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The Effects of Adding Attachments in Conventional Composite Hybrid Joints on Tensile Strength

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The Effects of Adding Attachments in Conventional Composite Hybrid Joints on Tensile Strength

In partial fulfillment of the requirements for the
Degree of Master of Science in Technology

A Directed Project Report

By

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Table of Contents

Abstract

Mechanical fasteners are commonly used in today’s composite aircraft adhesive joints. The primary purpose for using mechanical fasteners was to provide redundancy to the adhesive joints because of the uncertainties associated with an adhesive only joint. Therefore, the use of a fastener in a conventional composite hybrid joint was mainly a part of a fail-safe design. Acting as a safety backup, the fastener did not contribute tensile strength to the joint until the adhesive joint failed. When only being used for redundancy purposes in case of an adhesive joint failure, the existing fastener became simply an added weight to the aircraft structure. In this research, a proposed new design was incorporated into the composite hybrid joint where two different types of attachments were used in order to provide alternate load paths to redirect load to the fastener and utilize the fastener to provide strength to the joint once the joint was loaded. Two types of attachments were used: a stepped attachment and a curved attachment. The attachments would reduce the amount of load induced in the adhesive joint and increase the overall strength of the hybrid joint. Experiments were conducted with both the conventional hybrid joint and the new hybrid joint design with two different attachments to assess effectiveness of the new design, the more efficient attachment type, and whether the added weight of the attachments could be justified by the improvements in the overall strength of the joint. Each type of hybrid joints consisted of 15 specimens. A total of 45 specimens were prepared for this study. The specimens were tested with a MTS Systems Corporation testing apparatus with a 22 kip (±100kN) load cell. The ultimate tensile load data gathered were used to compare the strength of the different hybrid joints. From the tensile testing data collected of the three different

types of specimens, the hybrid joints with attachments showed a significant improvement in ultimate tensile strength compared to the conventional hybrid joints. Conventional hybrid joints had an average ultimate tensile strength of 5859.99 lbf. Hybrid joints with curved attachments had an average ultimate tensile strength of 10617.62 lbf, which was 81.19% higher than the conventional hybrid joints. Hybrid joints with stepped attachments had an average ultimate tensile strength of 10342.14 lbf which was 76.49% higher than conventional hybrid joints. Hybrid joints with curved attachments were also found to be more efficient compared to hybrid joints with stepped attachments and improved the ultimate tensile strength 2.66%.

Introduction

The composite material hybrid joint could be used for many different applications. One of these applications was in the aviation industry, specifically used in joint areas of the aircraft fuselage or other primary structural areas. A hybrid joint was a joint that utilized two different types of joining methods. A good example of a hybrid joint could be either a single or double lap joint bonded together with both adhesives and a metal fastener. Although the addition of a metal fastener helped to provide some strength to the joint, the main role of the metal fastener was that of a fail-safe device in the event the adhesive joint fails. The concept was that when the adhesive fails, the metal fastener could keep the joint in place for an additional period of time preventing a catastrophic failure. Along with a primary focus on safety, minimizing added weight to an aircraft from structural repairs throughout its lifecycle was a key concern. Weight is kept to a minimum in order to allow the aircraft to carry larger loads or improve performance. Unnecessary added weight affects aircraft flight characteristics and could lead to added cost in aircraft manufacturing and aircraft operation. Therefore, based on a previous study conducted by Kumar, Sun, Wang, and Sterkenburg (2010), the researcher proposed to expand the study by incorporating attachments to the existing metal fastener typical within hybrid joints described here, to provide more active strength to the joint as opposed to a passive secondary safety device.

A composite structural component according to Adams, Carlsson, and Pipes (2003) is “a thin layer consisting of reinforcing fibers all oriented in the same direction and imbedded in a matrix such as a polymer” (p.3). The fibers in a composite structure are available in many different forms. The fibers can be woven into a fabric either oriented all in the same direction or randomly oriented.

Statement of the Problem

The researcher investigated if adding attachments to a conventional composite hybrid joint could improve the hybrid joint’s tensile strength. An experimental research design was used in this research. In a conventional hybrid joint, the entire load was directed to the adhesive joint while the installed mechanical fasteners experienced no load. This made the mechanical fastener primarily a part of a failsafe design. In a failsafe design, mechanical fasteners were only used in the event of an adhesive joint failure to keep the structure together and prevent catastrophic failure. However, instead of mechanical fasteners only being used during non-routine adhesive failures while acting as passive non-load bearing weight for the majority of the time, it was proposed that adding alternative load paths to the hybrid joint might allow the mechanical fasteners to contribute to the hybrid joint load carrying integrity once a load was applied. This research would help structural designers utilize every component within a hybrid joint and improve joint designs while minimizing added weight to the structure.

Significance of the Problem

Adams, Carlsson, and Pipes (2003) stated that “composite materials, in the context of high-performance materials for structural applications, have been used increasingly since the early 1960s” (p.2). Today, new aircraft like the Boeing 787 consist of 50% composite material in its entire structure, compared to 12% in older aircraft such as the Boeing 777. The increase in popularity of composite materials was mainly due to the reason that composite materials had a very high strength to weight ratio and could be molded easier into complex shaped parts as other common aircraft materials such as aluminum. Large savings in weight were achieved by using large complex composite parts instead of aluminum parts, which were usually assembled using mechanical fasteners or rivets. Composite material weight savings compared to aluminum will give the aircraft a larger payload capability allowing the aircraft to fly further than before. The results from this research could significantly increase the strength of the composite aircraft fuselage by adding a minimal amount of weight.

Statement of the Purpose

The research provided answers to the question "Can a carbon fiber hybrid joint with stepped or curved attachments improve the tensile strength of conventional carbon fiber hybrid joints?" Conventional hybrid joint and hybrid joints using two different types of attachments was tested using a MTS tensile tester with a 22 kip (±100kN) load cell installed in order to determine if the attachments would improve the overall strength of the hybrid joint. The ultimate tensile load of the joints was compared to determine if the attachments provided sufficient improvement to the strength of the joints to justify the added weight of the attachments. The results also showed which attachment design was more efficient.

Definitions

Hybrid Joint – A hybrid joint is a joint that utilizes more than one method for joining such as bolting and bonding (Hoang-Ngoc & Paroissien, 2009).

Matrix - The matrix supports the fibers and bonds them together in the composite material. The matrix transfers any applied loads to the fibers, and keeps the fibers in their position and chosen orientation. The matrix also gives the composite environmental resistance and determines the maximum service temperature of a composite (Sterkenburg, 2008, p.4).

Polymer - Resin is a generic term used to designate the polymer. The resin, its chemical composition and physical properties, fundamentally affect the processing, fabrication and ultimate properties of composite materials (Sterkenburg, 2008, p.12).

Delaminations - Delaminations form on the interface between the layers in the laminate. Delaminations may form from matrix cracks that grow into the interlaminar layer or from low energy impact (Sterkenburg, 2008, p.29).

Assumptions

The researcher assumed that the holes drilled in the test specimens were defect free and that there was no delamination induced in the joint during the hole drilling process. The holes had clean edges with no fraying fibers exposed. All the plies within the laminates were also assumed to be laid down exactly in their intended orientation. It was assumed that all the mechanical fasteners were installed with the same amount of torque from the special pneumatic tool supplied by Monogram Aerospace Mechanical fasteners. It is also assumed that the MTS test equipment was properly calibrated and indicated correct data.

Limitations

The research was limited in both temperature control and humidity control during the testing of the specimens. The quality of holes in the specimens was also limited depending on the accuracy of the auto feed drill press.

Delimitations

All the test specimens that were used in this research were manufactured by the researcher using the same procedures and the same type of equipment. The materials that were used to manufacture the specimens were taken from the same batch of material to avoid variations within the materials. The specimens were also manufactured at the same time period and tested all together with the same MTS tensile tester under the same configuration and settings.

Literature Review

Most conventional joint designs utilized mechanical fasteners as a fail-safe device on bonded composite joints. The ideas behind the use of these mechanical fasteners were that in an event of an adhesive joint failure, the mechanical fasteners provided additional strength to prevent catastrophic failure of the aircraft structure. However, using the mechanical fastener as a failsafe device meant that the mechanical fasteners were acting as dead weights until a bond failure occured. On an aircraft, unnecessary weight should be avoided at all times. Therefore, a new design was needed to utilize the mechanical fasteners to help provide strength to the joint in addition to acting as a fail-safe device. An in depth discussion and review of studies related to bonded/bolted joints were presented in this section.

Hoang-Ngoc and Paroissien (2009) conducted a research study to simulate the fatigue life of balanced single-lap bonded joints and hybrid joints using flexible adhesives. The research was conducted using finite element analysis. Hoang-Ngoc and Paroissien defined a hybrid joint as a joint that combined different types of joining methods such as bolting and bonding. Hoang-Ngoc and Paroissien also suggested that in terms of security, the mechanical fastener in a hybrid joint supported the structure in the event of an adhesive bond failure.

Nelson, Bunin, and Hart-Smith (1983) conducted a study to reliably predict the strength of large bolted composite joints. This research was conducted under a contract from the National Aeronautics and Space Administration. In this study, the specimens were made from carbon fiber unidirectional tape consisting of T300 fibers, which was often used in the aviation industry. A thicker unidirectional tape was used for this study to simulate thick wing skins. Two types of fiber orientation were used. The first type consisted of 25% 0 degree fibers, 50% ±45 degree fibers, and 25% 90 degree fibers. The second type consisted of 37.5% of 0 degree fibers, 50% of ±45 degree fibers, and 12.5% of 90 degree fibers. A hole was drilled in the specimens to accommodate the three different types of mechanical fasteners used in the study. A total of 180 specimens were tested during this study. All the specimens had one hole drilled into them and the specimens were tested in different configurations such as loaded holes, unloaded holes, and with three different kinds of fastener sizes - 1/4 inch, 1/2 inch, and 3/4 inch. The specimens were tested in tension to describe the failure mechanism of the joints. The data obtained from this research study was used to predict other large bolted joints. This research showed that it is possible to predict the strength of these large composite multi-row bolted joints. However, Nelson, Bunin, and Hart-Smith (1983) were specifically concerned with the possibility of thermal delamination to the laminates while drilling the hole. Nelson, Bunin, and Hart-Smith did not specify any specific steps taken to prevent the thermal delaminations.

Nelson, Bunin, and Hart-Smith (1983) showed that the prediction of composite joint performances was possible. Experimental testing of the proposed new hybrid joint design would be usable for predictions of other similar joint design performances. To prevent thermal delamination problems, the researcher used a diamond tipped hole saw instead of a drill. The diamond hole saw will grind a hole into the composite material slowly to prevent delamination. Coolant was also used during the drilling process in order to avoid thermal delaminations.

Hart-Smith (1984) conducted a research study on bonded-bolted composite joints. The purpose of the research was to examine how a bonded-bolted composite joint compared in strength to an adhesive bonded joint. Hart-Smith utilized a joint that consisted of a 0.51 inch thick titanium piece bonded to a 0.81 inch thick carbon-epoxy laminate. The joint specimen was five inches long consisting of seven steps in the bonding area. The joint specimens were tested under tensile loads and the results were compared to an undamaged joint specimen. The results from the two different specimens were averaged and compared. Hart-Smith concluded from the results that the bonded-bolted joint does not provide superior strength compared to a well designed adhesive joint. However, the bolt did act as a good fail-safe device because the fastener would be able to carry the load after the initial failure of the adhesion, which could prevent a catastrophic failure of the joint.

Ganji (2007) investigated single lap hybrid joints with two bolts. He wanted to calculate the load transfer in hybrid composite single lap joint using finite element analysis. The results from the finite element analysis were compared with actual experimental results. From the results of the finite element analysis, Ganji concluded that the elastic properties of the adherents can significantly affect the load distribution of the bolt. Increasing the thickness of the adherents increased the load transfer of the bolt. Increase of the tensile load increased the load transfer by the bolt. Load transfer increased as bolt diameter increased. As the overlap increased, the load transfer decreased.

The conclusion of Hart-Smith’s research showed that the mechanical fastener did not provide any additional strength to the joint and were used to act as a failsafe device in structural joints. Ganji showed that if part of the load can be directed to the mechanical fastener, the mechanical fastener was able to provide additional strength to the joint. Based on the research results of Ganji and Hart-Smith it was decided to add attachments to the hybrid joint that will divert part of the load going through the composite joint and direct it to the mechanical fastener so the mechanical fastener carried some of the stresses going through the joint's bonded area.

Under load, an adhesive joint could be subjected to many different types of stresses. These stresses were examined by Petrie (2008). Petrie mentioned that when an adhesive joint was under load, there were five loading stresses that were common. The five loading stresses were tensile, shear, cleavage, peel, and compression. Any combination of these five stresses could be present on the joint depending on the type of load that the joint was subjected to.

From the article by Petrie, the types of stresses that were present on the adhesive joint could be determined to be shear stresses and peel stresses. The main adhesive joint area were subjected to primarily shear stresses while the edges of the adhesive joint experienced peel stresses as the edges tried to separate. From the identification of possible stresses acting on the adhesive joints, the researcher could properly identify whether the joints failed as expected and that there were no anomalies associated with the failure of the adhesive joint such as unexpected failure modes or manufacturing defects.

Before an adhesive can be applied to a bonding surface, the surface had to be free of dust, oil, or any other contaminants that could affect the bond. In an article by Petrie (2007), different passive cleaning practices were examined. Petrie explained that when a strong bond or structural bond was needed, aggressive methods that either physically or chemically treat the bonding surface were needed. These surface treatments ensured that failure always occurred within the adhesive and never at the interface between the adherent and the adhesive. Based on the article by Petrie, the researcher sanded the bond area in order to create a surface that allowed the adhesive to properly adhere and create a strong interface between the adherent and adhesive. The sanding process was accomplished so that only the surface area was treated and no fibers in the carbon fiber were damaged during the sanding process.

When manufacturing composite material bonded joints, especially using adhesives, it was very difficult to control the overflow of adhesive that created bulges at the joints' overlapping edges. Due to these bulges of excess adhesive, Wang, Wang, Guo, Deng, Tong, and Aymerich (2008) conducted a research study to determine the strain/stress distribution around the overlapping edge of a single lap joint. Strain gauges were attached to the edge of the overlaps to measure the strain in the area while the joint was subjected to a tensile load. Two specimens were used in this experiment. The dimensions of the adherents were 130mm by 20mm. The adherents were joined with a 30mm overlap. The adhesive was allowed to bulge along the edge of the overlap. Layers of fiber were left exposed intentionally in the adhesive bulge to determine if the bulge will create stress concentrations. This research used finite element analysis to model the specimens to support the experimental results gathered from the research. It was found that the stress concentration in the specimen that had the second layer of fiber exposed in the adhesive bulge was significantly higher than the other specimen which had the first layer of fiber exposed in the adhesive bulge. However, modeling the adhesive bulge for the finite element analysis proved to be difficult because a large amount of data was required to model the adhesive bulge precisely for the finite element analysis.

Wang, Wang, Guo, Deng, Tong, and Aymerich's (2008) research showed that the adhesive bulge affected the joints overall performance. A stress concentration significantly limited the performance of the joint because it caused the adhesive to crack and resulted in joint failing. Therefore, the researcher removed these adhesive bulges from the specimens prepared. A pneumatic grinder was used to remove the excess adhesive that formed the adhesive bulge after curing. The excess adhesives were grinded away until the adhesive was flush with the overlapping edge. By grinding the adhesive, the stress concentration in the area was removed and did not affect the structural performance of the joint allowing the adhesive to reach and fail at its maximum load.

Multiple research studies were found in the body of literature that discussed the number of specimens to be used for an experimental study. Schulz, Hietala, and Packman (1994) looked at creating a statistical model to predict the joint failure of a single-shear joint. During the study, Schulz, Hietala, and Packman tested a total of 570 specimens. The reason for such a large number of specimens was due to the fact that 384 specimens were tested to determine the base properties of the material used. More specimens were tested (170) with additional variables such as adding metallic hole inserts, oversized holes, nut-plated mechanical fasteners, and under-torqued mechanical fasteners. Sixteen specimens were made from identical carbon fiber but in a different weave. All the 570 specimens were tested with the Instron servohydraulic model 1350 tester. From the data obtained from the study, a statistical sub model was created to predict the joint strength. Using SAS statistical software, the partial slope generated for all the different variables were used for the prediction of the strength of the joint.

A study by Kelly (2005) involved only two laminates that had different stacking sequences. Kelly investigated the effect of adhesive material properties and laminate orientation on the joint's performance and failure modes. The two types of specimens were made using the resin transfer molding (RTM) method. The two types of specimens consisted of Toray T700 fibers impregnated with resin. The joint was bonded with two different types of adhesives: an adhesive with a low elastic modulus and an adhesive with a higher elastic modulus. The specimens were tested under tensile loads and the loads of the two specimens were compared. Kelly found that the hybrid joint with a flexible adhesive demonstrated a higher joint strength.

For the purpose of this study there was no need to use as many as 350 specimens because the base parameter of the laminate material did not need to be characterized. However, a sufficient number of data points were necessary so that consistency in the data could be monitored. Therefore, 15 specimens for each joint design were tested. A total of 45 specimens were prepared; 15 specimens of the conventional bonded joint design, and 15 specimens for each of the proposed new hybrid joint designs.

In a research study conducted by Chutima and Blackie (1995) the effect of pitch distance, row spacing, end distance, and bolt diameter on a composite joint were investigated. Their purpose was to determine the contact stress and load distribution in a double lap joint. The study was primarily performed with finite element analysis. The two types of specimens were subjected to tensile loads and the results were used to determine the best distance and spacing between mechanical fasteners. The specimens consisted of a composite material joined to steel. The dimensions of the specimens were 260.35mm long and 190.5mm and 202.406mm wide. The pins used for the specimens were 19.05 in diameter and the pitch distance used was 47.625mm. The edge distance and row spacing were 44.45mm and 38.1mm. Chutima and Blackie showed that the preferred spacing and edge distance for a multi-fastened double-lap joint was two times the pin diameter. The pitch was about six times the pin diameter.

Based on the result of the Chutima and Blackie research, the researcher decided that only one fastener was used and placed in the middle of the joint's overlapped area. This ensured that the mechanical fastener had enough spacing and edge distance from the edge of the specimen. The use of one mechanical fastener also prevented interference from other mechanical fasteners that were installed in the joint. Monogram Aerospace Fastener's Composi-Lok mechanical fasteners were used for this study. The Composi-Lok was a high strength fastener commonly used in the aviation industry; therefore it provided good relevance to today's materials.

After a review of the body of literature, the researcher proposed the specimen's holes were made with a diamond tipped hole saw and utilized coolant to prevent the laminate from thermal delamination. The researcher also grinded out all the adhesive bulges in order to remove all the stress concentration points so that the specimen would fail as intended. The researcher utilized attachments to divert some of the joint's loads into the fastener so the fastener could contribute to increasing the joint's strength. The specimen size used for this study was 15 specimens each for three types of joint designs.

Methodology

An experimental research design based on a study previously conducted by Kumar, Sun, Wang, and Sterkenburg (2010) was used for this study. There were three different types of specimens. The first type of specimen was a conventional hybrid joint, the second type of specimen was a hybrid joint with a curved attachment, and the third type of specimen was a hybrid joint with a stepped attachment. Fifteen specimens were made for each type. A total of 45 specimens were prepared. The specimens were subjected to a tensile load and tested until failure.

The purpose of the study was to investigate whether adding an alternative load path to the adhesive joint would improve the strength of the joint. The independent variable for the study was the addition of attachments to the conventional hybrid joint. The attachments served the purpose of creating this alternative load path. Therefore, instead of the entire load going straight to the joint's bond area, some loads were redirected to the bolt to utilize the bolt as an additional load carrying component in the joint.

The main adherents of the specimens were made with 20 plies of BMS8-168 plain weave carbon fiber pre-impregnated (prepreg) fabric. The adherents were laid up with the following $[0°, 0°, 90°, 90°, 0°, 0°, 0°, 90°, 90°, 0°]_s$ orientation. This was symmetric and balanced laminate. For the attachments, both types of attachments were made from 10 plies of the same BMS8-168 material. The attachments were laid up with the orientation of $[0°, 90°, 0°, 90°, 0°]_s$. The curved attachment required an aluminum mold to cure the BMS8-168 material into the curved shape. The stepped attachments had four individual steps sandwiched between the adherent and the attachment. BMS-

163 film adhesive was used for the adhesive bonding process. A hole was drilled through the center of the specimen using a diamond tipped hole saw. Liquid coolant was used to reduce the heat generated while the hole saw was cutting through the specimens in order to prevent thermal delamination. The mechanical fastener that was used to fasten the specimen and the attachments together was Composi-lok made by Monogram Aerospace Mechanical fasteners. The tool used to drive the fastener was a special tool provided by Monogram Aerospace Mechanical fasteners.

The dimensions of the adherents were 1.5 inches wide and 6 inches long. The overlap area of the joint was 1.5 inches making the total length of each specimen 10.5 inches long. Two 1.5 inches wide and 1 inch long tabs were bonded on the ends of the specimen to provide a grip area for the tensile tester. The attachments were also 1.5 inches wide but only 3 inches long. One end of the attachments was not bonded to the joint, the area over the bonded area was left un-bonded and the attachment was bonded 2 inches from the edge of the bond area. This allowed the attachment to stretch and allowed some load to travel through it taking some load away from the main bonding area. The mechanical fastener was placed in the middle of the bonding area fastening the attachment and the adherent together. The hybrid joint with curved attachments were on average 18.8g heavier than the conventional hybrid joint while the hybrid joint with stepped attachments were on average 29.04g heavier than the conventional hybrid joint. Figures 1, 2, and 3 showed the side views of the three different types of specimens. Figure 4 showed the side view of the three different types of specimens together for easier comparison while Figure 5 showed the top view of the specimens.

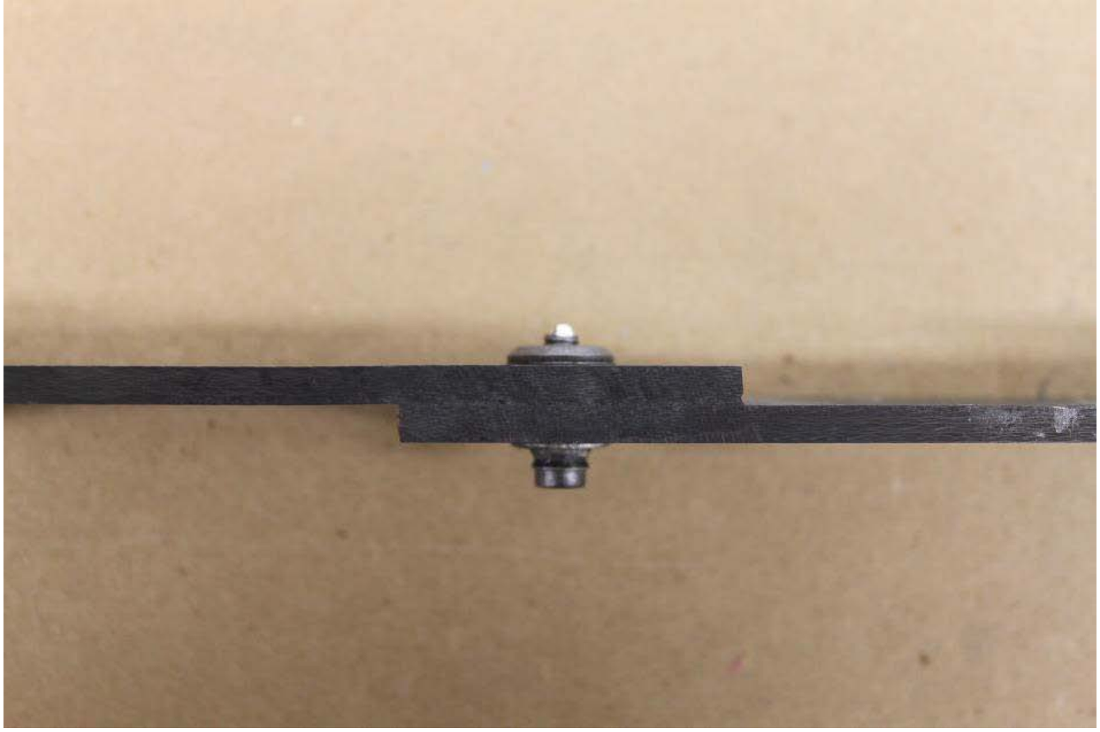

Figure 1. A side view of the conventional hybrid joint.

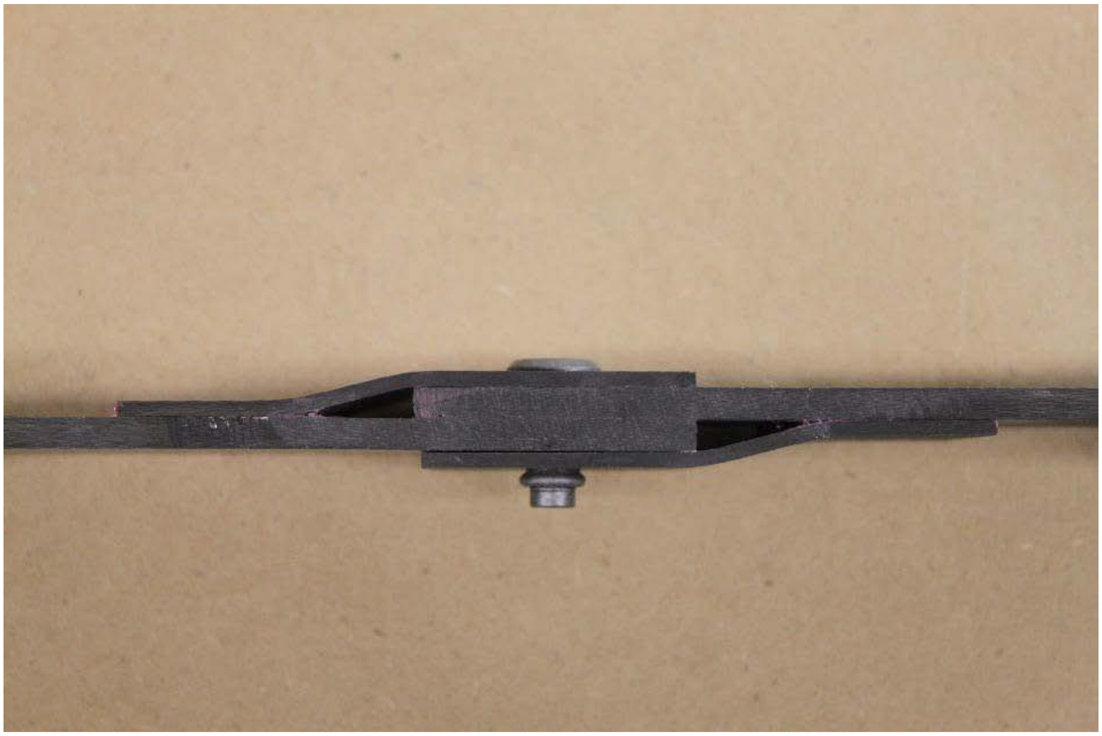

Figure 2. A side view of the hybrid joint with curved attachments.

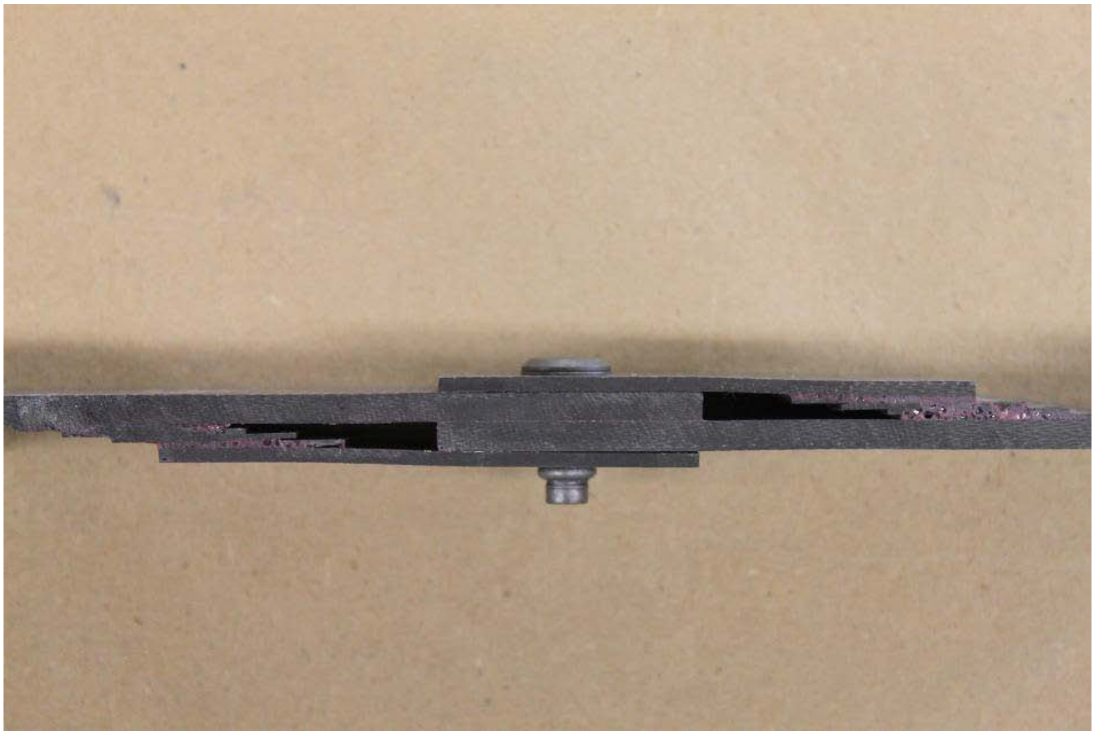

Figure 3. A side view of the hybrid joint with stepped attachments.

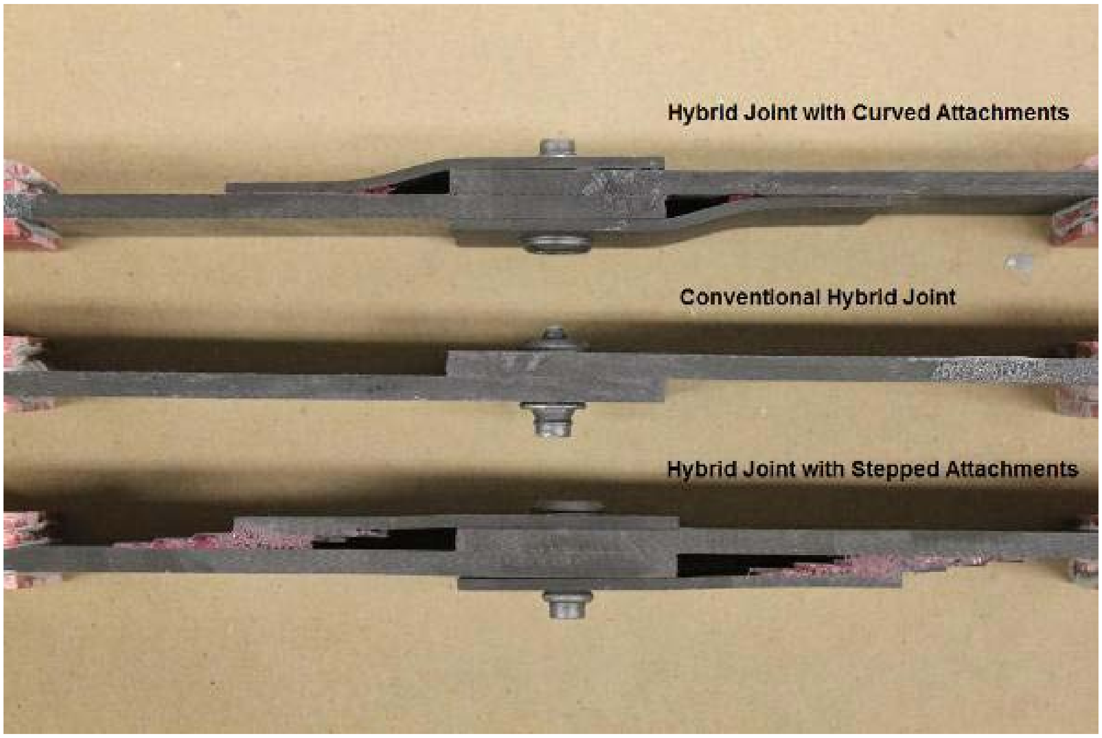

Figure 4. A side view of the three different types of hybrid joints.

Figure 5. A top view of the three different types of hybrid joints.

The specimens were tested with the MTS Systems Corporation tester with a 22 kip (±100kN) load cell shown in Figure 6. The data was recorded in pound force (lbf). All the 45 specimens were tested until failure in order to determine their maximum tensile load. Figures 7, 8, and 9 below showed the three different types of specimens before testing. The tester was connected to a computer that recorded displacement and tensile load data. The data output was used in the data analysis to generate graphs and identify specific failure points.

Figure 6. MTS Systems Corporation tensile tester with a 22 kip (±100kN) load cell.

Figure 7. 15 conventional hybrid joint test specimens.

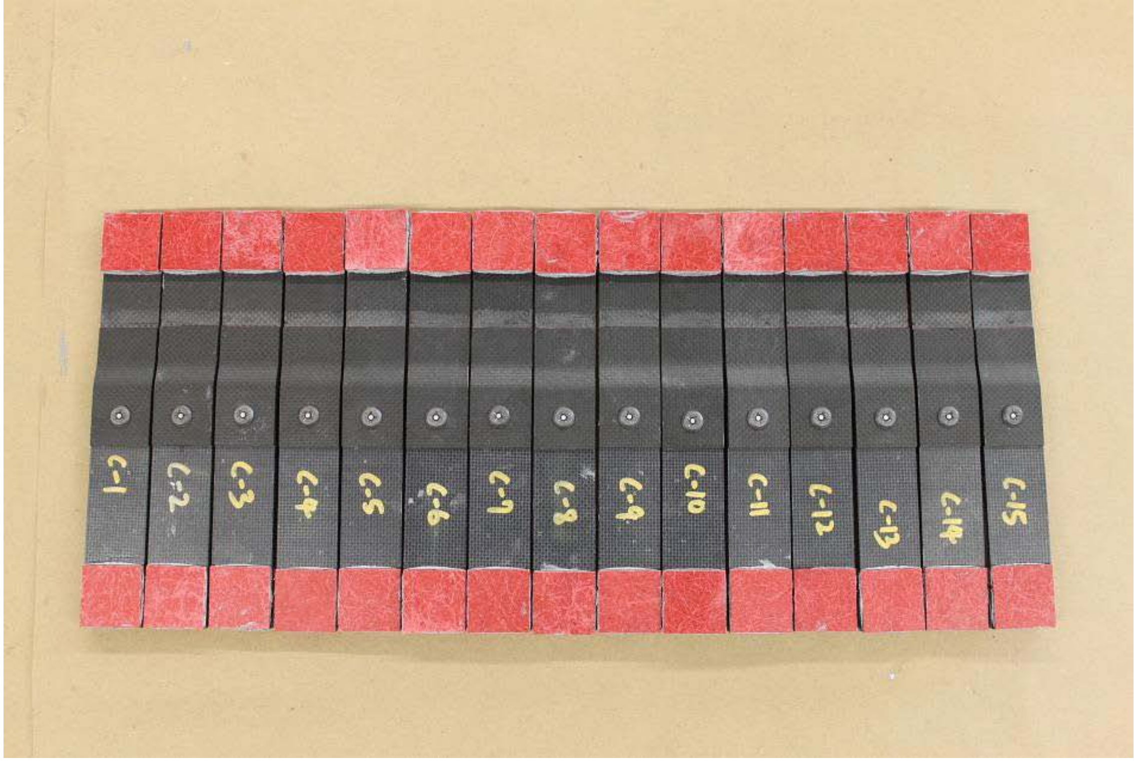

Figure 8. 15 test specimens of hybrid joint with curved attachments.

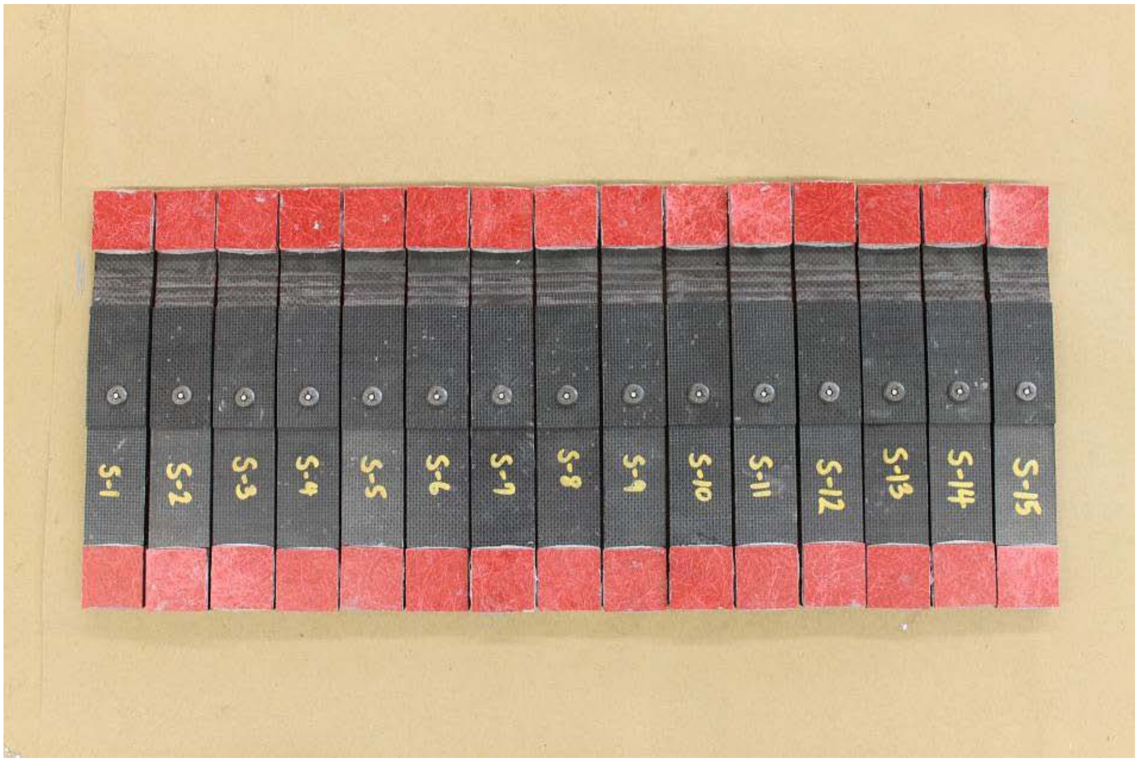

Figure 9. 15 test specimens of hybrid joint with stepped attachments.

Findings

All the specimens were tested using the MTS Systems Corporation tester with a 22 kip (±100kN) load cell until the catastrophic failure of the joints. All the test specimens failed catastrophically as expected. Figure 10 showed a conventional hybrid joint during tensile testing. The data collection was performed beyond the adhesive joint failure and only terminated once the fasteners sheared off from the specimens. From the data collected, the average ultimate tensile strength of the conventional hybrid joints were found to be 5859.99 lbf. All the conventional hybrid joints failed in a similar manner which consisted of the specimens failing first at the adhesive joint. Once the adhesive joint failed, the tensile load was then carried by the fastener until the fastener sheared off. The graphs of the 15 conventional hybrid joint specimens were shown in Figure 11. The graphs showed good consistency between the conventional hybrid joint test specimens. However, 3 of the 15 conventional hybrid joint specimens had a shorter holding time once the main adhesive joint failed. This was due to the fasteners shearing off earlier than expected. The three specimens’ adherents were bending more severely than usual which induced more stress onto the fasteners causing them to shear off earlier than the other fasteners.

Figure 10. A conventional hybrid joint being tested with the MTS tensile tester.

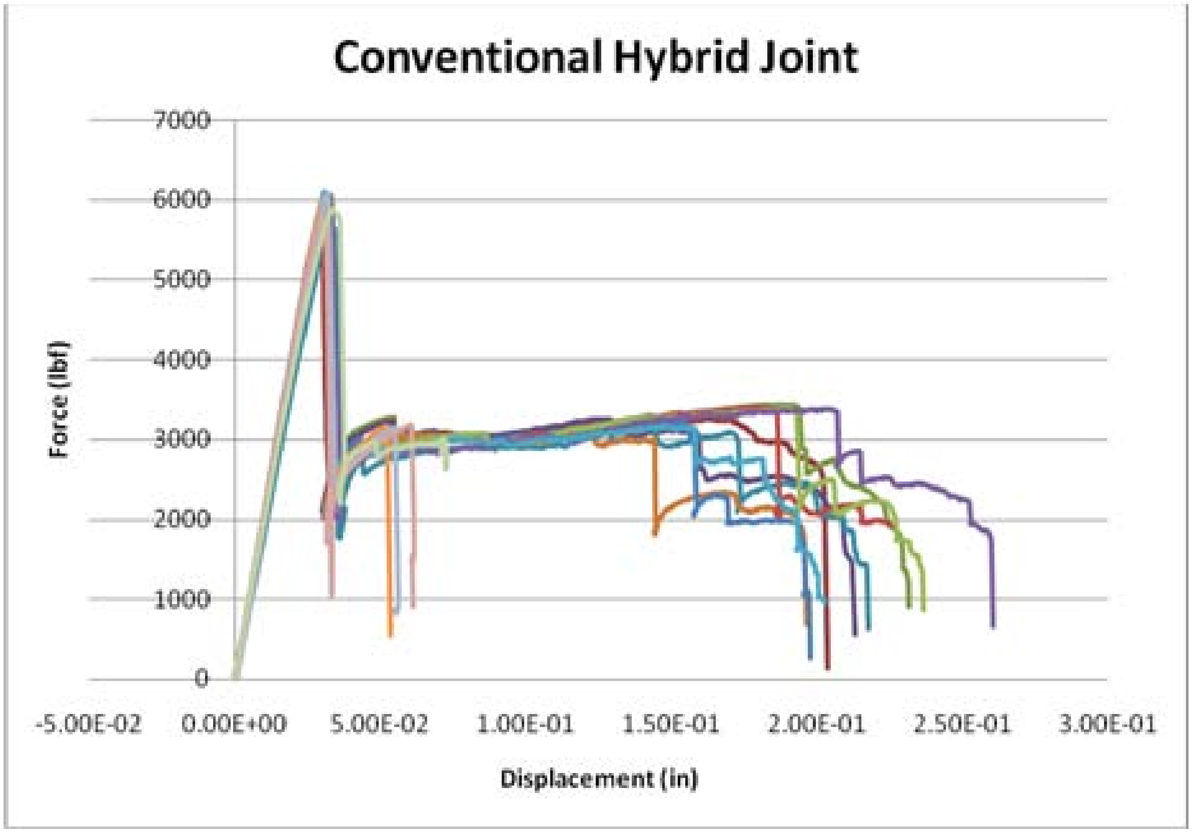

Figure 11. Displacement vs force graph for the conventional hybrid joints.

From the collected test data, the average ultimate tensile strength of the hybrid joints with curved attachments was found to be 10617.62 lbf. Figure 12 showed a hybrid joint with curved attachments being tested in the MTS tester. The average ultimate tensile strength of the hybrid joints with curved attachments was 81.19% higher than the conventional hybrid joints. Like the conventional hybrid joints, the 15 specimens of hybrid joints with curved attachments also failed in a consistent manner with a similar displacement vs force graph. All the specimens failed first at the adhesive joint. Once the adhesive joint failed, the fastener and the attachments carried the load until the attachments failed in bearing and the fastener sheared off. The graphs of the 15 hybrid joints with curved attachments were shown in Figure 13. Aside from the higher ultimate tensile strength of the joint, the joint also held at a higher load compared to the conventional hybrid joints once the adhesive joint had failed. The hybrid joint with curved attachments held at around 5000 lbf compared to the 3000 lbf holding load of the conventional hybrid joints. This could be a very important factor in an aircraft because the joints could take more load in the event of an adhesive joint failure.

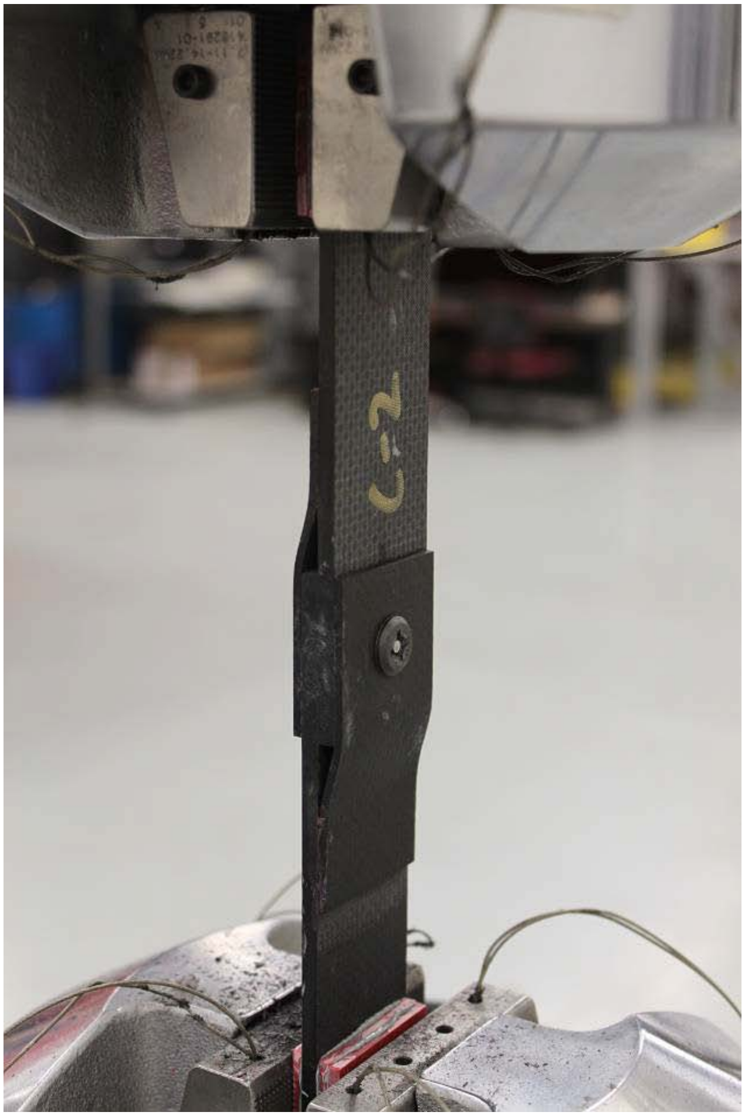

Figure 12. A hybrid joint with curved attachments being tested with the MTS tensile tester.

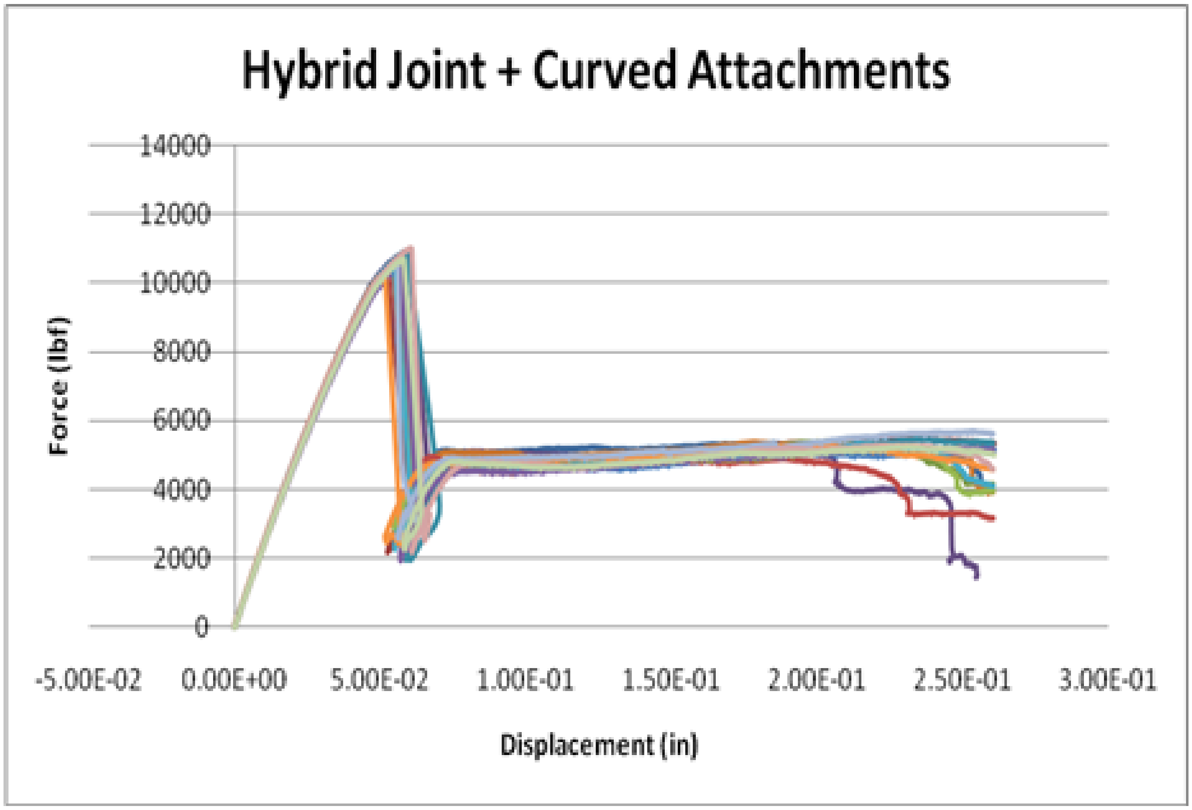

Figure 13. Displacement vs force graph for hybrid joints with curved attachments.

Similar to the hybrid joints with curved attachments, the hybrid joints with stepped attachments also failed at a higher ultimate tensile strength compared to the conventional hybrid joints. According to the data collected from the tensile tests, the average ultimate tensile strength of the hybrid joints with stepped attachments was found to be 10342.14 lbf. Figure 14 showed a hybrid joint with stepped attachments being tested in the MTS tensile tester. The hybrid joint with stepped attachements showed an increase of 76.49% in ultimate tensile strength compared to the conventional hybrid joints. Figure 15 showed that a similar failure was observed as from the previous two types of specimens. The 15 specimens of hybrid joint with stepped attachments failed first at the adhesive joint. Once the adhesive joint failed, the stepped attachments and the fastener carried the load until the stepped attachments failed in bearing and the fasterner sheared off. The specimens were also holding loads at about 5000 lbf once the adhesive joint had failed. However, problems with the data collection of one specimen within the hybrid joint with stepped attachments specimens required the testing of the specific specimen to be terminated early and restarted. This led to the specimen failing at a lower ultimate tensile strength compared with the other specimens with stepped attachments.

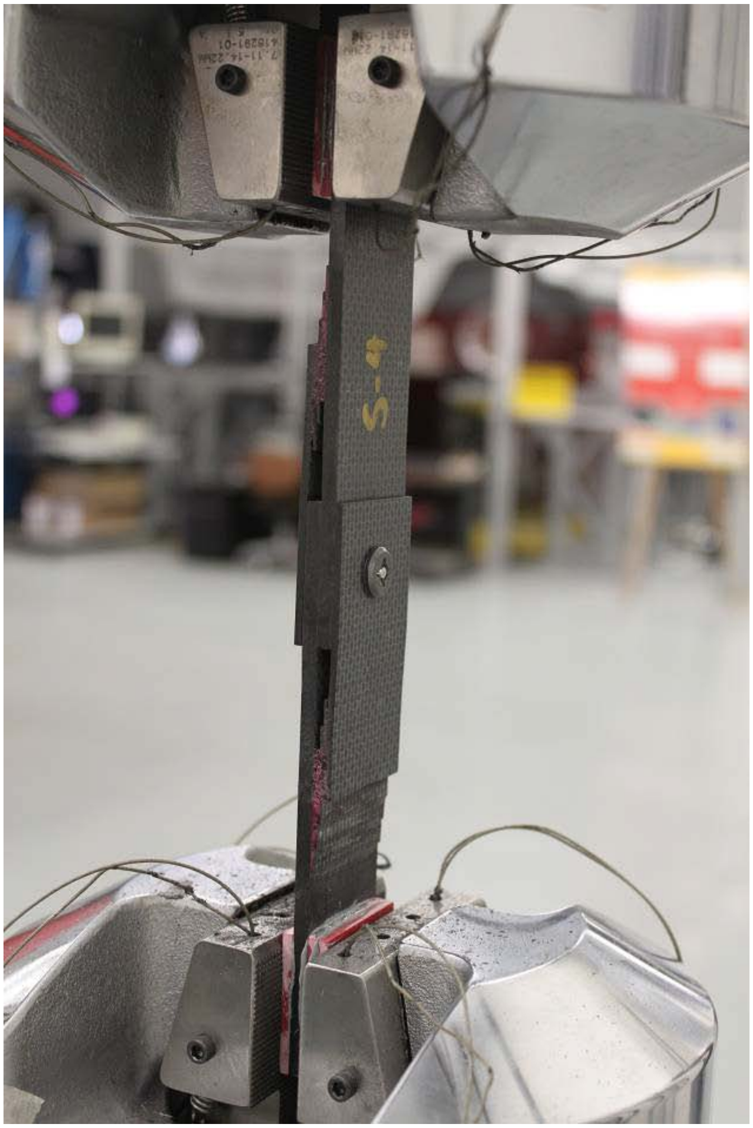

Figure 14. A hybrid joint with stepped attachments being tested with the MTS tensile tester.

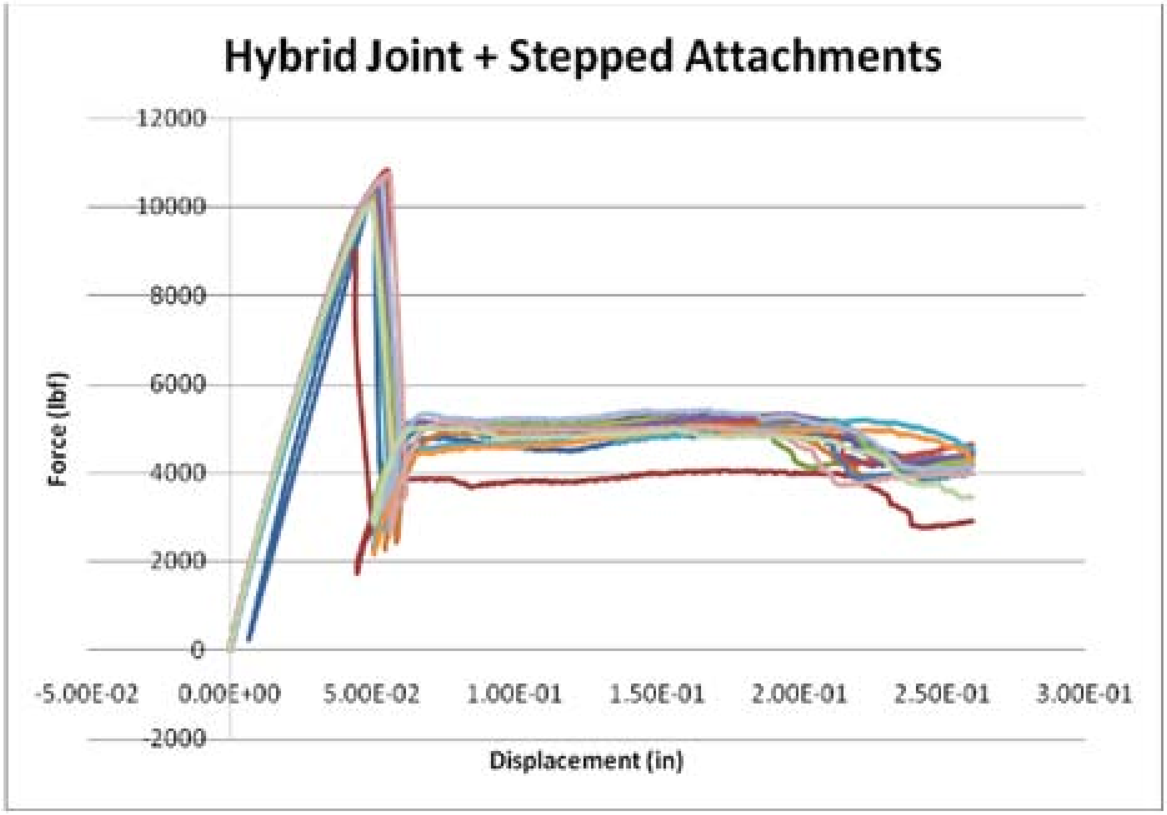

Figure 15. Displacement vs force graph for hybrid joints with stepped attachments.

Conclusions

According to the data collected from the tensile testing of the three different specimens consisting of conventional hybrid joints, hybrid joints with curved attachments, and hybrid joints with stepped attachments, the hybrid joints with attachments showed a significant improvement in ultimate tensile strength when compared to the conventional hybrid joints, which had an average ultimate tensile strength of 5859.99 lbf. The hybrid joint with curved attachments had an average ultimate tensile strength of 10617.62 lbf, which was an 81.19% increase over the conventional hybrid joints. The hybrid joint with stepped attachments had a slightly lower average ultimate tensile strength of 10342.14 lbf, which was a 76.49% increase over the conventional hybrid joints. Once the adhesive joint failed both the hybrid joints with curved attachments and the hybrid joints with stepped attachments also held at a higher load of 5000 lbf compared to the 3000 lbf of the conventional hybrid joints. The data showed that adding attachments to a conventional hybrid joint could improve the ultimate tensile strength of the hybrid joint. From the data, the curved attachments were also shown to be more efficient compared to the stepped attachments. The hybrid joint with curved attachments were on average 19.91% or 18.8g heavier than the conventional hybrid joint while the hybrid joint with stepped attachments were on average 30.76% or 29.04g heavier. The hybrid joint with curved attachments was the lighter joint of the two new joint designs. In addition to being lighter, the hybrid joints with curved attachments also showed a 2.66% higher ultimate tensile strength when compared to the hybrid joints with stepped attachments due to the fewer stress points the curved attachments had compared to the stepped attachments.

Recommendations

From the results of this research, the data showed that adding attachments to conventional hybrid joints did improve the ultimate tensile strength of the hybrid joint. However, further research will be required to properly understand how effectively the hybrid joints with attachments could improve conventional hybrid joints. The researcher recommends future research that incorporates larger test specimens which are able to accommodate multiple fasteners similar to an actual aircraft structure. This will help determine if the hybrid joints with attachments will still perform as expected when there are multiple fasteners present. The researcher also recommends a longer test specimen to be prepared for future research in order to allow the loads from the tensile tester grips to stabilize and straighten before reaching the adhesive joint and the fasteners.

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