-lb	No Creep
6000	250 hrs.	350 F	-	0 hrs.	0 in-lb	No Creep
7000	250 hrs.	350 F	-	0 hrs.	0 in-lb	Creep
8000	250 hrs.	350 F	-	0 hrs.	0 in-lb	Bearing Failure
9000	250 hrs.	350 F	-	0 hrs.	0 in-lb	Bearing Failure

E-18-X 33
#10

Creep Bearing Behavior of Highly Loaded Composite Joints

Quarterly Report No. 2
June 1996

Prepared For
Lockheed Martin Corporation

Prepared By:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview:

Bearing creep testing begun in December, 1995 continues and has mapped out baseline figures for the bolted joint performance envelope. Cumulative data from testing through June 20 is presented in this quarterly report. Upcoming tests will explore variable clamp-up effects, change in clamp-up forces on a joint under load, and effects of constraint to a joint after deformation has begun.

Progress:

Bearing Creep Tests- Bearing creep testing has continued to fill out the unclamped bearing section of the test matrix. Tests have been performed on material aged at 177°C (350°F) for 5000 hours as well as material aged at 204°C (400°F) for 5000 hours. For each test, one duplicate has been performed. Thus far, all duplicates have performed identically to the original specimens.

Experimental Results And Discussion:

Bearing Creep- Bearing creep tests have all been run at 177°C (350°F). All specimens are dried for 240 hours at 116°C (250°F) to remove any volatile content before being put in the creep frames for testing. Each test runs for a continuous 250 hours under load at temperature. Four basic series of bearing creep tests have been run: First, testing joints clamped up to 5.65 N·m (50 in-lb) torque with unaged coupons. Second, testing of unclamped bearing on unaged coupons where no washers or other constraint was present to prevent deformation of the specimens (measurement wire was present). Third, testing of unclamped bearing on specimens aged at 177°C (350°F) for 5000hrs. Fourth, unclamped bearing testing on material aged at 204°C (400°F) for 5000 hrs. Data given in Figures 1, 2, 3, and 4 is the average from each experimental test and its duplicate.

Failure Criterion- Failure is defined as any permanent deformation of the bolt hole of 4% of its diameter or more (MIL-HDBK-5G Section 9), which is .038cm (.015") in

this instance. This failure criterion is illustrated here (as in Figure 1) as being the largest elastic deformation seen (immediately after loading in the 31.1kN (7000lb.) test shown in Figure 2) with the 4% of the diameter added to it.

Clamped-Up Tests- These tests were done on unaged specimens with standard aircraft washers providing clamp up force on either side of the specimens. As seen in Figure 1, the presence of clamp-up appears to have prevented bearing creep at loads up to 40 kN or 473 MPa (9000lbs. or 68.6 ksi), or 150% of the baseline load for the joint, 26.7kN or 315 MPa (6000 lbs. or 45.7 ksi). During testing, the washers on either side left marks on the specimens; these were found to be smoothed areas and not measurable indentations. The bolt holes in all of the test coupons recovered elastically to the original bolt hole diameter of .953cm (.375").

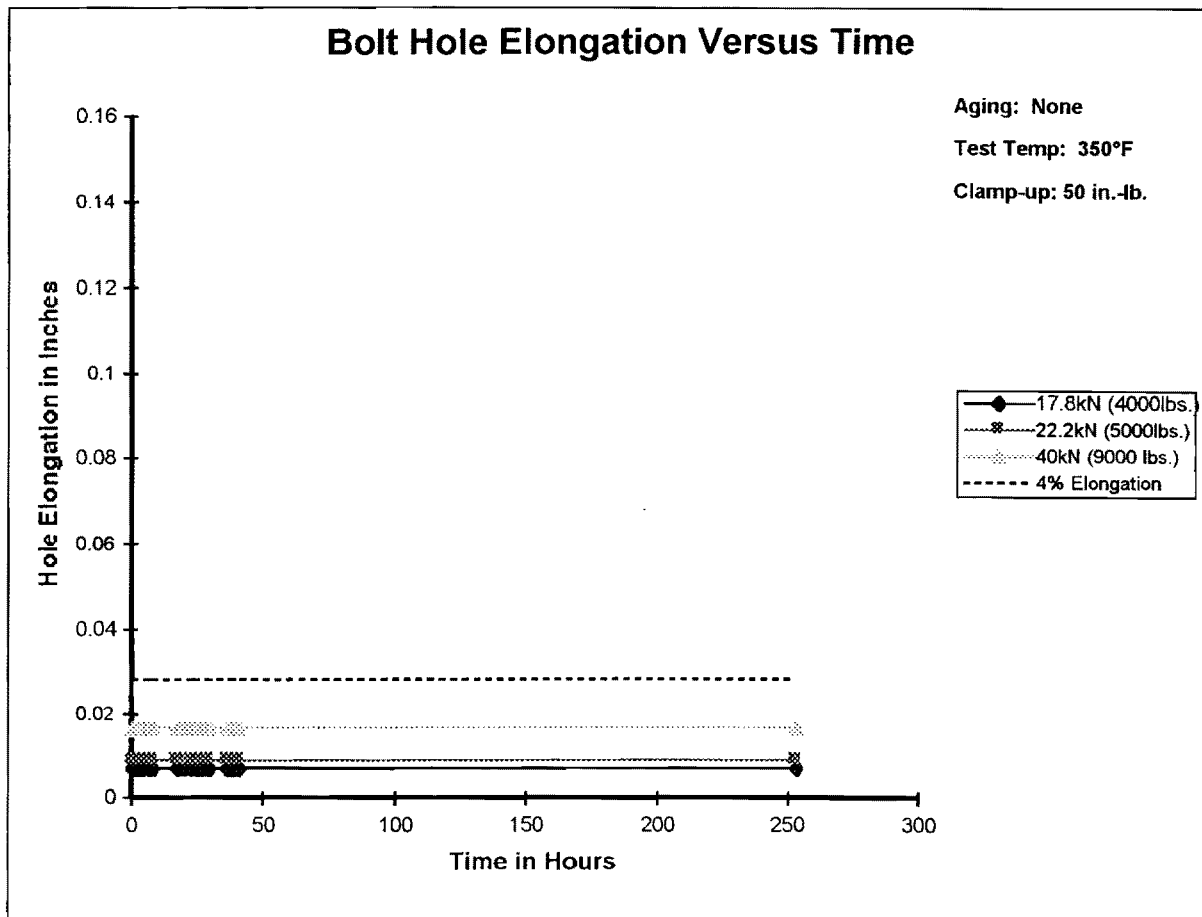


Figure 1: Clamped-up Bolt Bearing Behavior of Unaged Material

Unclamped Bolt Bearing Tests- Based on the results of the clamped up specimens, the researchers decided to look at the worst case scenario for this joint system:

Unclamped bearing, where the washers are absent from the bolt so that there is no constraining clamp-up force to prevent spreading out of the material and failure of the laminate. In these tests, it was revealed that the laminate was sustaining loads with clamp-up that would result in nearly instantaneous bearing failure without the constraining clamp-up force.

Unclamped Bolt Bearing In Unaged Material- The first series of unclamped bearing tests was carried out in unaged material. The testing started at a load of 40kN or 473MPa (9000lbs. or 68.6ksi). This load produced rapid bearing failure, as seen in Figure 2. It appears that the critical value for sustaining loads is somewhere around 31.1 kN or 365.4 MPa (7000lbs. or 53ksi). At this load, the joint showed a creep-like failure pattern which moved until the material spread out enough to fill the clevis, thus producing the “Knee” visible in Figure 2. The damage to the specimen, however, appeared to be identical to the crushing and intralaminar cracking produced by outright bearing failure. Given the known properties of the matrix material in regard to brittleness increasing with temperature, this result is consistent. Note the absence of any time dependent behavior in material at a slightly lower load of 28.9 kN or 341.5MPa (6500lbs. or 49.5ksi). Specimens tested at loads below 31.1 kN or 365.4 MPa (7000lbs. or 53ksi) recovered elastically to its original dimensions.

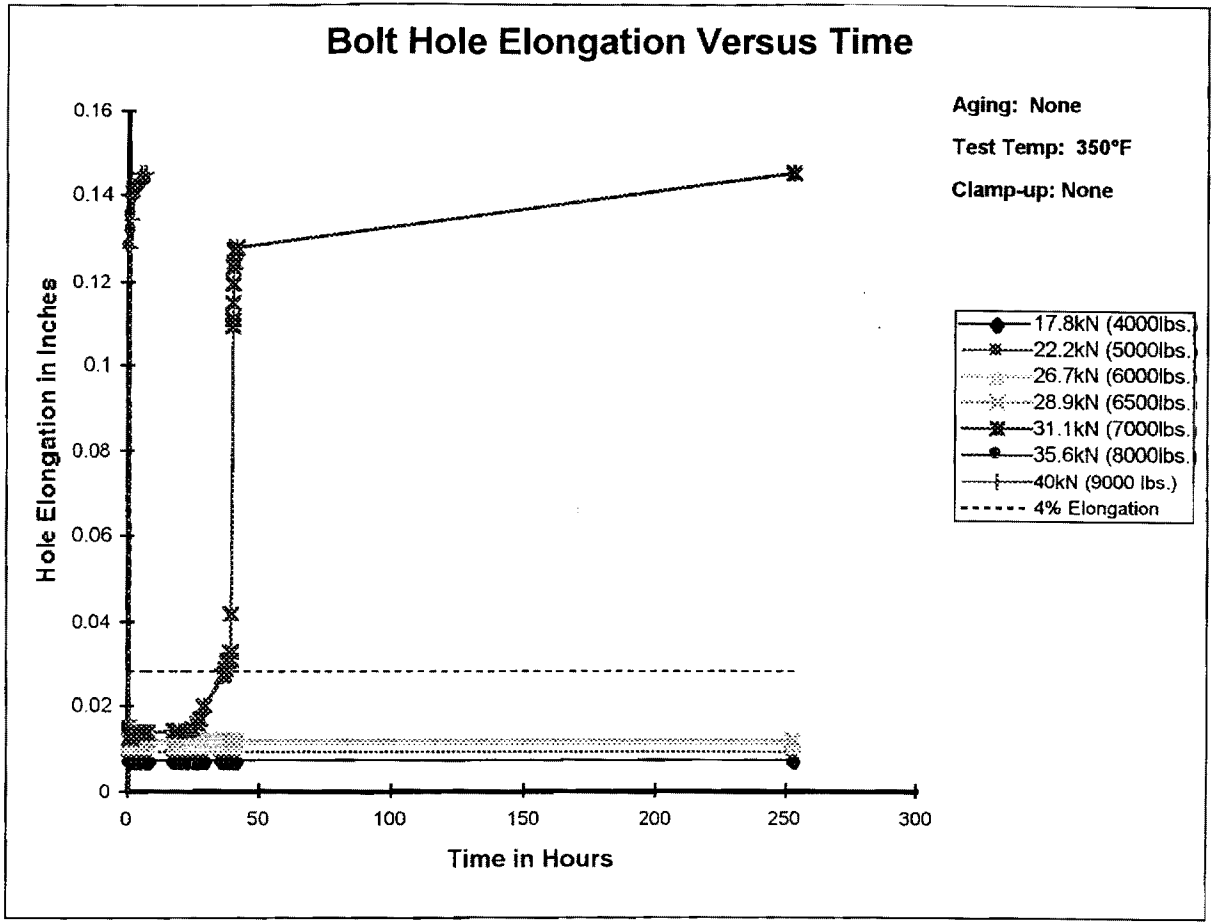


Figure 2: Unclamped Bearing Behavior of unaged material

Unclamped Bearing In Material Aged 5000 Hours At 177°C (350°F)- The second series of unclamped bearing tests was performed with material which had been aged for 5000 hours at 177°C (350°F). In these tests, the target loads were the highest loads the unaged material had survived in the unaged unclamped tests. As seen in Figure 6, the material aged at 177°C (350°F) showed immediate bearing failure at 28.9 kN or 341MPa (6500 lbs. or 49.5 ksi). More interestingly, the material showed time dependent deformation that arrested itself at 26.7kN or 315 MPa (6000 lbs or 46.2 ksi). The specimens in the latter case had clear delaminations on either side above the bolt hole with the outer 45° plies pushed out from the specimen, creating bulges or “Ears”. From these tests it is clear that there has been loss of unclamped bearing strength after aging at 177°C (350°F). At the same time, the damage

remained self-similar (bearing failure with delamination, crushing under the bolt, and outer ply separation).

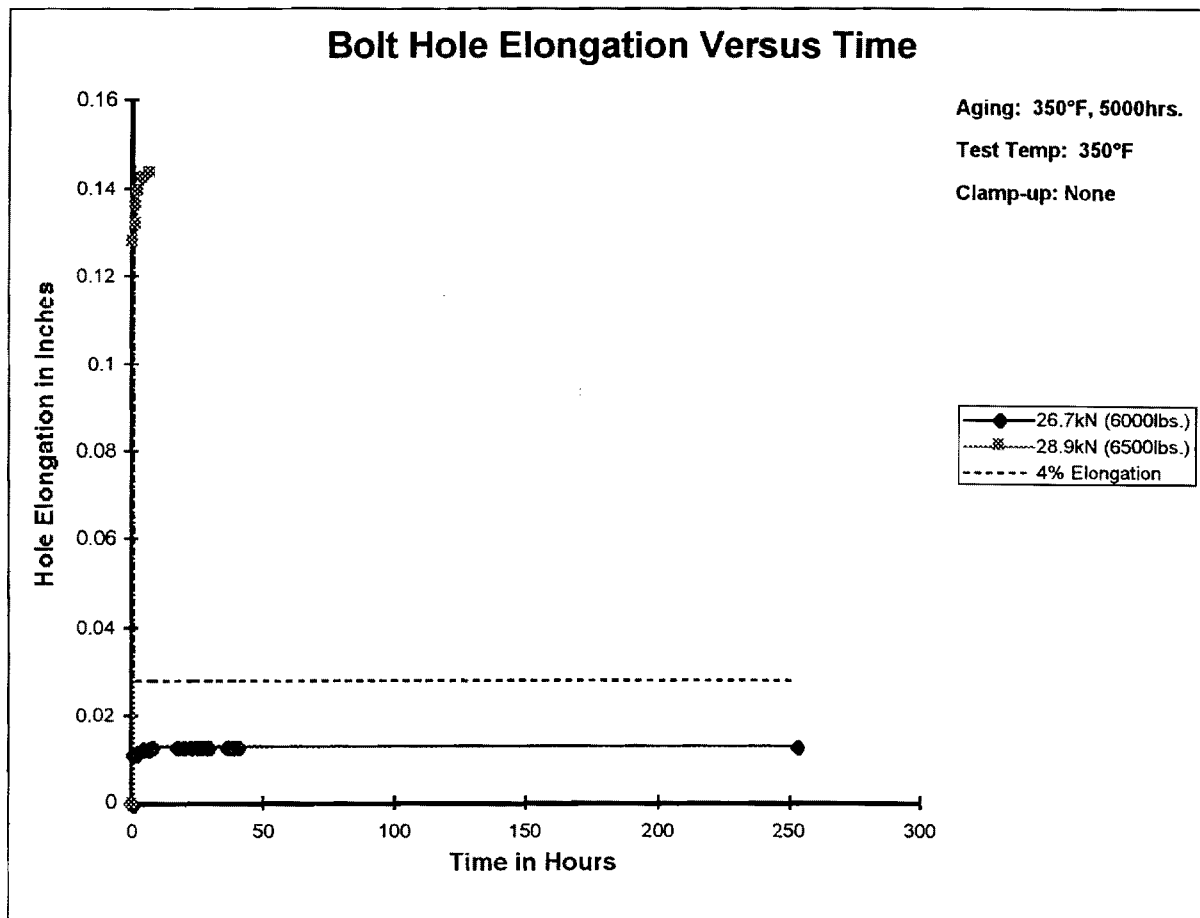


Figure 3: Unclamped Bearing Behavior of Material Aged 5000 hours at 177°C (350°F)

Unclamped Bearing In Material Aged 5000 Hours At 204°C (400°F)- Unclamped bearing tests were conducted with material aged for 5000 hours at 204°C (400°F). As in the earlier testing, the strategy was to use the highest load the previous test had survived. For this test, the load was 26.7kN or 315 MPa (6000lbs. or 45.7ksi). The unexpected result was that the material apparently was less affected by aging at temperatures of 204°C (400°F) than it was when aged at 177°C (350°F). As seen in Figure 4, the material aged at the higher temperature did not show deformation at 26.7kN or 315 MPa (6000lbs. or 45.7ksi) the way material aged at 177°C (350°F) had.

The specimens aged at 204°C (400°F) recovered elastically to its original dimensions. In comparison, the coupons aged at 177°C (350°F) tested at this same load both showed significant “Ears” on either side above the bolt hole where delamination had begun and apparently arrested when enough crushed material gathered to distribute the load.

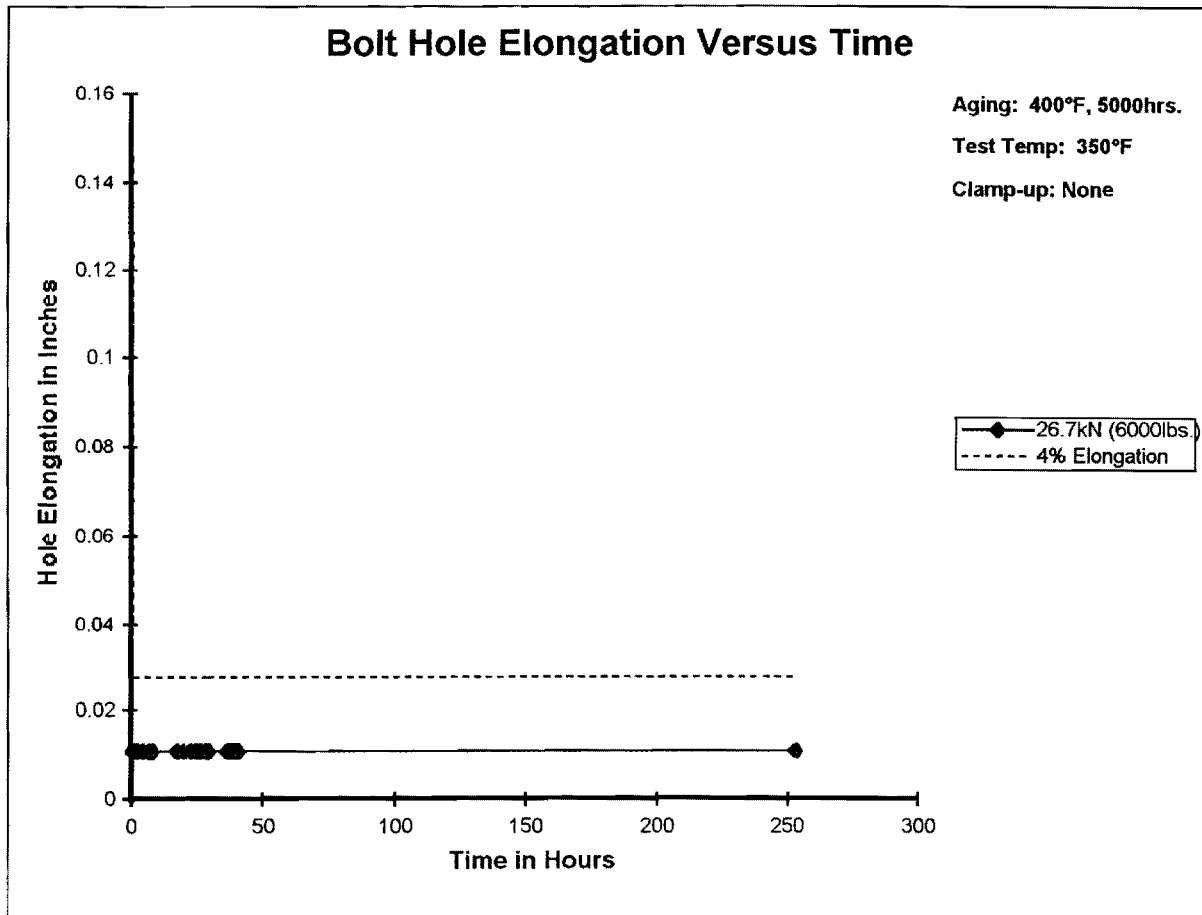


Figure 4: Unclamped Bearing Behavior of Material Aged 5000 hours at 204°C (400°F)

Summary- IM7/K3B has shown itself to be insensitive to time dependent deformation. It is apparent from testing that time dependent behaviors can be expected to only show up in a very narrow band of loadings. Early testing has pointed to clamp-up force as the source of the most obvious change in coupon strength at temperature. Unclamped bearing testing has shown that these materials

can withstand significant loads at temperature, even without clamp-up force to prevent delamination.

Thus far, there have been some interesting results as far as aging and accelerated testing are concerned. As can be seen in the data, the material has lost bearing strength as an apparent consequence of being aged at the supersonic cruise temperature regime being explored. However, since the material aged at the higher temperature of 204°C (400°F) showed neither the same degree nor enhancement of the aging process which apparently reduced the strength of the material aged at 177°C (350°F) there is doubt as to whether simple aging acceleration strategies will give accurate results for this class of material.

Plans:

In order to form a complete picture of the performance of the highly loaded bolted joints under consideration, the remaining bolt bearing creep testing matrix will contain three different test types:

1. Measured variable clamp-up force tests. In these tests, clamp-up forces will be monitored at different load levels with the aid of a load cell.
2. Near- constraint bearing tests. In these tests, the effect of small gaps in the joint will be monitored by spacing the constraining washers away from the specimen by a very short distance.
3. Comparison of aged to unaged properties. In addition to the 5000 hr. specimens tested thus far, 10,000 hr. specimens will be available for testing in August.

In addition to these tests, other tests will be done if time is still available. These supplementary tests include comparisons between K3B matrix composites and PETI-5 matrix lay-ups.

D-15-X-33
#13

Creep Bearing Behavior of Highly Loaded Composite Joints

Second Quarter Report
September 1996

Prepared For
Lockheed Martin Corporation

Prepared by:

R. J. Wright
Experimental Investigator

Approved By:

W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

Overview:

Bearing creep testing begun in December, 1995 continues and has mapped out baseline figures for the bolted joint performance envelope. Cumulative data from testing through June 20 is presented in this quarterly report. Upcoming tests will explore variable clamp-up effects, change in clamp-up forces on a joint under load, and effects of constraint to a joint after deformation has begun.

Progress:

Bearing Creep Tests- Bearing creep testing has continued to fill out the unclamped bearing section of the test matrix. Tests have been performed on material aged at 177°C (350°F) for 5000 hours as well as material aged at 204°F (400°F) for 5000 hours. For each test, one duplicate has been performed. Thus far, all duplicates have performed identically to the original specimens.

Experimental Results And Discussion:

Bearing Creep- Bearing creep tests have all been run at 177°C (350°F). All specimens are dried for 240 hours at 116°C (250°F) to remove any volatile content before being put in the creep frames for testing. Each test runs for a continuous 250 hours under load at temperature. Four basic series of bearing creep tests have been run: First, testing joints clamped up to 5.65 N·m (50 in-lb) torque with unaged coupons. Second, testing of unclamped bearing on unaged coupons where no washers or other constraint was present to prevent deformation of the specimens (measurement wire was present). Third, testing of unclamped bearing on specimens aged at 177°C (350°F) for 5000hrs. Fourth, unclamped bearing testing on material aged at 204°C (400°F) for 5000 hrs. Data given in Figures 1, 2, 3, and 4 is the average from each experimental test and its duplicate.

Failure Criterion- Failure is defined as any permanent deformation of the bolt hole of 4% of its diameter or more (MIL-HDBK-5G Section 9), which is .038cm (.015") in this instance. This failure criterion is illustrated here (as in Figure 1) as being the

largest elastic deformation seen (immediately after loading in the 31.1kN (7000lb.) test shown in Figure 2) with the 4% of the diameter added to it.

Clamped-Up Tests- These tests were done on unaged specimens with standard aircraft washers providing clamp up force on either side of the specimens. As seen in Figure 1, the presence of clamp-up appears to have prevented bearing creep at loads up to 40 kN or 473 MPa (9000lbs. or 68.6 ksi), or 150% of the baseline load for the joint, 26.7kN or 315 MPa (6000 lbs. or 45.7 ksi). During testing, the washers on either side left marks on the specimens; these were found to be smoothed areas and not measurable indentions. The bolt holes in all of the test coupons recovered elastically to the original bolt hole diameter of .953cm (.375”).

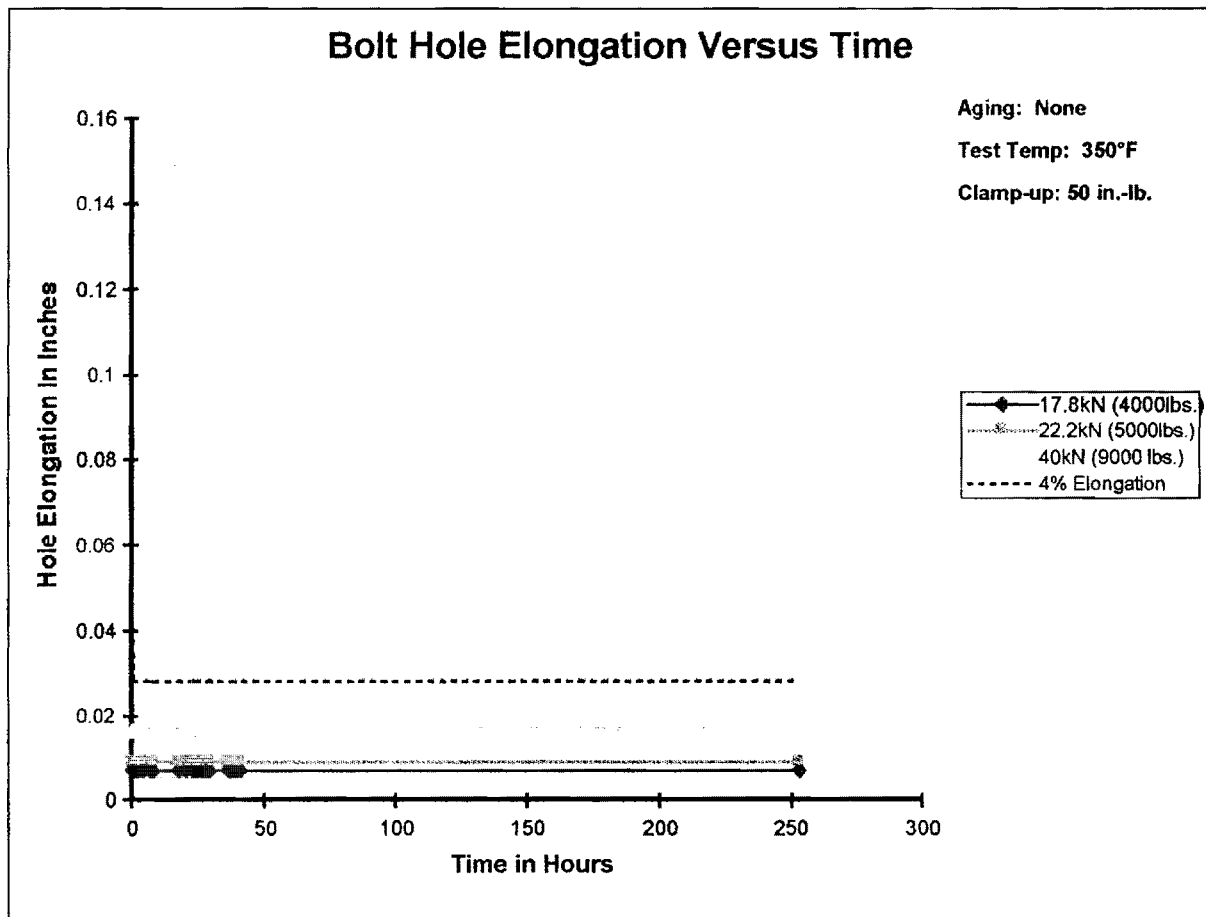


Figure 1: Clamped-up Bolt Bearing Behavior of Unaged Material

Unclamped Bolt Bearing Tests- Based on the results of the clamped up specimens, the researchers decided to look at the worst case scenario for this joint system:

Unclamped bearing, where the washers are absent from the bolt so that there is no constraining clamp-up force to prevent spreading out of the material and failure of the laminate. In these tests, it was revealed that the laminate was sustaining loads with clamp-up that would result in nearly instantaneous bearing failure without the constraining clamp-up force.

Unclamped Bolt Bearing In Unaged Material- The first series of unclamped bearing tests was carried out in unaged material. The testing started at a load of 40kN or 473MPa (9000lbs. or 68.6ksi). This load produced rapid bearing failure, as seen in Figure 2. It appears that the critical value for sustaining loads is somewhere around 31.1 kN or 365.4 MPa (7000lbs. or 53ksi). At this load, the joint showed a creep-like failure pattern which moved until the material spread out enough to fill the clevis, thus producing the "Knee" visible in Figure 2. The damage to the specimen, however, appeared to be identical to the crushing and intralaminar cracking produced by outright bearing failure. Given the known properties of the matrix material in regard to brittleness increasing with temperature, this result is consistent. Note the absence of any time dependent behavior in material at a slightly lower load of 28.9 kN or 341.5MPa (6500lbs. or 49.5ksi). Specimens tested at loads below 31.1 kN or 365.4 MPa (7000lbs. or 53ksi) recovered elastically to its original dimensions.

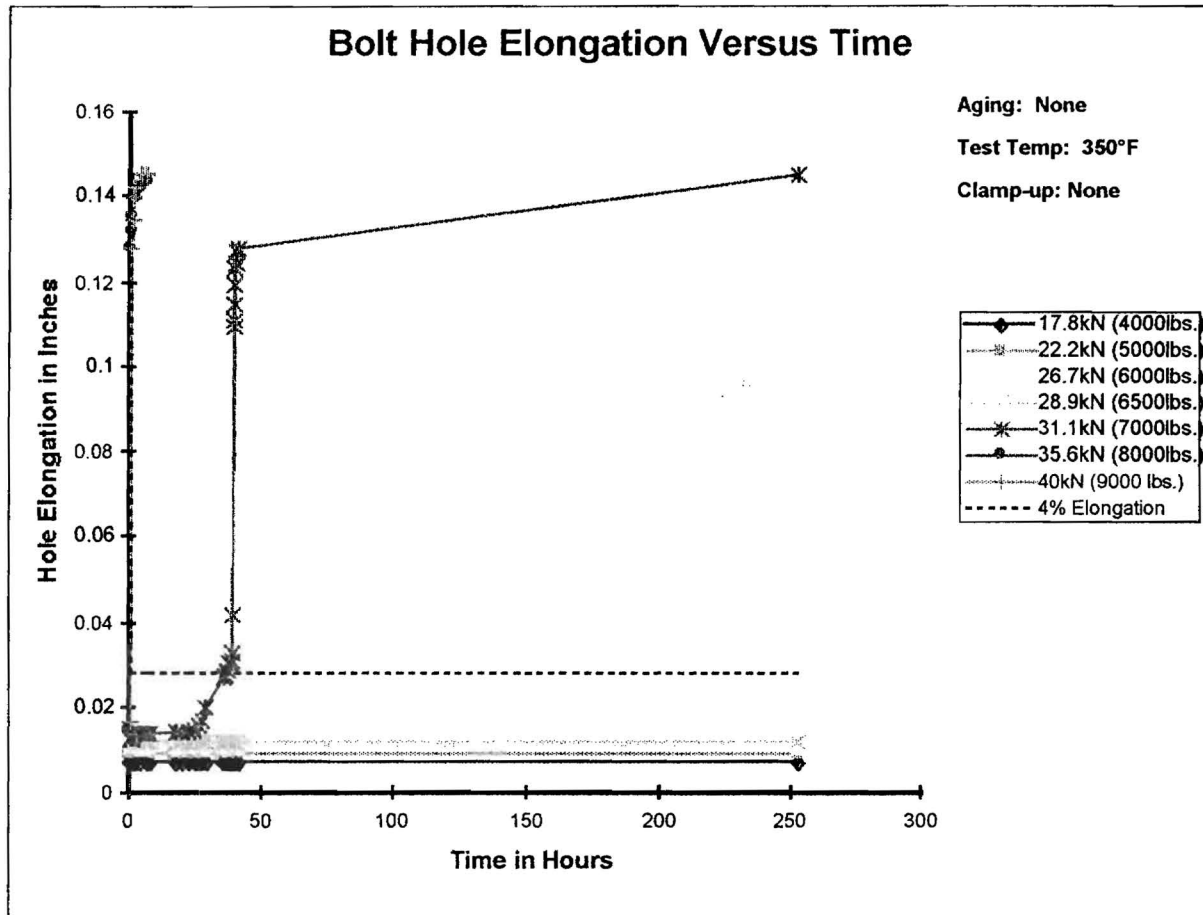


Figure 2: Unclamped Bearing Behavior of unaged material

Unclamped Bearing In Material Aged 5000 Hours At 177°C (350°F)- The second series of unclamped bearing tests was performed with material which had been aged for 5000 hours at 177°C (350°F). In these tests, the target loads were the highest loads the unaged material had survived in the unaged unclamped tests. As seen in Figure 6, the material aged at 177°C (350°F) showed immediate bearing failure at 28.9 kN or 341MPa (6500 lbs. or 49.5 ksi). More interestingly, the material showed time dependent deformation that arrested itself at 26.7kN or 315 MPa (6000 lbs or 46.2 ksi). The specimens in the latter case had clear delaminations on either side above the bolt hole with the outer 45° plies pushed out from the specimen, creating bulges or “Ears”. From these tests it is clear that there has been loss of unclamped bearing strength after aging at 177°C (350°F). At the same time, the damage

remained self-similar (bearing failure with delamination, crushing under the bolt, and outer ply separation).

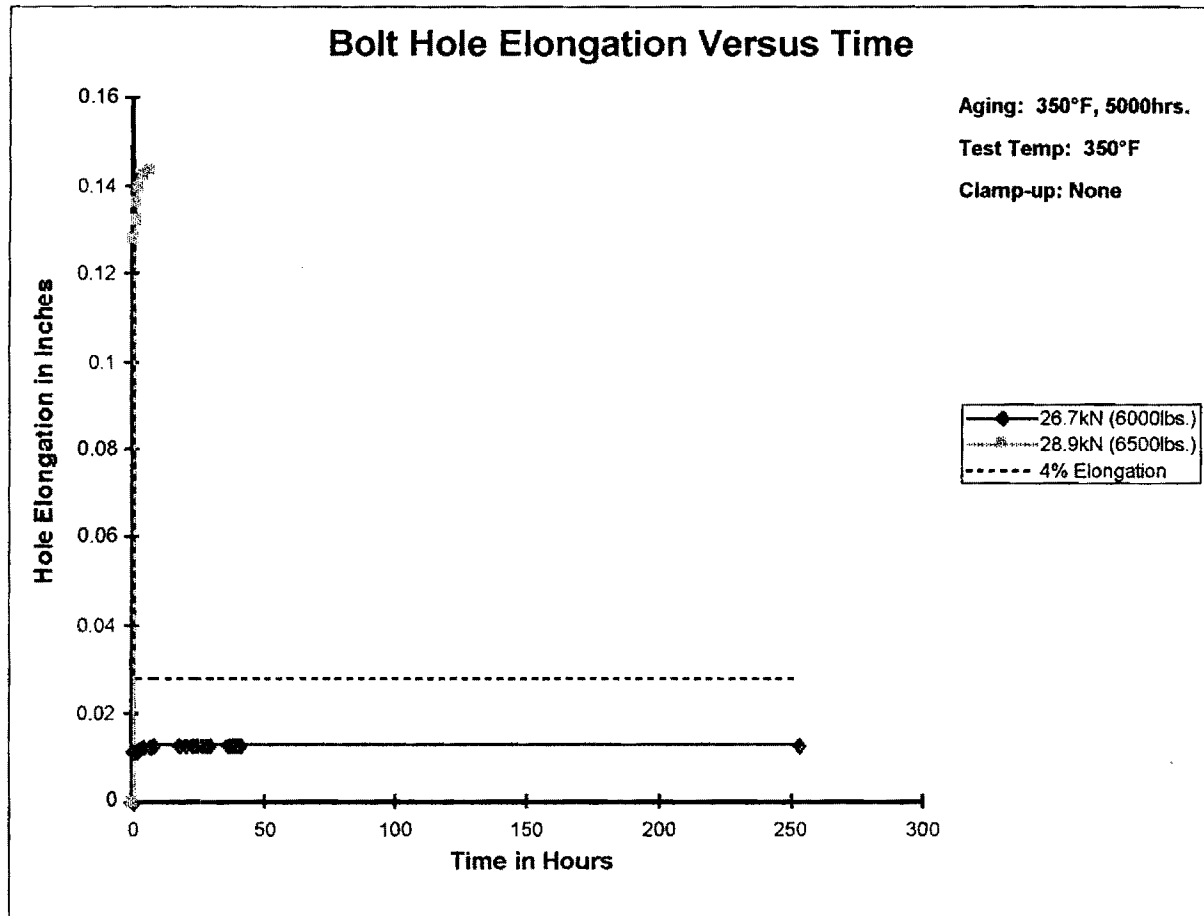


Figure 3: Unclamped Bearing Behavior of Material Aged 5000 hours at 177°C (350°F)

Unclamped Bearing In Material Aged 5000 Hours At 204°C (400°F)- Unclamped bearing tests were conducted with material aged for 5000 hours at 204°C (400°F). As in the earlier testing, the strategy was to use the highest load the previous test had survived. For this test, the load was 26.7kN or 315 MPa (6000lbs. or 45.7ksi). The unexpected result was that the material apparently was less affected by aging at temperatures of 204°C (400°F) than it was when aged at 177°C (350°F). As seen in Figure 4, the material aged at the higher temperature did not show deformation at 26.7kN or 315 MPa (6000lbs. or 45.7ksi) the way material aged at 177°C (350°F) had. The specimens aged at 204°C (400°F) recovered elastically to its original dimensions.

In comparison, the coupons aged at 177°C (350°F) tested at this same load both showed significant “Ears” on either side above the bolt hole where delamination had begun and apparently arrested when enough crushed material gathered to distribute the load.

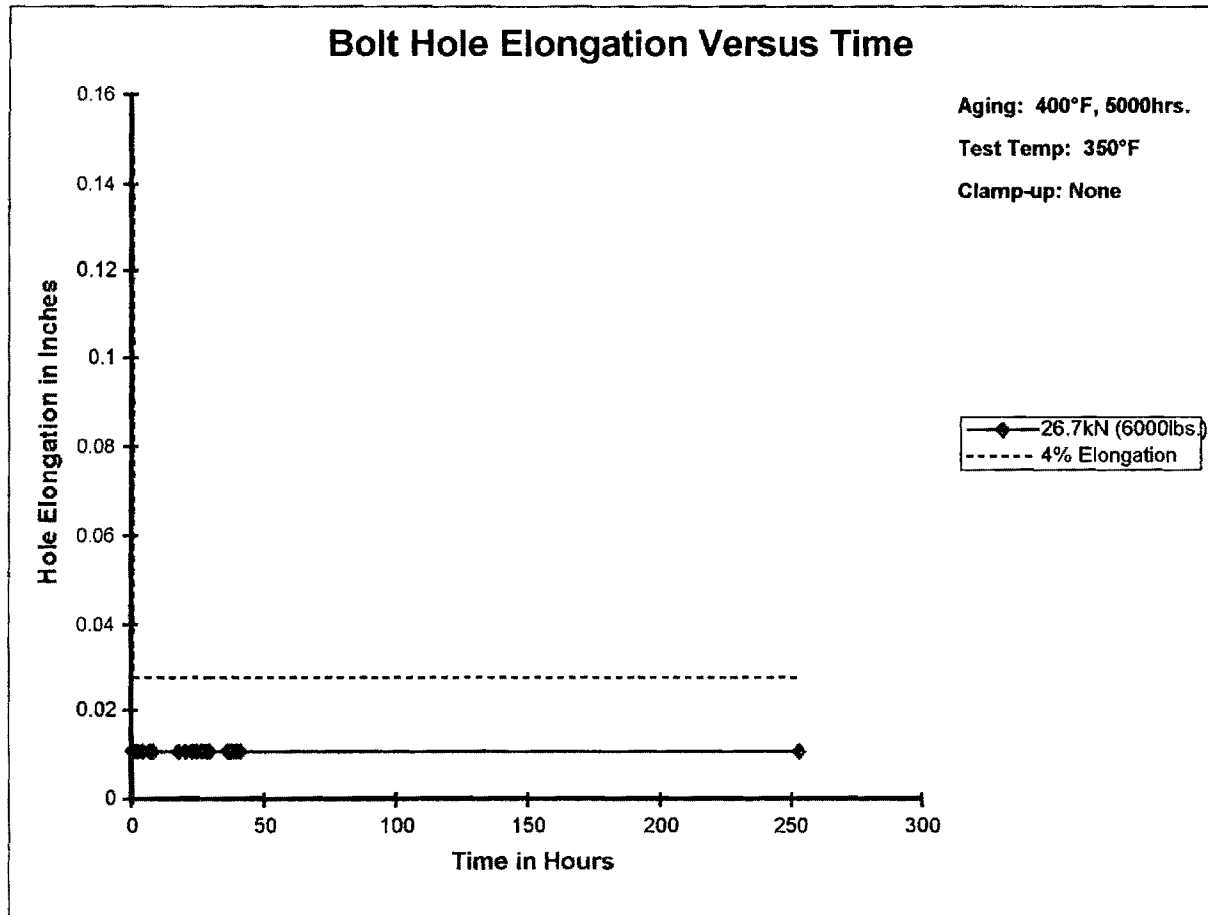


Figure 4: Unclamped Bearing Behavior of Material Aged 5000 hours at 204°C (400°F)

Summary- IM7/K3B has shown itself to be insensitive to time dependent deformation. It is apparent from testing that time dependent behaviors can be expected to only show up in a very narrow band of loadings. Early testing has pointed to clamp-up force as the source of the most obvious change in coupon strength at temperature. Unclamped bearing testing has shown that these materials can withstand significant loads at temperature, even without clamp-up force to prevent delamination.

Thus far, there have been some interesting results as far as aging and accelerated testing are concerned. As can be seen in the data, the material has lost bearing strength as an apparent consequence of being aged at the supersonic cruise temperature regime being explored. However, since the material aged at the higher temperature of 204°C (400°F) showed neither the same degree nor enhancement of the aging process which apparently reduced the strength of the material aged at 177°C (350°F) there is doubt as to whether simple aging acceleration strategies will give accurate results for this class of material.

Plans:

In order to form a complete picture of the performance of the highly loaded bolted joints under consideration, the remaining bolt bearing creep testing matrix will contain three different test types:

1. Measured variable clamp-up force tests. In these tests, clamp-up forces will be monitored at different load levels with the aid of a load cell.
2. Near- constraint bearing tests. In these tests, the effect of small gaps in the joint will be monitored by spacing the constraining washers away from the specimen by a very short distance.
3. Comparison of aged to unaged properties. In addition to the 5000 hr. specimens tested thus far, 10,000 hr. specimens will be available for testing in August.

In addition to these tests, other tests will be done if time is still available. These supplementary tests include comparisons between K3B matrix composites and PETI-5 matrix lay-ups.

E-18-X33

17

(Final)

Creep Bearing Behavior of Highly Loaded Composite Joints

Final Project Report
December 1996

Prepared For
Lockheed Martin Corporation

Prepared By:



R. J. Wright
Experimental Investigator

Approved By:



W. S. Johnson, Ph.D.
Research Supervisor

Georgia Institute of Technology
Atlanta, GA 30332

1.0 Summary

Throughout 1996, the researchers conducted testing of time dependent behavior for bolted joints. Specimens from panels aged at temperatures of 177°C (350°F) and 204°C (400°F) for 5000 hours and 10,000 hours to simulate cumulative effects of supersonic flight conditions on a bolted composite joint have been tested. Changes in joint bearing capacity, determination of time dependent behavior, and exploration of accelerated testing methods for evaluating the bolt bearing performance of future materials have been conducted. Specimens were tested with a wide range of loads both with and without clamp-up forces on the joint. All testing was done at a temperature of 177°C (350°F), the supersonic cruise temperature.

Bearing creep testing revealed time dependent behavior only in a very narrow loading region, above which bearing failure occurred almost instantaneously, and below which no damage occurred. Testing of aged material has shown degradation in material aged at 177°C (350°F) for 5000 hours. Comparison with material aged at 177°C (350°F) for 10,000 or at 204°C (400°F) for 5000 and 10,000 hours showed neither equivalent nor increased performance degradation. All specimens, regardless of aging temperature or time, have performed satisfactorily at a bearing load of 26.7kN (6000 lbs.).

2.0 Testing

2.1 Test Setup

The specimen is sized and proportioned to represent a typical highly loaded bolted composite joint (Figure 1). The basic experimental test setup for the bolt bearing tests is similar to that used in past research (Crews and Naik, 1986) and consists of a clevis with a bushing in it to apply clamp-up force to the coupon. A .95 cm (.374") diameter high strength steel aircraft bolt is put through the clevis and the coupon.

Specimen

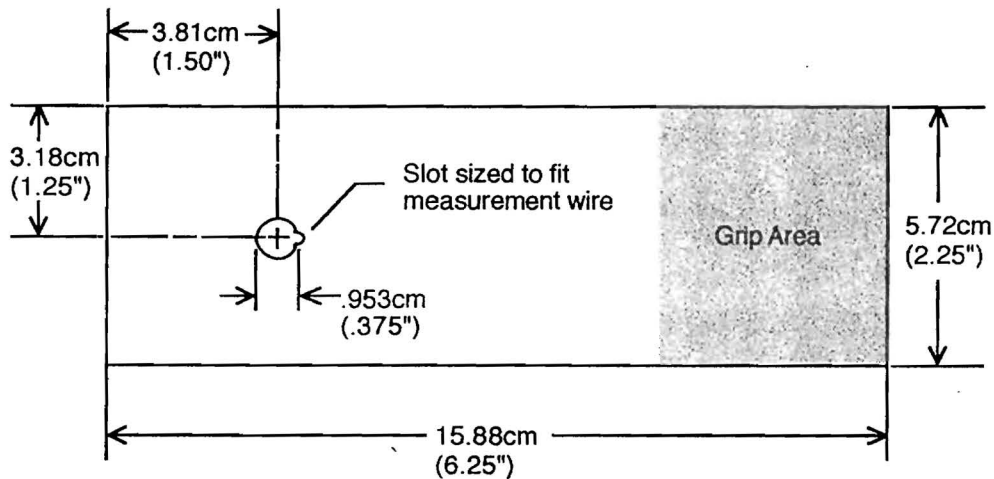


Figure 1: Bolt bearing testing coupon and its dimensions.

An Extensometer mounted between the stainless steel measurement wire hanging in the slot below the bolt hole and a pin attached to the clevis measures hole elongation. A bolted grip with fine tungsten carbide teeth designed for use with polymer matrix composites holds the other end of the specimen as seen in Figure 2.

A 20:1 lever arm creep machine supplies a static load for the duration of each bearing creep test, which represents 100 flights with 2.5 hours per flight of supersonic cruise (250 hours total). An analog amplifier boosts extensometer output and sends it to a pen chart recorder to plot hole displacement data as a function of time. In tests where bolt clamp up force is measured, this is plotted simultaneously on the chart recorder. One duplicate of each test was conducted, and data plots show the average of the results for the two tests. Very little scatter between duplicate tests was found.

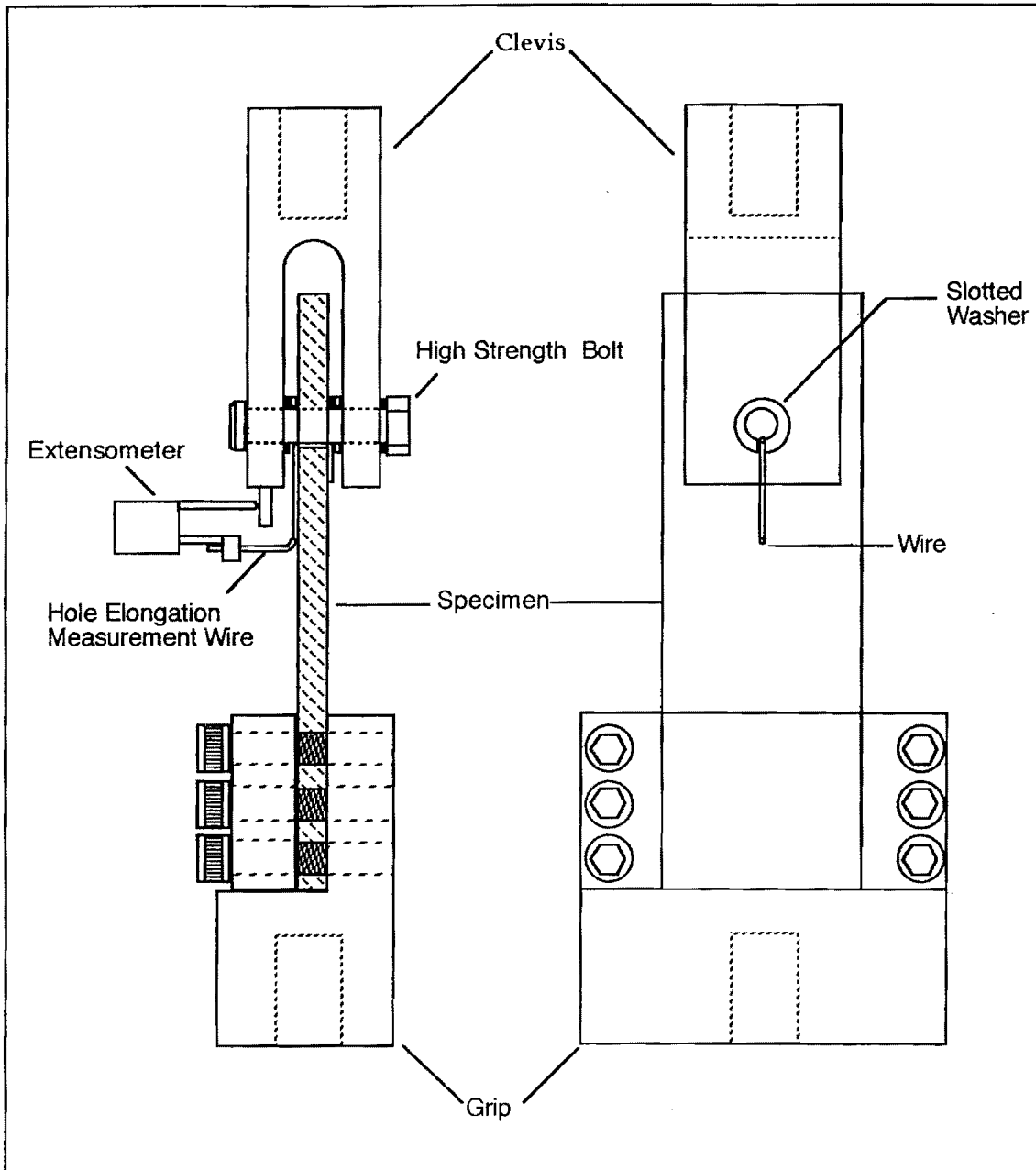


Figure2: Test fixtures with measurement wire and extensometer.

2.2 Material Description and Aging Methodology

The composite material used for these tests is IM7 carbon fibers with K3B thermoplastic polyimide (manufactured by DuPont). Sixty-four ply quasi-isotropic ($[\pm 45^\circ/90^\circ/0^\circ]_2s$) lay-up panels of material were fabricated by DuPont. Besides the panels left unaged for testing original properties, other panels and cut specimens were put into forced air aging ovens for aging at 177°C (350°F) and at 204°C (400°F). The aged panels were wrapped in fiberglass cloth to provide separation and cushioning without sacrificing surface exposure to airflow. Panels and pre-cut

specimens were removed for testing after either 5000 hours or 10,000 hours of thermal aging.

2.3 Tests Performed

All bearing creep tests were conducted at 177°C (350°F). Specimens were dried for 240 hours at 116°C (250°F) to remove volatile/moisture content before testing. Each test ran 250 hours under load at temperature. Loads for bearing creep tests represent the maximum loads predicted for the joint so testing results would give conservative performance predictions for the material. Seven series of bearing creep tests have been run:

- (1) Testing joints clamped up at 5.65 N·m (50 in-lb) torque with unaged coupons (Data in Figure 3).
- (2) Testing of unclamped bearing on unaged coupons where no washers or other constraint to prevent deformation of the specimens (Data in Figure 4).
- (3) Unclamped bearing testing on specimens aged at 177°C (350°F) for 5000 hrs. (Data in Figure 5).
- (4) Unclamped bearing testing on material aged at 204°C (400°F) for 5000 hrs. (Data in Figure 6).
- (5) Unclamped bearing testing on material aged at 177°C (350°F) for 10,000 hrs. (Data in Figure 7).
- (6) Unclamped bearing testing on material aged at 204°C (400°F) for 10,000 hrs. (Data in Figure 8).
- (7) Testing of clamped up joints in unaged material with a spool type load cell on the bolt to measure clamping force during the experiment (Data in Figure 9).

2.4 Failure Criterion

Failure is defined as any permanent hole elongation deformation of the bolt hole greater than 4% of its diameter, which is .038cm (.015") in this instance (MIL-HDBK-5G Section 9). This failure criterion is illustrated here (as in Figure 3) as being the largest elastic deformation seen (immediately after loading in the 31.1kN (7000lb.) test shown in Figure 4) with 4% of the diameter added to it. Joint performance in

this regard is judged based on how large the failure load is compared to the predicted maximum design load for the joint, 26.7 kN (6000 lbs.).

3.0 Experimental Data and Discussion of Results

3.1 Clamped-Up Tests

These tests were done on unaged specimens with standard aircraft washers providing clamp up force on either side of the specimens. As seen in Figure 3, the presence of clamp-up appears to have prevented bearing creep at loads up to 40 kN applied load or 473 Mpa bearing stress (9000lbs. or 68.6 ksi respectively), 150% of the baseline load for the joint, 26.7kN applied load or 315 Mpa bearing stress (6000 lbs. or 45.7 ksi respectively). During testing, the washers on either side left marks on the specimens; these were found to be smoothed areas rather than measurable indentions. The bolt holes in all of the test coupons recovered elastically to the original bolt hole diameter of 0.953cm (.375").

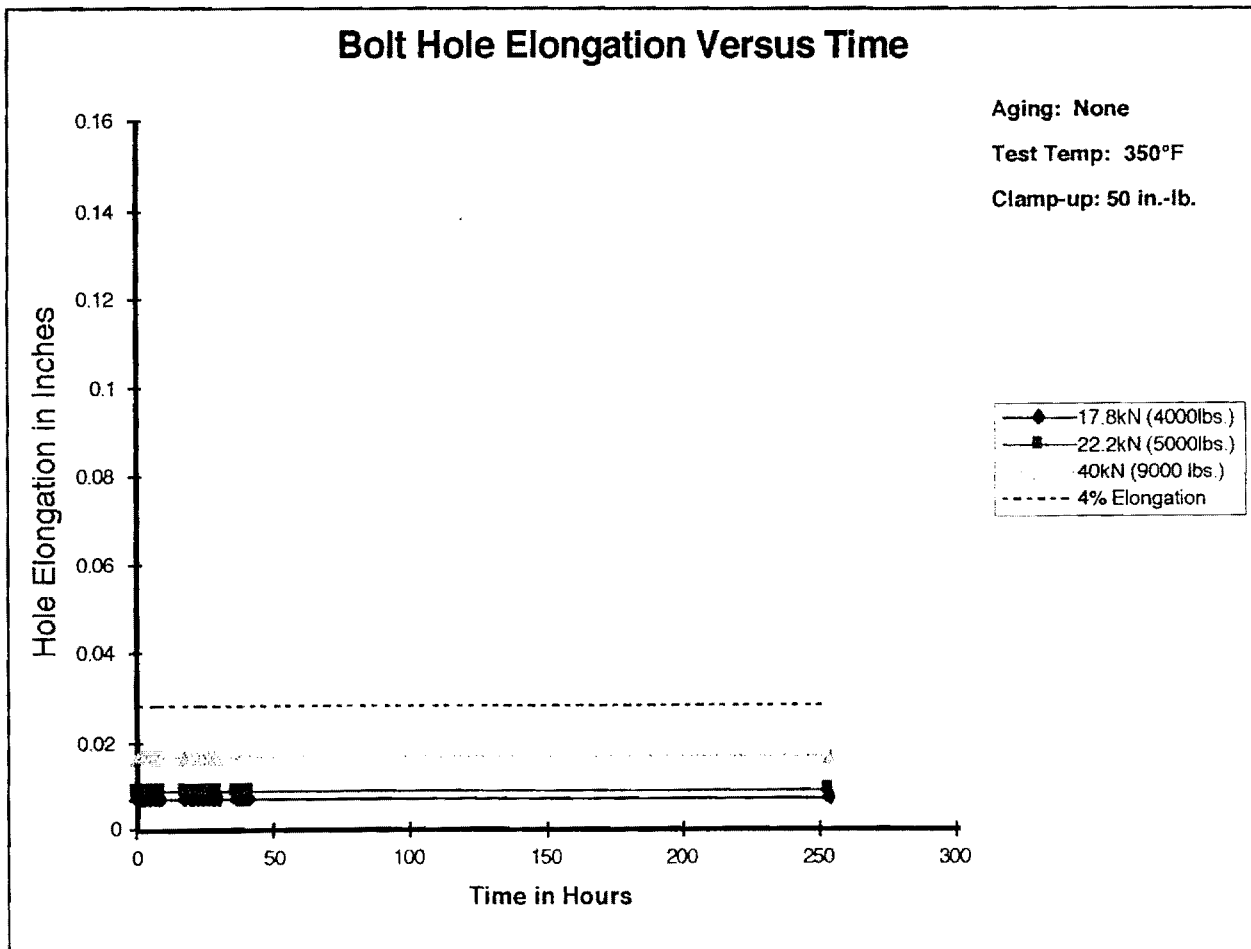


Figure 3: Clamped-up Bolt Bearing Behavior of Unaged Material

3.2 Unclamped Bolt Bearing Tests

Based on the results of the clamped up specimens, the researchers decided to look at the worst case scenario for this joint system: Unclamped bearing. In this loading situation, the washers are removed from the bolt so that there is no constraining clamp-up to prevent delamination and failure. In these tests, it was revealed that the laminate had sustained loads with clamp-up that would result in nearly instantaneous bearing failure without the constraining clamp-up force.

3.2.1 Unclamped Bolt Bearing In Unaged Material

The first series of unclamped bearing tests was carried out in unaged material. The testing started at a load of 40kN applied load or 473MPa bearing stress (9000lbs. or 68.6ksi respectively). This load produced rapid bearing failure, as seen in Figure 4. It appears the critical value for sustaining loads is somewhere around 31.1 kN applied load or 365.4 Mpa bearing stress (7000lbs. or 53ksi respectively). At this load, the joint showed a creep-like failure pattern which moved until the material spread out enough to fill the clevis, thus producing the "Knee" visible in Figure 4. The damage to the specimen, however, appeared to be identical to the crushing and intralaminar cracking produced by outright bearing failure. Note the absence of time dependent behavior in material at a slightly lower load of 28.9 kN applied load or 341.5Mpa bearing stress (6500lbs. or 49.5ksi respectively). Specimens tested at loads below 31.1kN applied load or 365.4 Mpa bearing stress (7000lbs. or 53ksi respectively) recovered elastically to original dimensions.

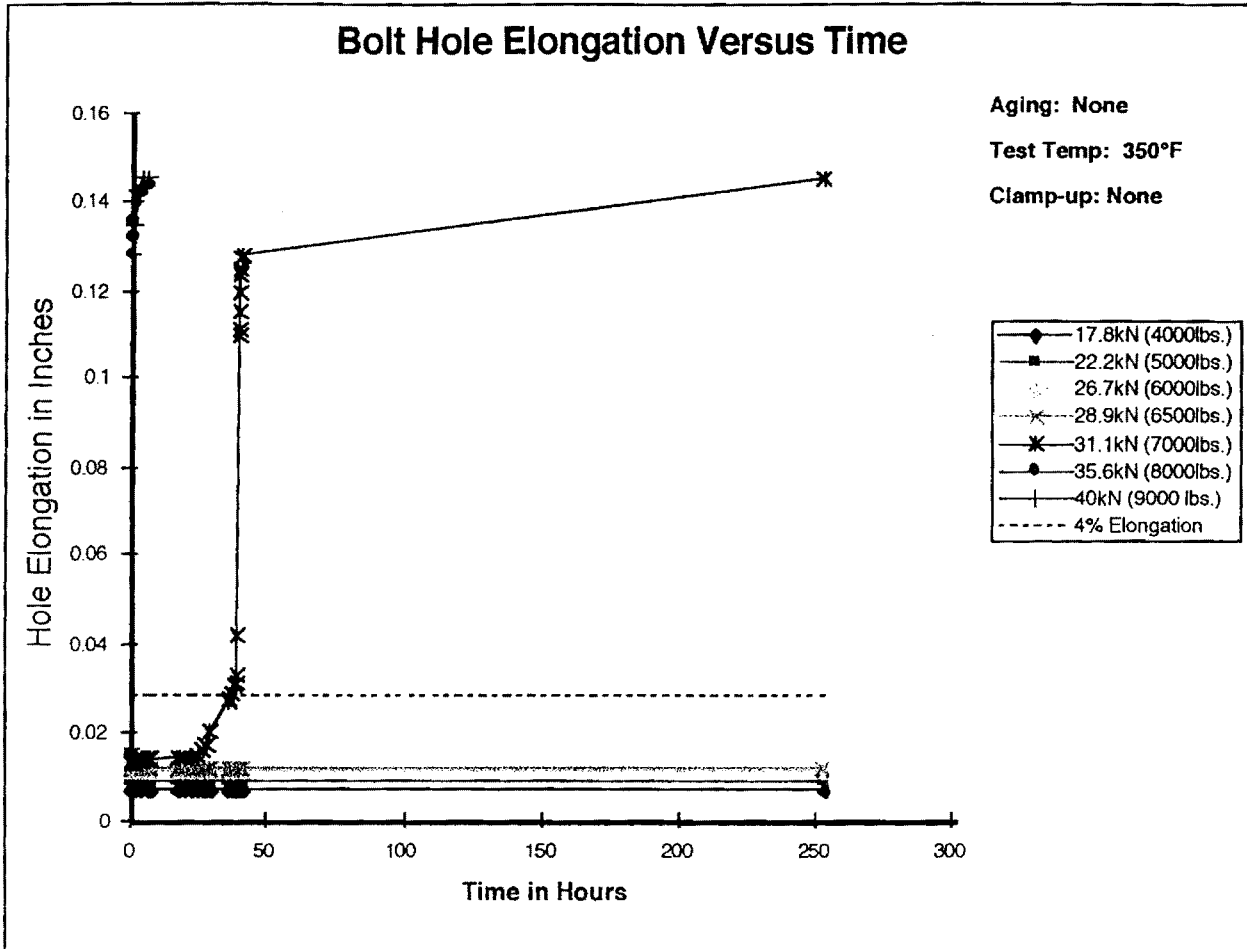


Figure 4: Unclamped bearing behavior of unaged material.

3.2.2 Unclamped Bearing in Unaged Material Aged 5000 Hours At 177°C (350°F)

The second series of unclamped bearing tests was performed with material aged for 5000 hours at 177°C (350°F). In these tests, the target loads were the highest loads the unaged material had survived. As seen in Figure 5, the material aged at 177°C (350°F) showed immediate bearing failure at 28.9 kN applied load or 341MPa bearing stress (6500 lbs. or 49.5 ksi respectively). More interestingly, the material showed time dependent deformation that arrested itself at 26.7kN applied load or 315 Mpa bearing stress (6000 lbs or 46.2 ksi respectively). The specimens in the latter case had clear delaminations on either side above the bolt hole with the outer 45° plies pushed out from the specimen, creating bulges or "Ears." From these tests it is clear there has been loss of unclamped bearing strength after aging at 177°C (350°F). At the same time, the damage remained bearing failure with delamination, crushing under the bolt, and outer ply separation.

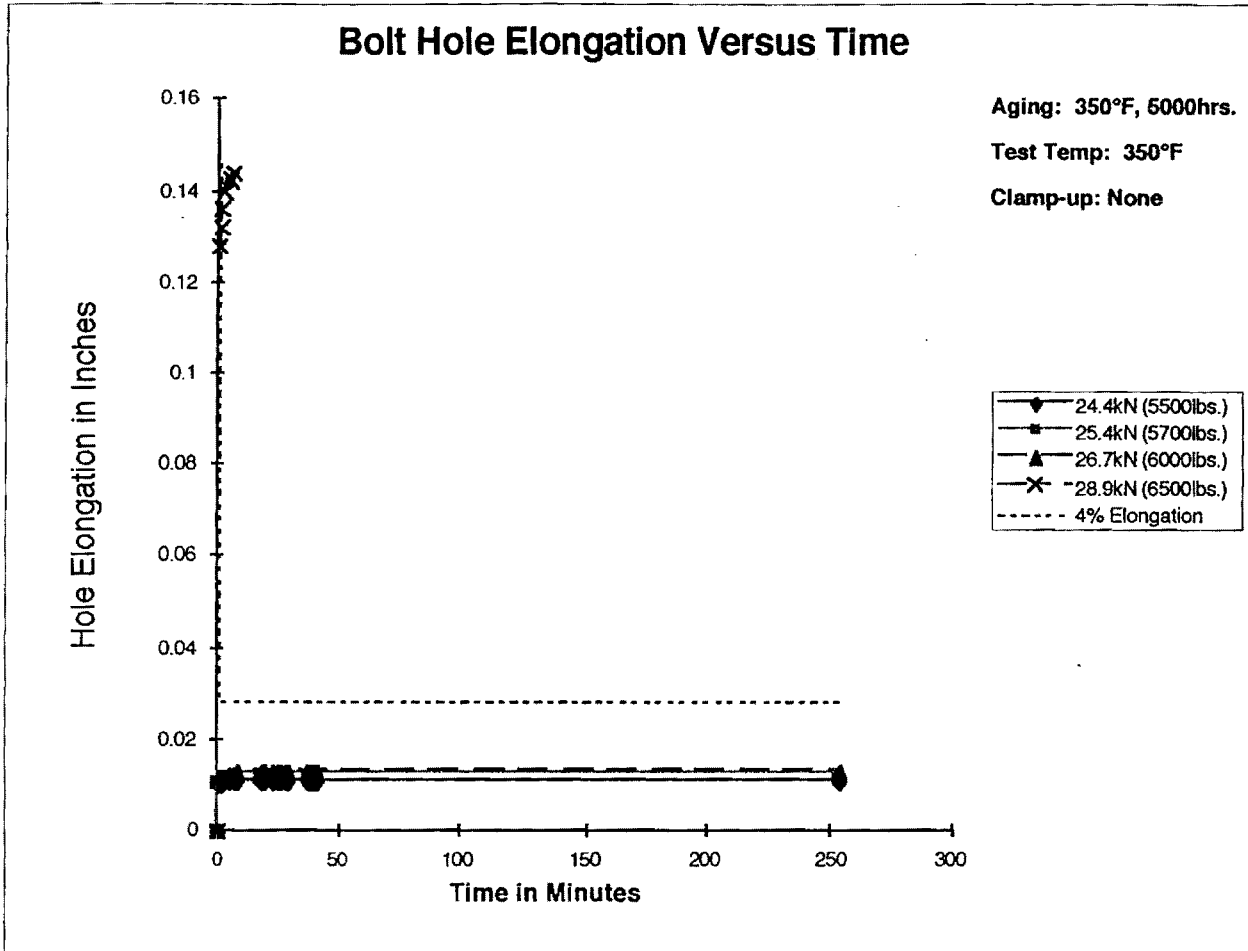


Figure 5: Unclamped Bearing Behavior of Material Aged 5000 hours at 177°C (350°F)

3.2.3 Unclamped Bearing In Material Aged 5000 Hours At 204°C (400°F)

Unclamped bearing tests were conducted with material aged for 5000 hours at 204°C (400°F). The unexpected result in this testing was that the exposure to temperatures of 204°C (400°F) appeared to be less damaging than aging at 177°C (350°F). As can be seen in Figure 6, the material aged at the higher temperature did not show deformation at 26.7kN applied load or 315 Mpa bearing stress (6000lbs. or 45.7ksi respectively) the way material aged at 177°C (350°F) had. In addition, the coupons aged at 177°C (400°F) for 5000 hours survived loading to 28.9 kN applied load (6500 lbs.) and recovered elastically to their original dimensions. The material aged at this temperature withstood loading to 31.1 kN or 365.4 MPa (7000lbs. or 53ksi) for 4.55 hours.

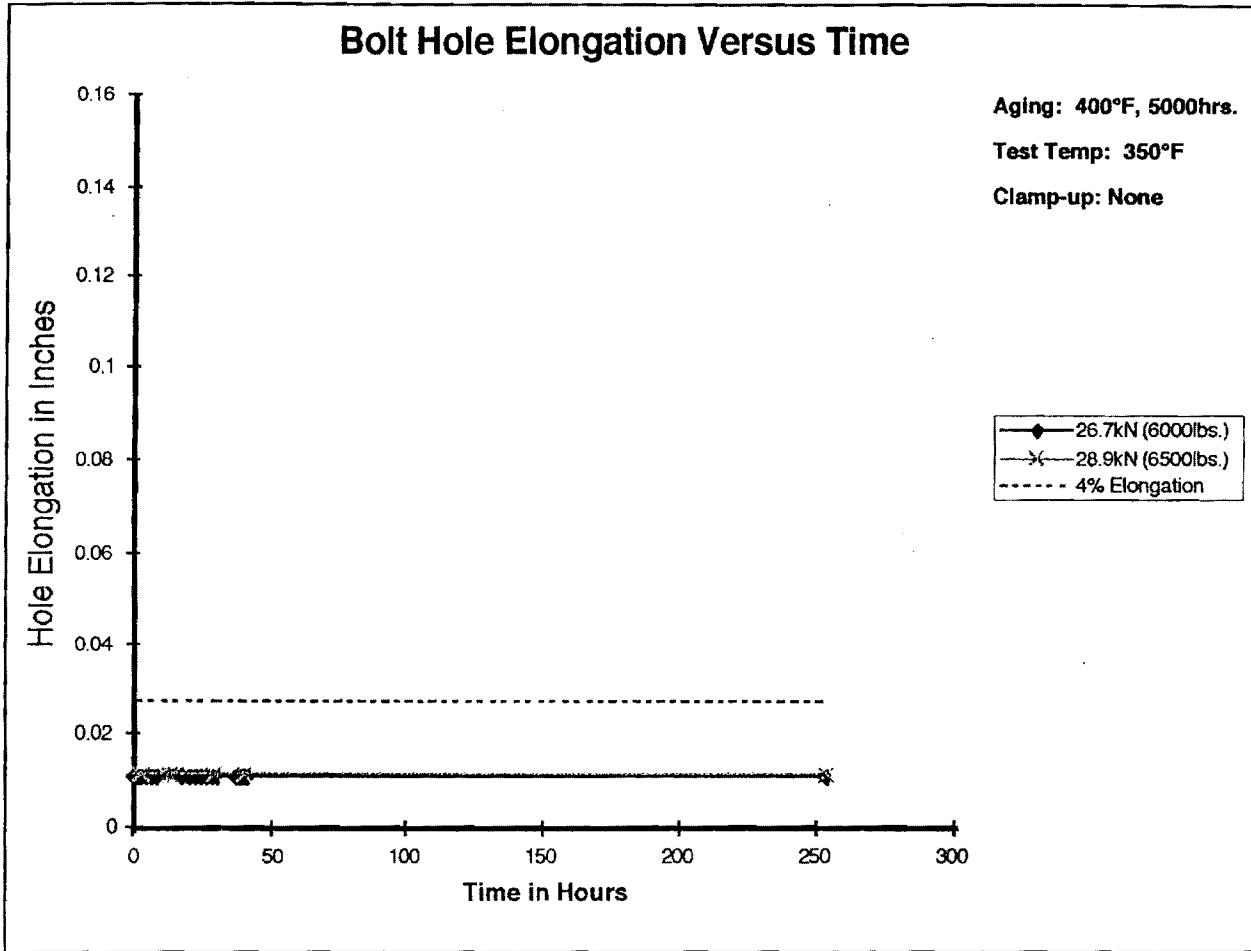


Figure 6: Unclamped Bearing Behavior of Material Aged 5000 hours at 204°C (400°F)

3.2.4 Unclamped Bearing in Material Aged 10, 000 Hours At 177°C (350°F)

The fifth series of unclamped bearing tests was performed with material aged for 10,000 hours at 177°C (350°F). As seen in Figure 7, the material aged at 177°C (350°F) withstood loading 28.9 kN 341MPa (6500 lbs. or 49.5 ksi) without damage. The material also survived loading to 31.1 kN applied load or 365.4 Mpa bearing stress (7000lbs. or 53ksi respectively) for 2.83 hours. Although the material aged at 177°C (350°F) for 10,000 hours didn't perform as well as unaged material or material aged at 204°C (400°F), it does appear there has been substantial recovery of strength when compared to the material aged 5000 hours at 177°C (350°F).

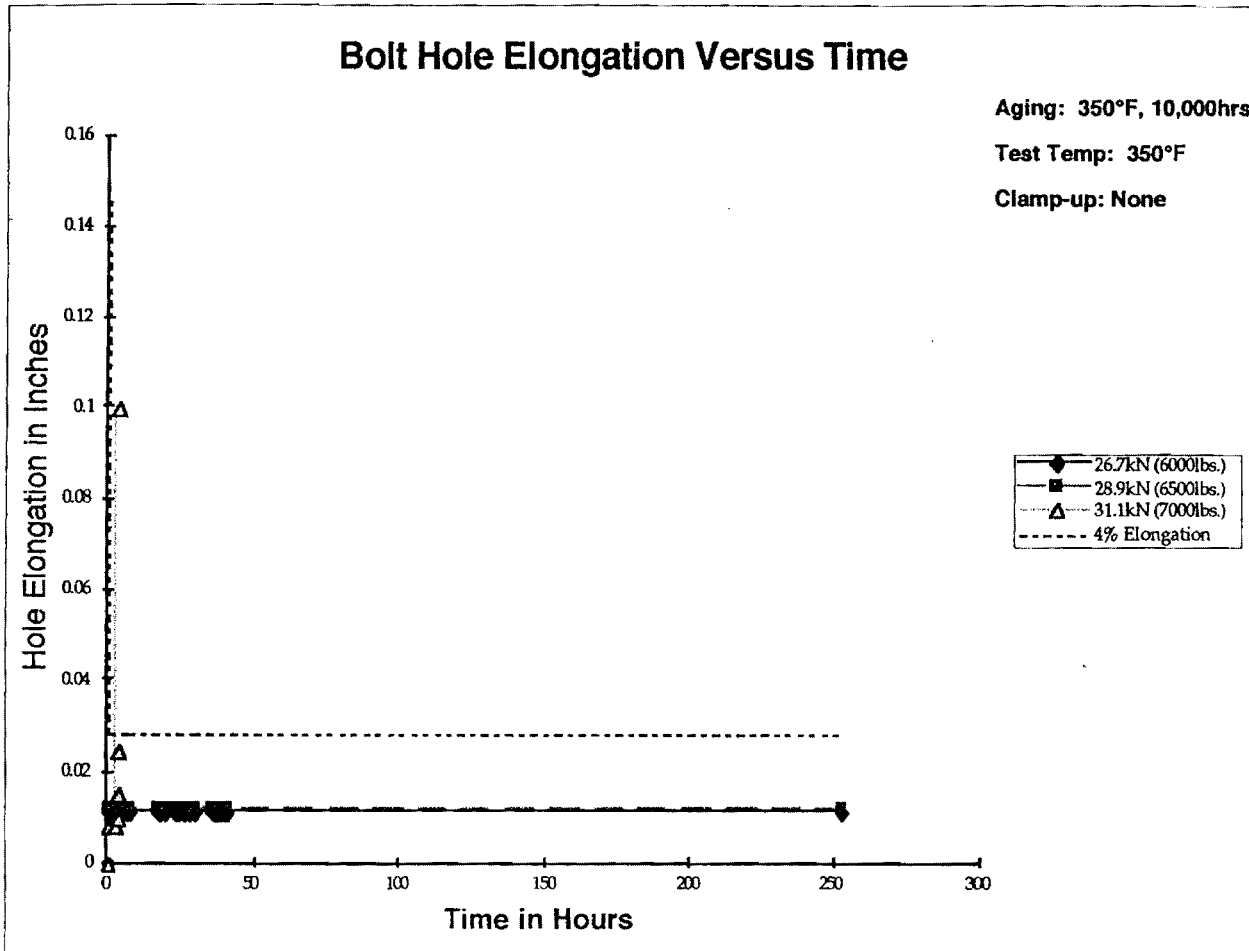


Figure 7: Unclamped Bearing Behavior of Material Aged 10,000 hours at 177°C (350°F)

3.2.5 Unclamped Bearing In Material Aged 10,000 Hours At 204°C (400°F)

The sixth set of tests was conducted with material aged for 10,000 hours at 204°C (400°F). The unexpected result in this test was that the exposure to temperatures of 204°C (400°F) seems to have actually increased time dependent deformation resistance over that of the unaged material. As seen in Figure 8, the material did not show deformation at 28.9 kN applied load or 341Mpa bearing stress (6500 lbs. or 49.5 ksi respectively), and recovered elastically to its original dimensions. When loaded to 31.1 kN applied load or 365.4 Mpa bearing stress (7000lbs. or 53ksi respectively), the material survived for 52.25 hours, or 29% longer than the unaged material did before undergoing rapid bearing failure. This is the best performance this material has shown in this regard. Note the time dependent elongation curve before ultimate failure is flatter than for the unaged specimens (Figure 4). This is believed to be a consequence of embrittlement of the matrix material during aging.

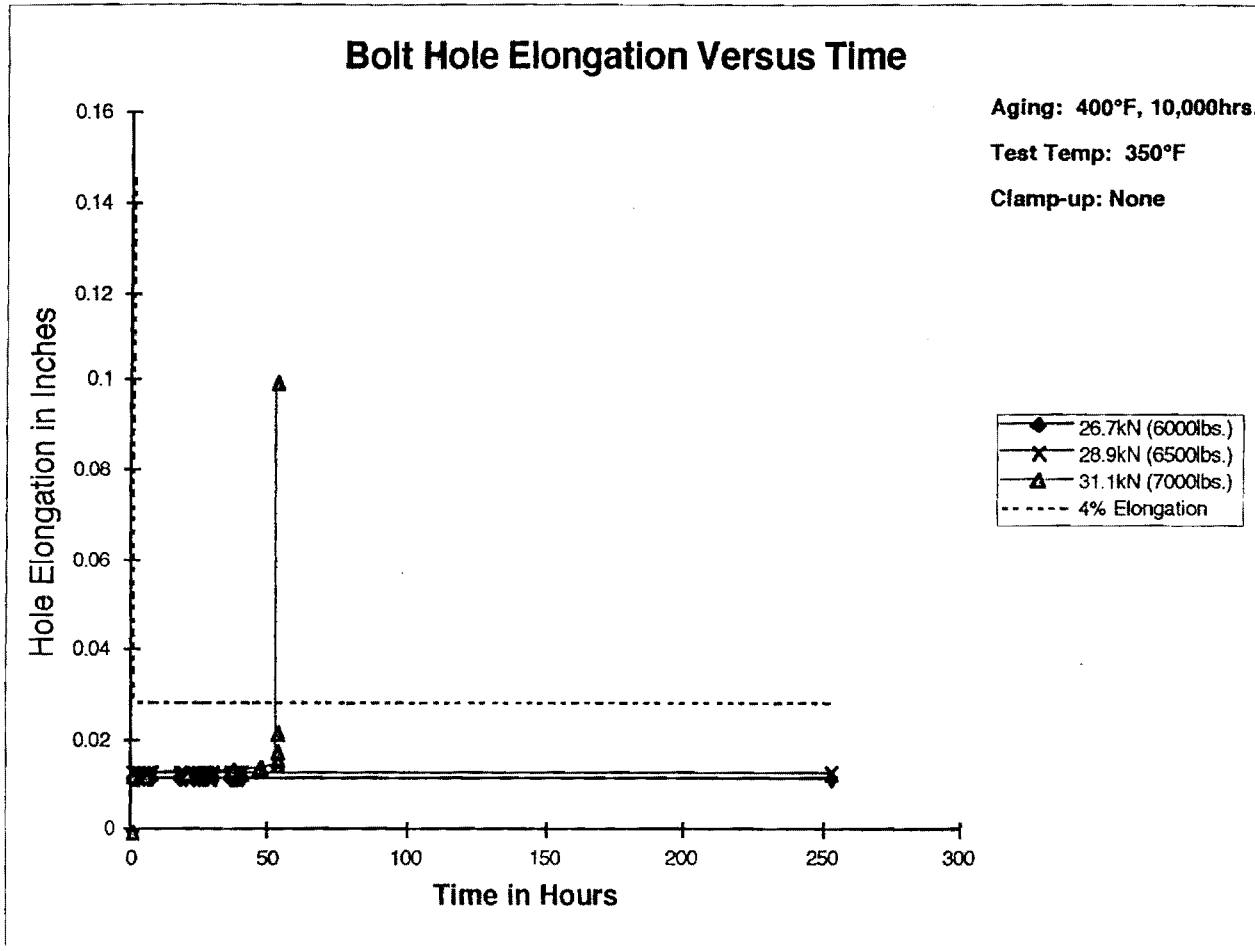


Figure 8: Unclamped Bearing Behavior of Material Aged 10,000 hours at 204°C (400°F)

3.3 Bolt Bearing with Measured Clamp-up

The most recent testing effort has been to measure changes in joint clamp-up forces during bearing creep testing. To accomplish this, a spool-type load cell on the bolt measures clamp-up forces. As seen in Figure 9, early tests have shown that the applied clamp up force decreases during the 250 hour experiment at 31.1 kN applied load (7000 lbs.). During heat-up, the clamp up force increased to 194% of the force from the 5.65 N·m (50 in-lb) torque applied to the bolt when the fixtures were assembled at room temperature. By the end of the standard four hour temperature soak, the clamp-up was at 183% of the initial value. When the load was applied at time zero, clamp-up force increased to 224% of the initial value and then dropped off as a function of time as seen in Figure 9. This testing is still ongoing at this time.

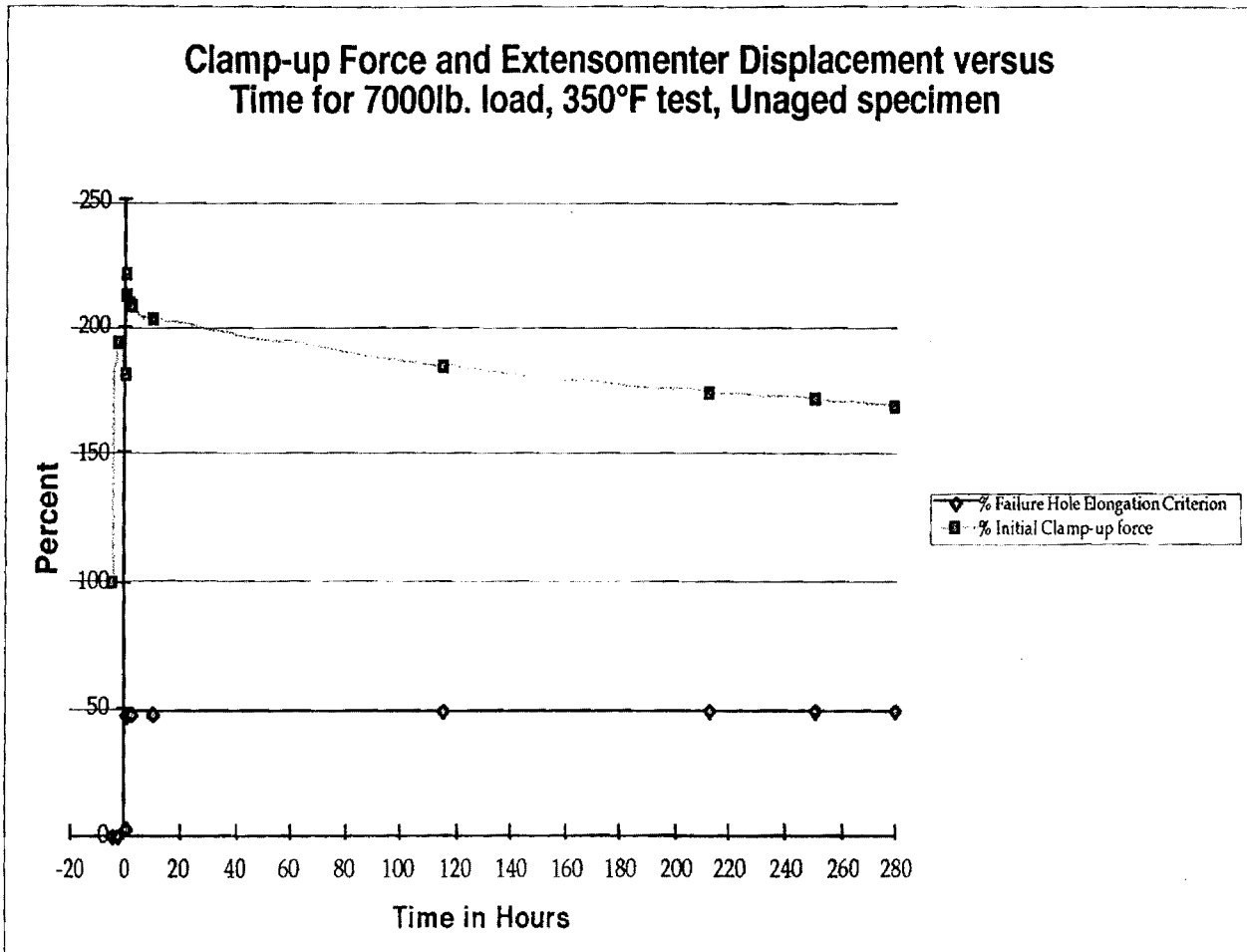


Figure 9: Clamp-up Load and Hole Elongation for unaged material.

4.0 Conclusion

IM7/K3B has shown itself to be insensitive to time dependent deformation. It is apparent from testing that time dependent behaviors can be expected to only show up in a very narrow band of loadings. Testing has pointed to clamp-up force as the source of the most obvious change in coupon strength at temperature. Unclamped bearing testing has shown these materials can withstand the maximum predicted design ultimate loads at temperature, even without clamp-up force to prevent delamination.

There have been some interesting results in regard to aging and accelerated testing. As can be seen in the data, the material has lost bearing strength as an apparent consequence of being aged at the supersonic cruise temperature of 177°C (350°F) at 5000 hours. However, there appears to be an improvement in properties at further

aging to 10,000 hours at 177°C (350°F). In the case of the material aged at 204°C (400°F) there is an actual improvement over the unaged material in terms of time dependent deformation resistance. Since the material aged at the higher temperature of 204°C (400°F) for 5000 and 10,000 hours continues to outperform the strength of the material aged at 177°C (350°F), there is some doubt as to whether or not simple aging acceleration strategies are giving accurate results for this class of materials.

5.0 Acknowledgments

This work has been supported by Lockheed Martin Aeronautical systems under NASA HSR contract NAS1-20220 Task 24- Wing Structures. The authors extend their thanks to Dr. Hafiz Ahmad, Mr. Ed Ingram, and Mr. Brian Cornell at Lockheed Martin for their support in this effort.

6.0 References

Crews, J. H., jr. and R. V. A. Naik. 1986. "Failure Analysis of a Graphite/Epoxy Laminate Subjected to Bolt Bearing Loads", *Composite Materials: Fatigue and Failure*, ASTM STP 907,; 115-133, H. T. Hahn, Ed., American Society for Testing and Materials, Philadelphia.

MIL-HDBK-5G. 1994. *Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures*.