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Creep Bearing Behavior of Highly Loaded Composite Joints

Final Project Report
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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.

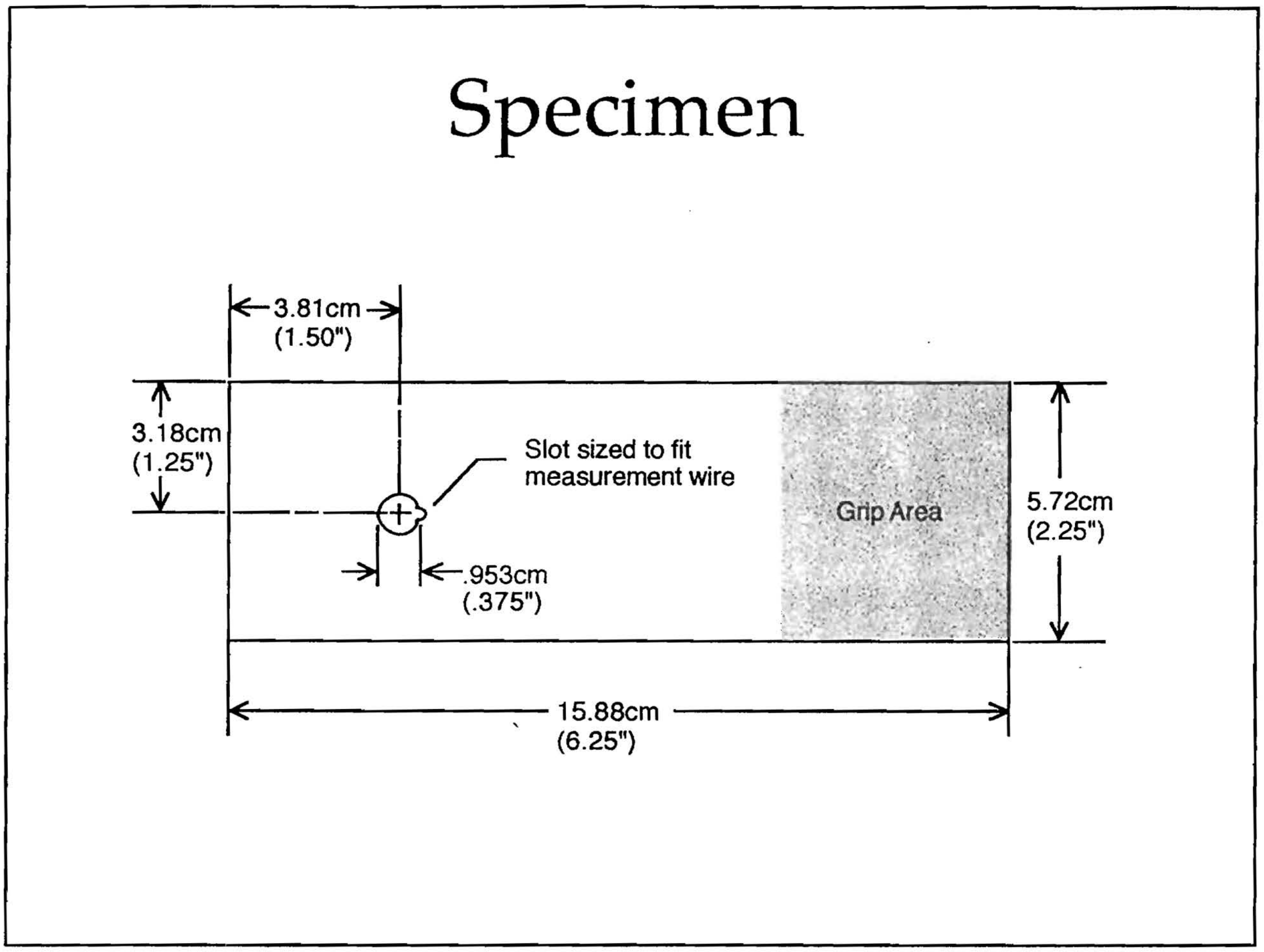

Figure 1: Bolt bearing testing coupon and its dimensions.

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.

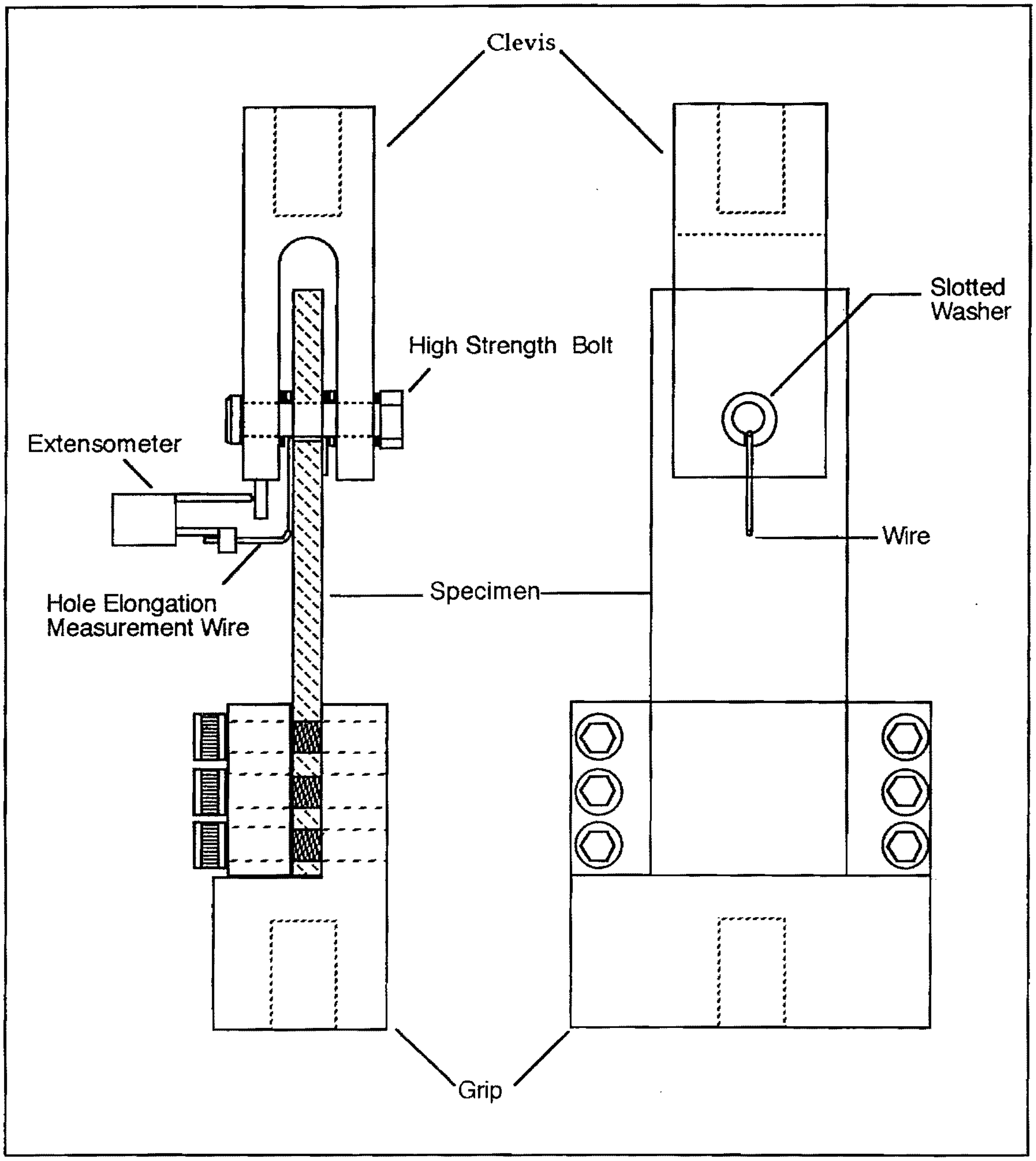

Figure2: Test fixtures with measurement wire and extensometer.

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 ([±45°/90°/0°s]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").

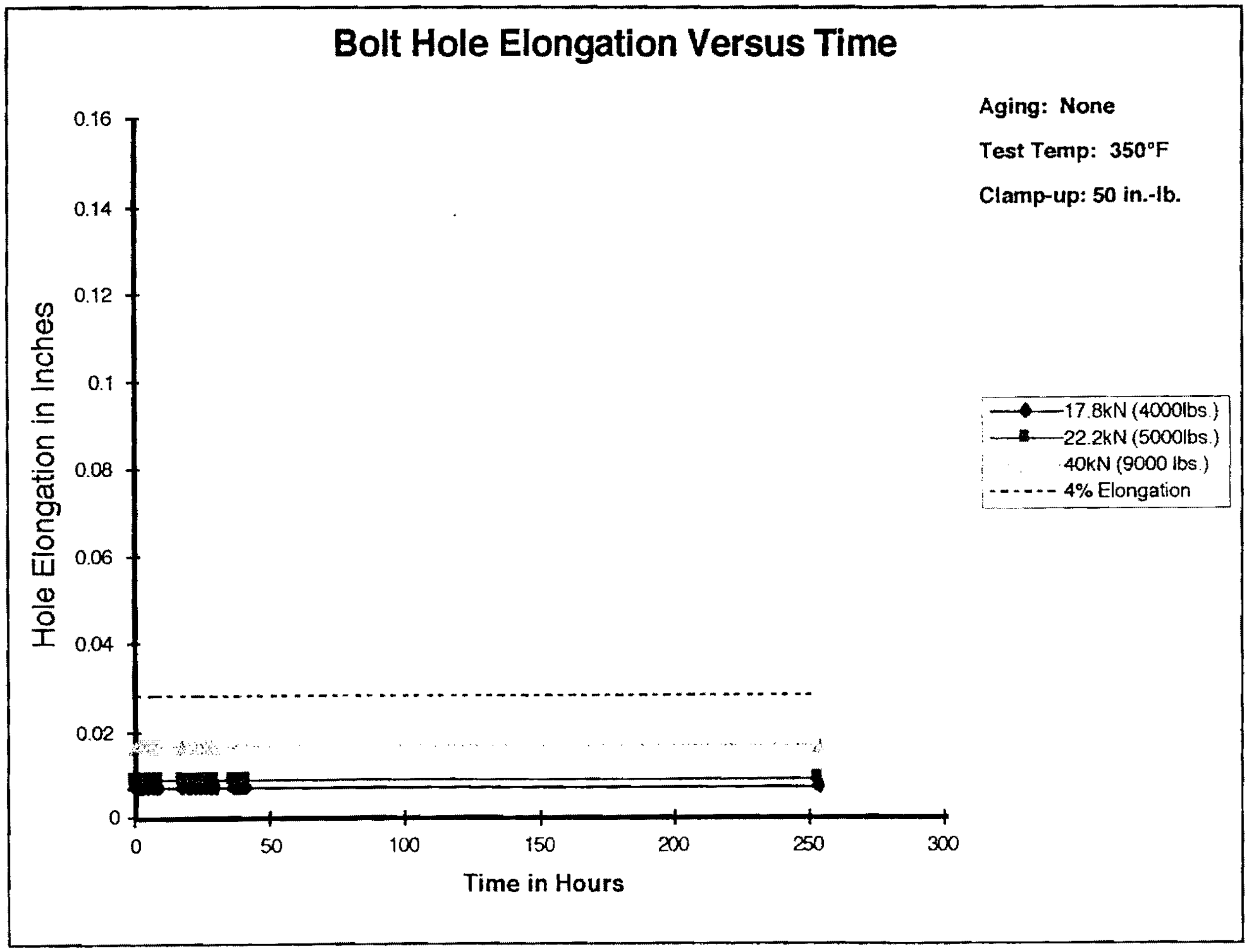

Figure 3: Clamped-up Bolt Bearing Behavior of Unaged Material

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 apllied load or 365.4 Mpa bearing stress (7000lbs. or 53ksi respectively) recovered elastically to original dimensions.

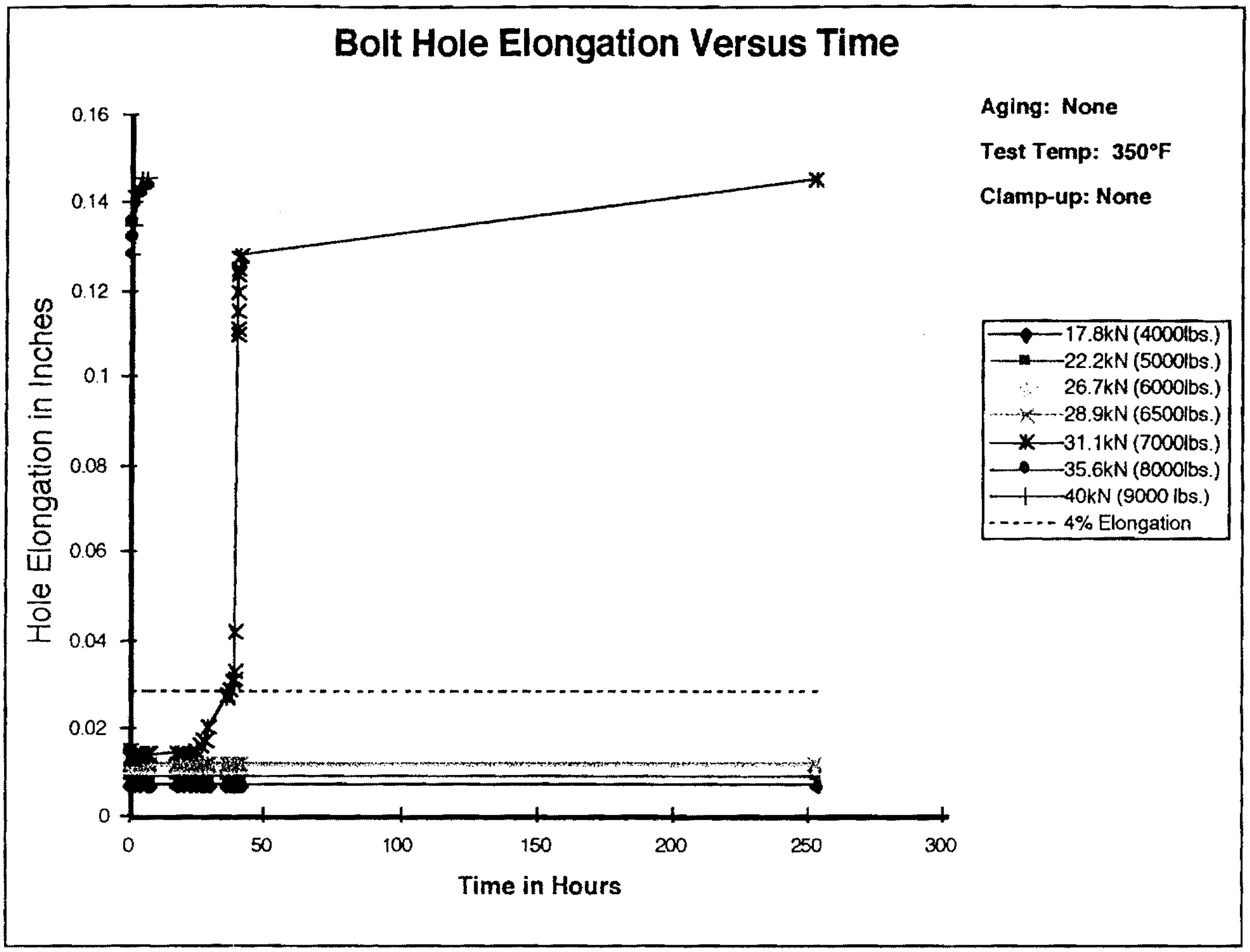

Figure 4: Unclamped bearing behavior of unaged material.

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.

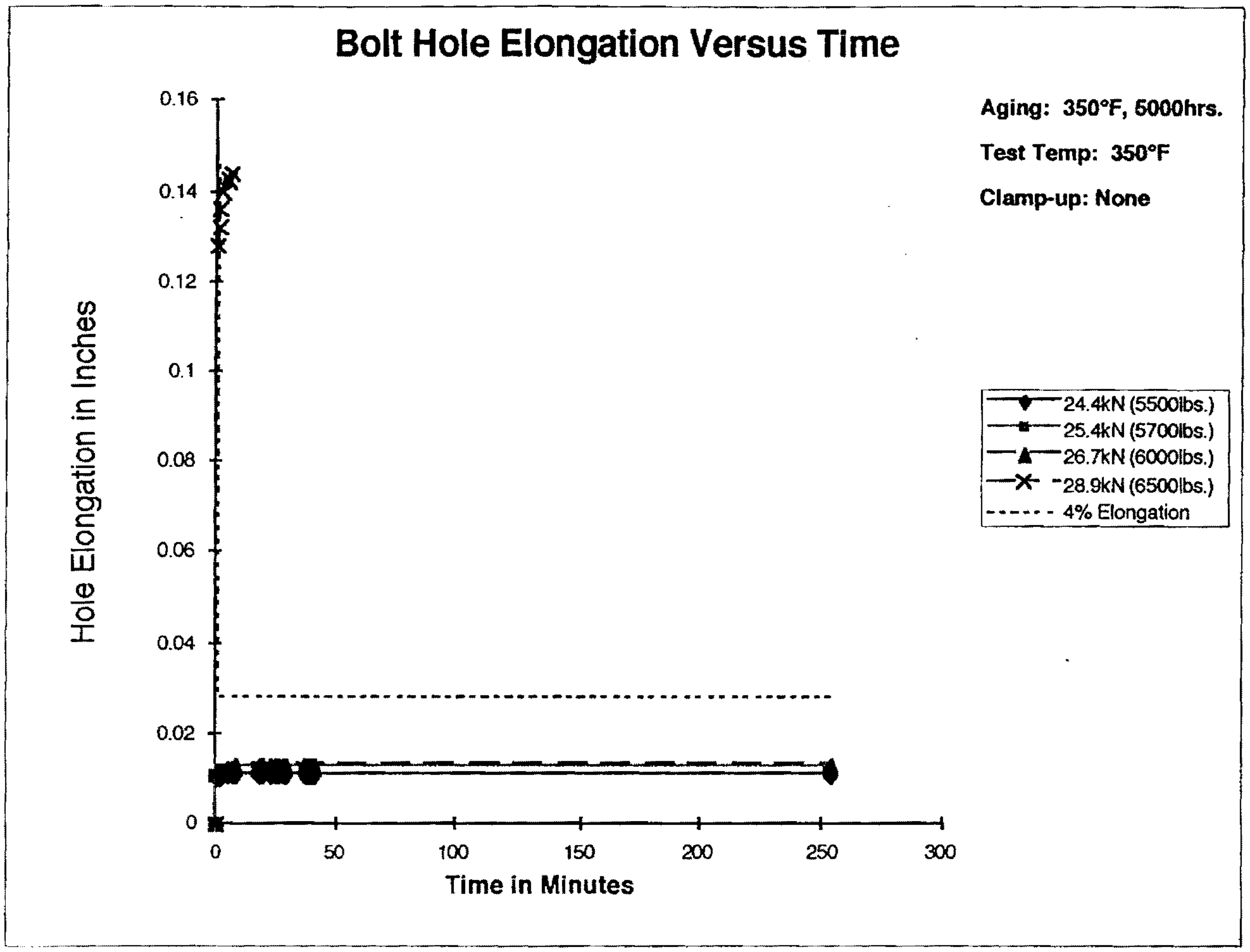

Figure 5: Unclamped Bearing Behavior of Material Aged 5000 hours at 177°C (350°F)

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.

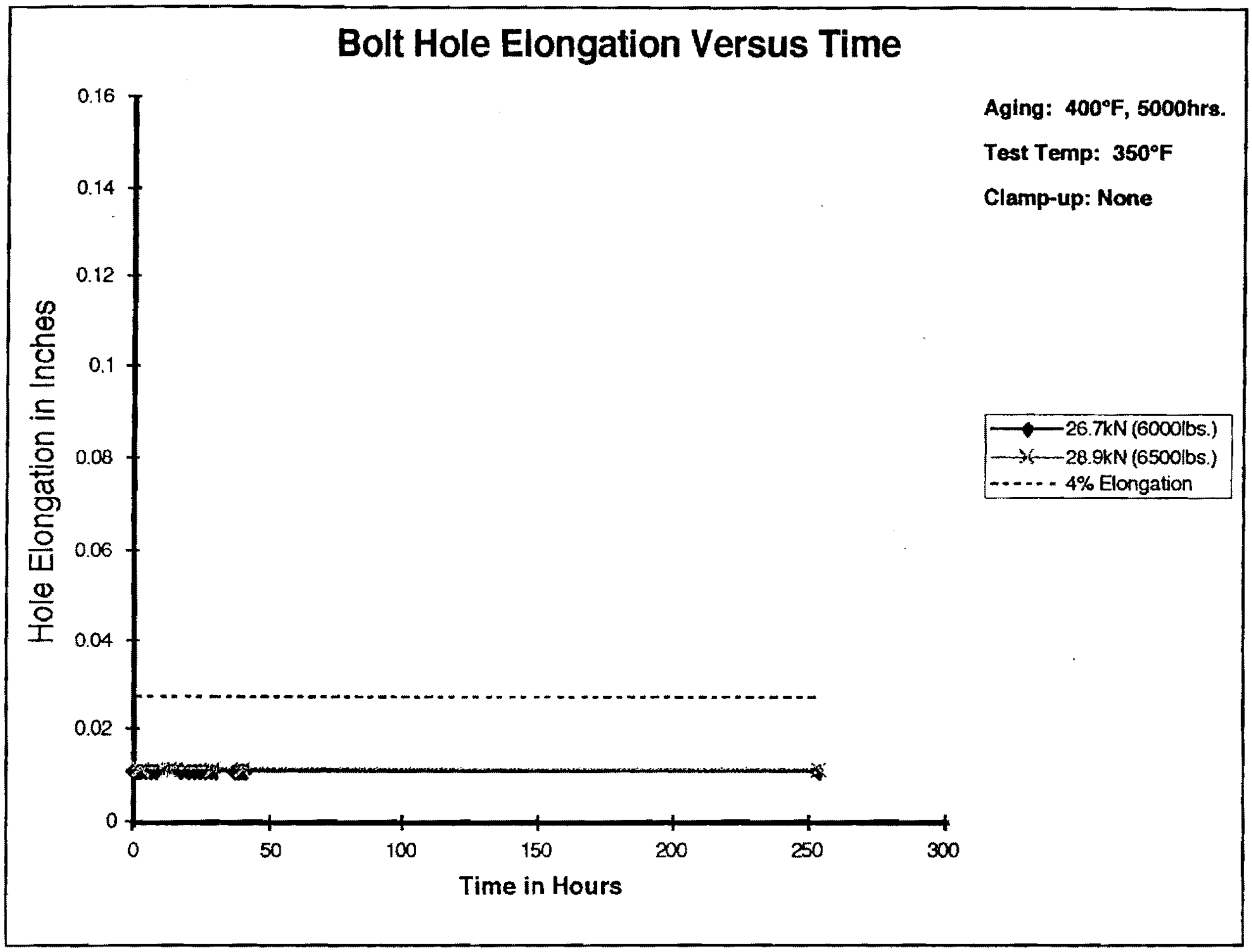

Figure 6: Unclamped Bearing Behavior of Material Aged 5000 hours at 204°C (400°F)

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).

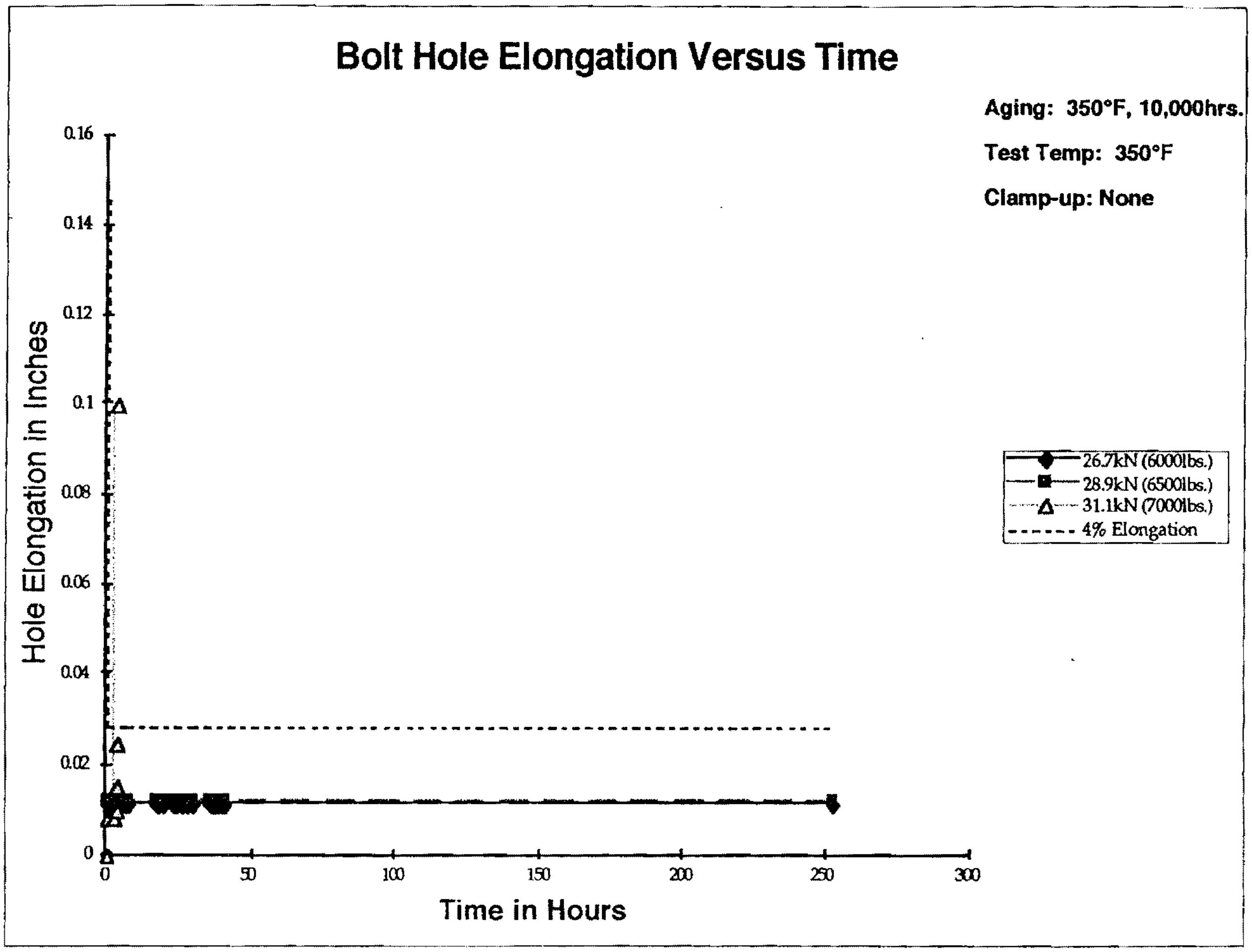

Figure 7: Unclamped Bearing Behavior of Material Aged 10,000 hours at 177°C (350°F)

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.

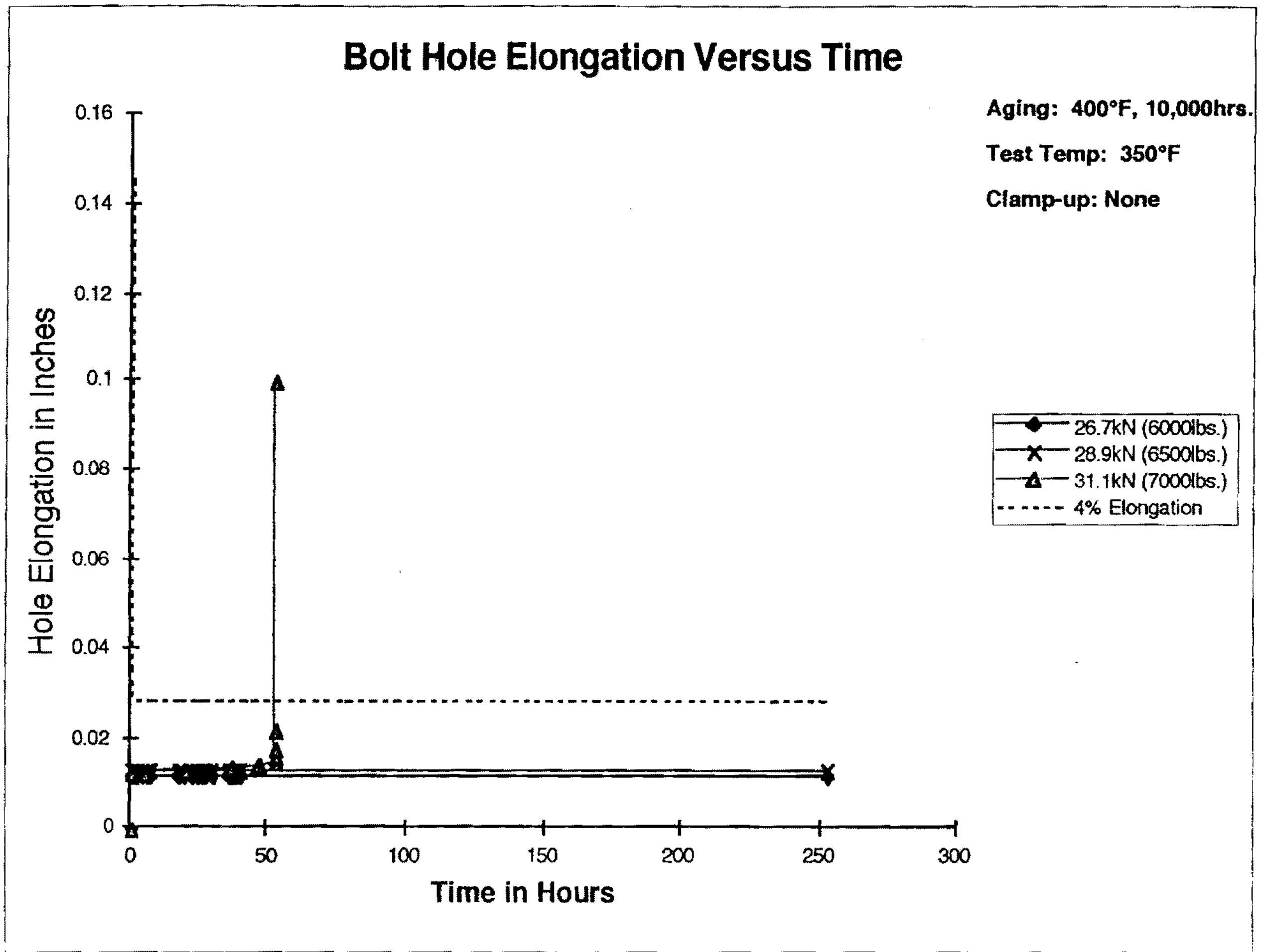

Figure8: Unclamped Bearing Behavior of Material Aged 10,000 hours at 204°C (400°F)

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.

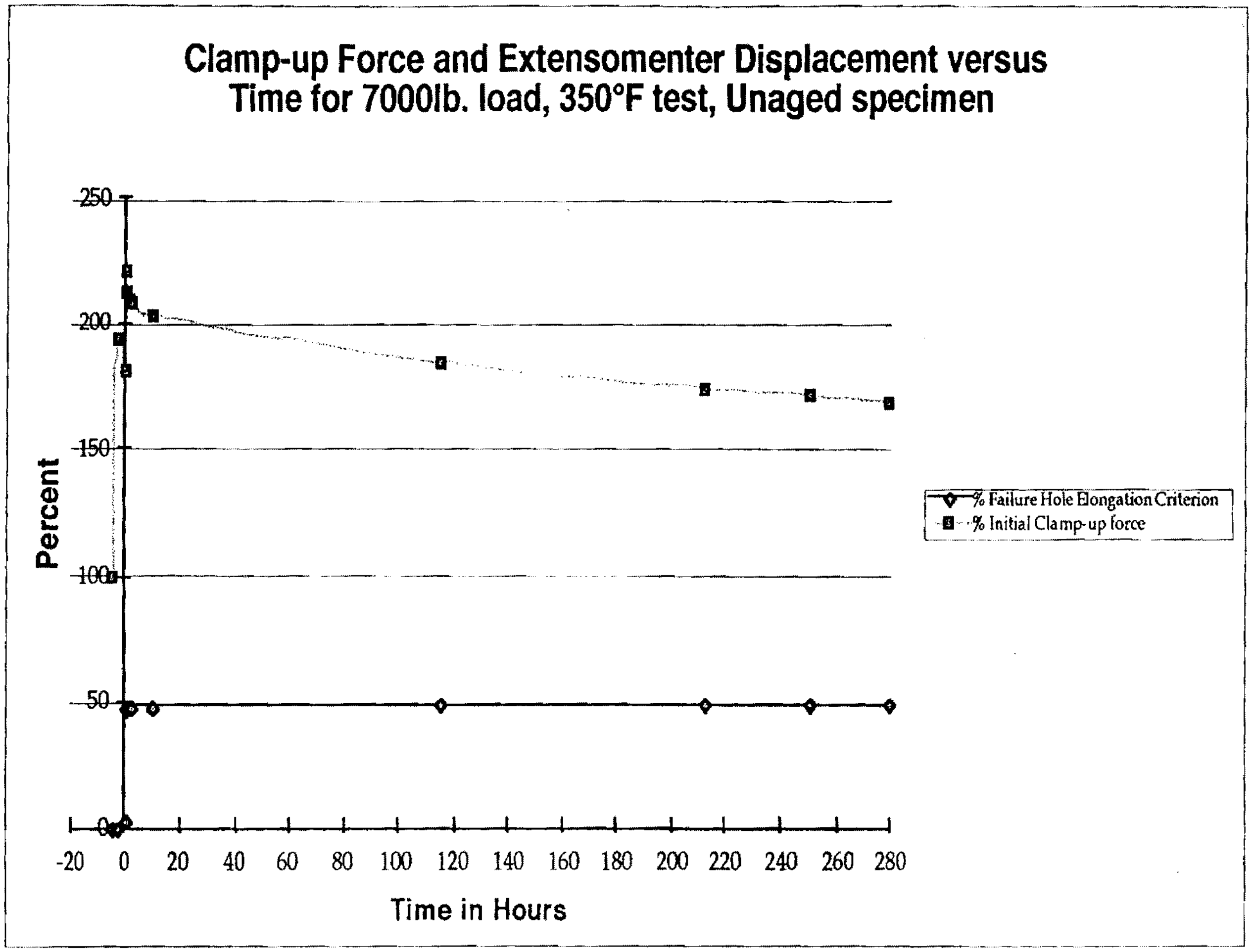

Figure 9: Clamp-up Load and Hole Elongation for unaged material.

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

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6.0 References

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