TEMPERATURE AND AGING EFFECTS ON ULTIMATE BEARING STRENGTH AND FATIGUE OF POLYMERIC COMPOSITE JOINTS

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ABSTRACT

The ultimate bearing strength (UBS) and fatigue performance of IM7/PETI-5 composite materials in a quasi-isotropic lay-up, 64 plies thick was determined using a compressive bearing test set-up. Strength testing was performed at room temperature, 177°C (350 ^{o}F) and –50°C (-58 ^{o}F). Fatigue tests were performed at 177°C (350 ^{o}F). Some specimens were thermally aged at 177°C (350 ^{o}F) for up to 10,000 hours. It was found that the IM7/PETI-5 composite material's UBS and fatigue performance was essentially unaffected by the thermal aging. The elevated temperature tests resulted in a lower UBS and the cold temperature tests resulted in a slightly higher UBS. However, the cold temperature bearing failure was quite dramatic, resulting in widespread delamination due to the brittleness of the matrix.

KEYWORDS

ply buckling, thermal aging, durability, compression

INTRODUCTION

The high strength to weight ratio of composite materials makes them attractive for aerospace applications. In some of these applications, it may be necessary to use mechanical fasteners to assemble composite structures on aircraft. As new aircraft are designed and built to fly faster and higher, the temperature range over which the composite joint will be exposed also increases. At supersonic cruise, the exposure temperature can reach as high as 177^{o}C (350^{o}F), while during subsonic cruise, the exposure temperature can become as low as –50^{o}C (-58^{o}F). As part of a larger program on the mechanical properties of composite joints, the authors had already investigated composite bearing fatigue [1], fastener fatigue [2], composite bearing creep [3] and bearing strength [4]. This paper presents a review of the temperature and aging effects on the bolt bearing strength and fatigue behavior.

Polymer matrix composites have long been recognized as an attractive structural material. The concerns in high temperature applications are (1) the time dependent creep concerns and (2) degradation in mechanical properties due to the extreme temperatures and thermal aging. Previous work by the authors [3] have shown that bolt bearing creep is not an issue at 177^{o}C (350^{o}F) at bearing stresses up to 383 MPa (56 ksi). The concerns addressed in this paper are the fatigue and strength properties under bearing loads at extreme temperatures and after aging for 10,000 hours at 177^{o}C (350^{o}F)

APPROACH

Elevated temperature, 177^{o}C (350^{o}F), bearing fatigue tests were conducted on IM7/PETI-5, using a traditional double shear test set-up by the authors [1,3]. During the course of these fatigue experiments, the high strength steel fastener used to apply the load to the composite failed before the composite. In order to increase the applied load a compression test set- up with a fully supported bolt was adopted. The compression test set-up was based in concept on Wang's test set up but was slightly modified to use existing fixtures and run at low and elevated temperatures [5].

By fully supporting the bolt in the compression test set-up, higher bearing stresses could be applied to the composite without greatly increasing the stress in the steel fastener. However, to fully support the bolt, the applied bearing load had to be changed from tension to compression. In previous work, Eriksson [6] had shown the loading direction had a minimal effect on the bearing properties.

A picture of the specimen is shown in Figure 1 with a schematic of how the load was applied. The edge and width distance of the compression specimen are also included on the figure and were chosen such that bearing failure was the preferred failure mode. One advantage of the compression set-up over the traditional double shear test set-up is the smaller specimen size. The compression set-up specimen was roughly a quarter of the size of the double shear specimen. Consequently, the compression test set-up can decrease the amount of material needed for bearing tests and thus decrease the cost of testing.

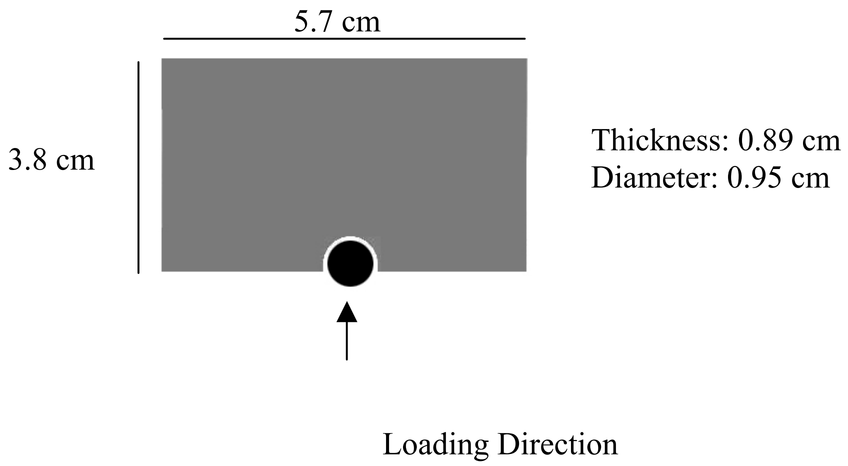


Figure 1 Compression Specimen Geometry

MATERIAL

IM7 carbon fibers in a PETI-5 slightly crosslinked polyimide matrix (manufactured by Cytech Fiberite) was made into laminates of 64 plies in a quasi-isotropic lay-up ($[\underline{+}45^{o}/90^{o}/0^{o}]_{8s}$). One panel of IM7/PETI-5 was placed in a forced air aging oven for 10,000 hour aging at 177^{o}C (350^{o}F) to simulate exposure conditions in an aircraft travelling at supersonic cruise.

TEST PROCEDURE

The parameters for all the bearing strength tests were conducted in displacement control, at a rate of 1.41 x 10^{-3} cm /sec (5.54 x 10^{-4} in/sec), using the compression test set-up. Also, all of the composite specimens were tested without any clamp up. By not clamping up the composite, the results presented are the natural bearing strength of the composite and provide a worst case scenario for the composite joint.

Two aging conditions were tested: (1) as received and (2) 10,000 hour (1.1 years) aging at 177°C (350°F). At least three UBS tests were conducted per aging condition at each temperature and the results of the UBS tests were averaged.

The original failure criteria for all composite joint testing was 4%, or 0.038 cm (0.015"), permanent bolt hole elongation, as per Mil-Handbook-5. During the first ultimate bearing strength (UBS) tests, it became clear that maximum load was reached well before the bolt hole permanently elongated 0.038 cm (0.015"). The permanent bolt hole elongation at failure as approximately 0.023 cm (0.009"), well below the 4% permanent hole elongation failure criterion. Therefore, failure in the UBS tests was redefined at the maximum load.

The bearing fatigue failure criterion was based on the failure displacement observed during ultimate bearing strength (UBS) testing. To ensure that the fatigue specimens had failed, an additional 0.03 cm (0.01") was added to the 0.07 cm (0.03") overall, not permanent, UBS failure displacement to determine the fatigue failure criteria of 0.1 cm (0.04") of displacement. All of the fatigue tests were duplicated (2 tests at each condition).

RESULTS AND DISCUSSIONS

Ultimate Bearing Strength

Ultimate bearing strength (UBS) tests were run on IM7/PETI-5 unaged and aged at 177 °C (350 °F) for 10,000 hours. UBS tests were run at elevated temperature, room temperature, and low temperature to determine the effect of testing temperature and aging on the strength of the composite.

All bearing stresses were calculated using equation 1

$$\sigma_b = \frac{P}{td} \qquad (1)$$

where P = load t = thickness d = hole diameter.

UBS tests run on aged and unaged IM7/PETI-5 reveal that the UBS is unaffected by 10,000 hours aging regardless of the test temperature. The results of the UBS tests are shown in Figure 3. The UBS in all three cases was slightly higher in the unaged case, but the greatest observed difference between the two was 5%, which occurred at low temperature. At room temperature, there was virtually no difference, within 1%, and at elevated temperature, there was only a 3% difference. Thus the UBS of IM7/PETI-5 is unaffected by 10,000 hour elevated temperature aging between –50°C (-58°F) and 177°C(350°F).

While aging did not affect the UBS of IM7/PETI-5, temperature did affect the UBS. As expected, the room temperature UBS was higher than the elevated temperature UBS. For both the unaged and aged composites, the elevated temperature UBS dropped 20-25% compared to the room temperature UBS. This reduction in bearing strength was primarily due to matrix softening at elevated temperature. However, at low temperature, the UBS of IM7/PETI-5 increased 3-5% compared to the room temperature. This increase in UBS is consistent with the results of other composite systems at low temperature.

While the UBS was not greatly affected by low temperature, the failure mode was greatly affected by low temperature. A number of bearing stress vs. displacement curves for room temperature (RT) tests and low temperature (LT) tests are shown in Figure 4.

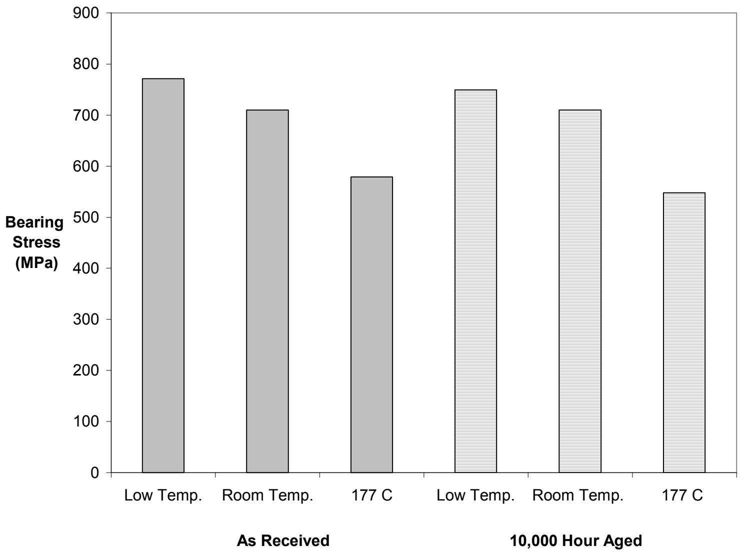


Figure 3 – Effect of Temperature on the UBS of IM7/PETI-5

Notice how much the load drops for the low temperature tests after bearing failure compared to the room temperature data. After failure, the load carrying capability of the composite tested at room temperature dropped about 20%. For the composites tested at low temperature, the load carrying capability dropped about 50% and in some cases as much as 80%. This large drop in load carrying capability after failure at low temperature is due to the brittle nature of the matrix material at these low temperatures. The resulting delaminations due to bearing failure are much more extensive at the low temperatures. was caused by delaminations. The damage on the free edge is extensive. Large cracks on each side propagate from the bolt hole to the specimen edge. During testing, this splitting of the specimen was audible. The damage on the free edge of the failed elevated temperature, room temperature, and low temperature specimens is shown in Figure 5.

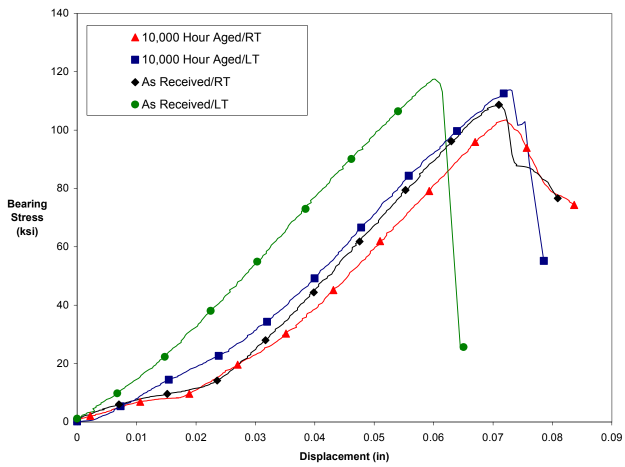
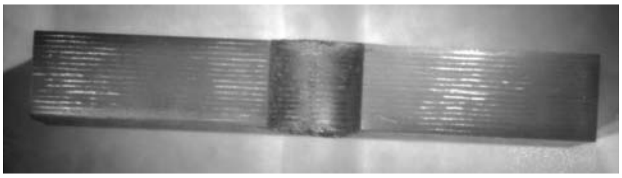


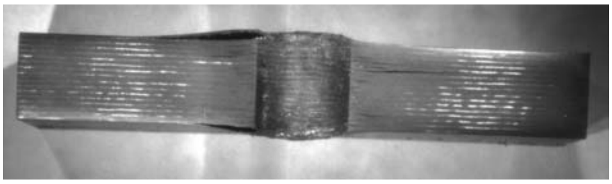
Figure 4 – Comparison of low temperature and room temperature stress vs. displacement curves.

Fatigue Behavior

To determine the effect of aging on the bearing fatigue life of the composite joint, fatigue tests were run on 10,000 hour aged material and compared to fatigue results of as received material. All the tests were run on IM7/PETI-5 material at 177^{o}C (350^{o}F), 10 Hz, and R=0.1. The results of the 10,000 hour aged and as received fatigue tests are shown in Figure 6.



(a) Elevated Temperature



(b) Room Temperature

(c) Low Temperature

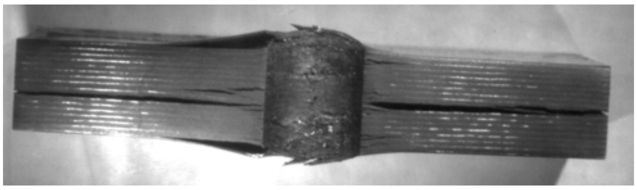


Figure 5 – Free Edge of the Failed UBS Specimens

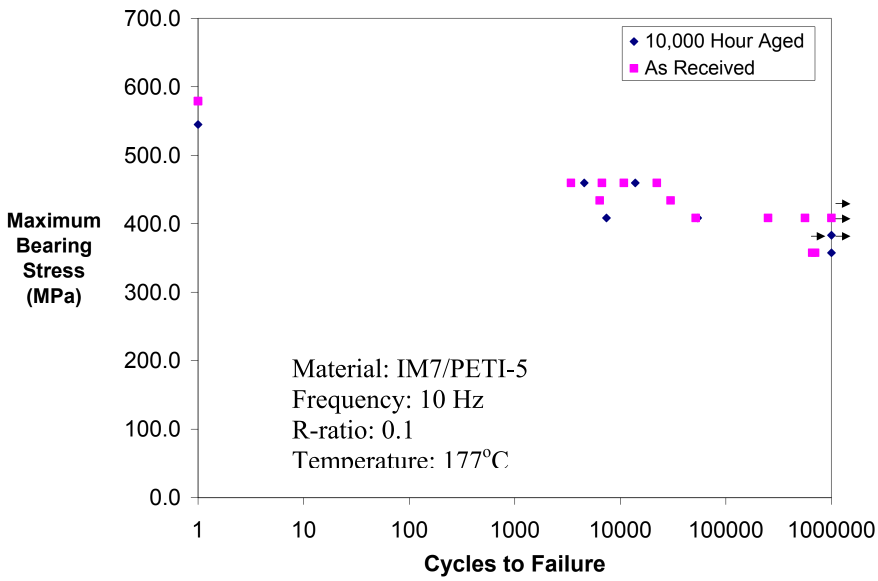


Figure 6 Aging Effect on fatigue

The results of the 10,000 aged and as received fatigue tests show that the fatigue lives of both materials fall in the same general area on the S-N plot with neither data set forming individual scatter bands. The run-out stress level for aged material was around 400 MPa (58 ksi), which is similar to that for the as received material. Therefore, aging up to 10,000 hours does not affect the bearing fatigue life of IM7/PETI-5.

SUMMARY

IM7/PETI-5 composite material with 64 plies in a quasi-isotropic lay-up were tested in static bolt bearing to determine the ultimate bearing strength, UBS, and under fatigue loading. Bearing strength tests were conducted at room temperature (RT), 177°C (350°F), and –50°C (-65°F) while all fatigue tests were conducted at 177°C (350°F). Some of the specimens had experienced thermal aging up to 10,000 hours at 177°C prior to testing. The following conclusions were reached:

1. IM7/PETI-5 composite materials experienced no decrease in UBS after 10,000 of thermal aging at 177°C (350 °F).
2. IM7/PETI-5 composite materials experience a 26% reduction in UBS when tested at 177°C (350 °F) compared to room temperature.
3. IM7/PETI-5 composite materials showed a small increase in UBS when tested at –50°C (-58 °F) compared to room temperature data. However, the bearing failures at cold temperature were much more dramatic, resulting in much more local delamination/damage. This was attributed to the matrix material being much more brittle at the low temperatures.
4. Fatigue performance was not significantly influenced by thermal aging at 177°C (350°F) for 10,000 hours.

The IM7/PETI-5 composite material has been shown to retain significant UBS and fatigue performance at elevated temperature and long term thermal aging at 177°C. Thus IM7/PETI-5 is an excellent candidate for long term structural applications at temperature. However one must be aware of the reduction in interlaminar toughness that result in some very dramatic failure under bolt bearing at low temperatures.

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