Aerospace Fastening: Bolts & Rivets, Welding, and Adhesives

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Executive Summary

Whether joining spacecraft structural members together or attaching skin to the wings of an airplane, it is critically important to consider all possible fastening methods available; choosing the wrong one could result in thermal or structural failure. This paper investigates three common types: bolts & rivets, welding, and adhesives within aerospace applications. Bolts are exceptional at connecting structural frame members, rivets are low profile and great for shear lap joints, welding offers a leakproof and mechanically sound joining option, and adhesives are best for hybrid joints and distributing the load over a larger area.

Introduction

Before selecting a method of fastening, the loads on the joint must be fully understood by the designer; common loads include tensile, shear, torsional, double shear (where two shear planes intersect the joint along its axis), and cleavage/peel (load is concentrated on one end of the joint as the two materials are pulled apart at a non-zero angle to their midplane). Fasteners can also be selected for their superior performance at high temperatures, fatigue resistance, shape, and weight.

Bolts & Rivets

Bolts and rivets offer a strong and removable mechanical fastening method that can join different material types. However, stress concentrations can often form around their attachment points. Bolts are made from a variety of materials, including stainless steel, titanium, zinc, and silicon bronze. A very common design used in aerospace is 316 stainless bolts, which have a large proportion of chrome and nickel in the alloy for excellent corrosion resistance. Zinc plated steel is also extremely common and is ranked by their "grade". Grade 2 is known as the low strength version, moderate properties at Grade 5, and excellent strength and corrosion resistance properties with Grade 8 fasteners. The bolt's grade is indicated by markings on its head. Rivets are typically aluminum and are used in larger quantities than bolts on the frame or skin of an aircraft. 2117-T3 is generally used for rivets under relatively low loading conditions, whereas 2024-T3 for compression and 7075-T73 for tension is used for frame members and stringers. Rivets are often clad to reduce corrosion; however, this can adversely affect fatigue life properties. [1]

Rivets are meant to be loaded in shear, whereas bolts can be loaded in shear or tension. It is therefore common for aircraft skins to be fastened to the frame with rivets and each other in lap or butt joints. Rivets also offer a lower profile head shape for increased aerodynamics, which makes sense as the longitudinal axis is not meant to take a load, like a bolt and nut combination. Figure (1) shows a basic butt splice joint between two rivetted surface skins. Bolts are more commonly used on the interior of aerospace designs, with their higher strength utilized for structural joints. Bolts can be used to create a slip-critical joint, where high tensile clamping forces create frictional forces between the joined members to resist slip, rather than all the load being exerted directly into the fastener as shear.

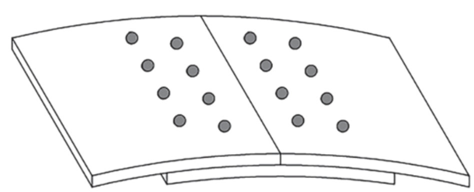

Figure 1: Riveted Butt Splice Joint

Dire consequences can come from bolt and rivet failure, with one of the most common concerns being corrosion. Because these fasteners are often used to secure lap joints, crevice and pitting corrosion are particular issues, where moisture is trapped underneath the rivet heads and can go unseen from an outside observer. Figure (2) shows pitting corrosion at the interface of two materials joined by bolts. Series 2000 and 7000 aluminum, common aerospace alloys, are especially susceptible to crevice corrosion because they exhibit interangle attacks, where the elongated grain boundaries along the rolling direction preferentially corrode. [2]

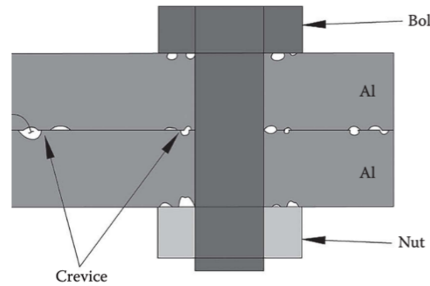

Figure 2: Pitting Corrosion

Bolt pre-tensioning is important in many applications to control the friction in a slip critical joint or to properly secure the fastener from vibration, which can be indirectly controlled through a few methods. The most common technique is utilizing a torque wrench and approximating the tension in the bolt to the torque enacted on it. To make the correlation, a nut factor K is used that is based on thread geometry and lubrication, acting as a proportionality constant for each design. Due to approximately 90% of inputted energy lost to friction (and 10% going into actually tensioning the bolt), this method could result in up to 30% errors off the ideal torque-tension relationship. Although more expensive, direct methods to measure pretension are more accurate. These include options such as direct tension indicating (DTI) washers that compress during tightening, hydraulic tensioners to pull up on the bolt to a precise tension that a nut is tightened on to secure, or ultrasonic measurements of the material's structure under tensile load. [1]

Welding

Welding offers joint connections that are fully tight and sealed from leaks, typically do not cause stress concentrations and a relatively inexpensive and lightweight option. Various types of metals can be welded for aerospace applications, such as aluminum, titanium, nickel-based alloys, steel, and some dissimilar metals (steel to nickel-based alloys through friction welding).

A common scenario in aerospace applications is the need to weld aluminum frame members into a larger structure. This can prove difficult with conventional methods such as gas turbine arc welding, plasma arc welding, and gas metal arc welding. Instead, a common technique known as friction stir welding (FSW) is used as a defect-free method to join aluminum that is stronger than typical arc welds. Figure (3) displays the FSW process. Unlike arc welds, FSW does not melt the adjacent materials but rather creates a soft region around the rotating tool, generated by frictional heat. Within the "stir zone", the resulting grains are equiaxed and significantly smaller than the original materials. Defects in the area can occur if the particles become varied in size, which can affect the overall strength of the joint. [3]

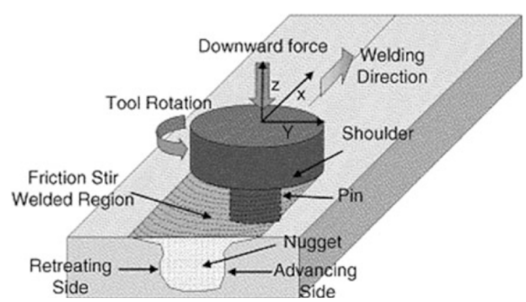

Figure 3: Friction Stir Welding

Despite all of its advantages, welding is sometimes not a viable option for fastening because of the thermal distortion it can cause in the joined material. Any uneven heating during the welding process can cause excessive internal compressive and tensile stress as different areas of the weld zone's lattice structure cool down. If the stress exceeds the material's yield, local plastic deformation will occur and permanently distort the structure. The intended shape of the component can be decreased longitudinally or transversely, resulting in incorrect angles, which can often be drastic if the error is propagated across the entire structure.

Welded joints can be designed to mitigate issues stemming from thermal distortion and human error in the process. Figure (4) displays various butt joint weld types that can be preprocessed before the weld. The single square groove configuration lacks sufficient volume for the weld metal to penetrate the joint and fully bind the two materials together. Instead, the double-V or double-U grooves are commonly used for proper mixing and to reduce distortion from over-welding. Critical steps can also be taken during the welding process to ensure tightly-toleranced parts. Jigs and fixtures help maintain accuracy, and starting with tacks to locate individual parts and then going over multiple times to increase the weld bead size will reduce the thermal expansion effects. [4]

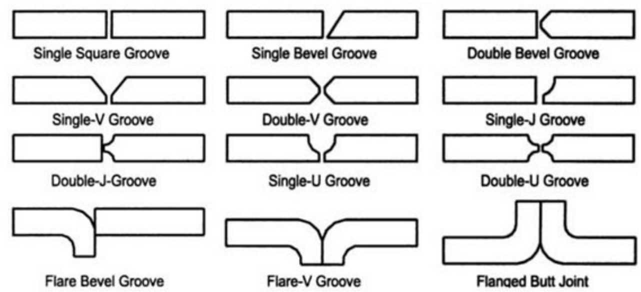

Figure 4: Butt Joint Weld Configurations

Adhesives

Adhesive bonding is becoming more popular in hybrid metal/composite joints and distributes the load through the joint over a large area, reducing stress concentrations. Adhesives have exceptional strength to weight ratios, as well as resistance to fatigue and corrosion, but require extensive testing and preparation for effective utilization. A major benefit of adhesive joining is that no local damage occurs to the bonded materials, such as with welding or bolt/rivet holes.

The most common type of adhesive is epoxy, which consists of a resin mixed with a hardener. When a two-part epoxy is mixed, an acidic hydroxyl group and epichlorohydrin come into contact to initiate a coupling reaction. Bisphenol A and Novolak are both commonly used compounds in commercial based epoxies for a hydroxyl group, a subclass of the phenols. Figure (5) shows the structure of the Bisphenol A molecule group, with the bracketed section repeated up to 25 times per chain [5]. After mixing, three-dimensional cross-linked thermoset structures form within the adhesive, solidifying against the bonded materials and generating heat. Adhesive strength is derived from the resistance between it and the bonded surface, Sometimes, the exothermic reaction can be enough to cause thermal degradation to the joint, which must be accounted for. Some reactions require heat above room temperature to begin, for which epoxies are one part, with heating instructions to begin the curing process.

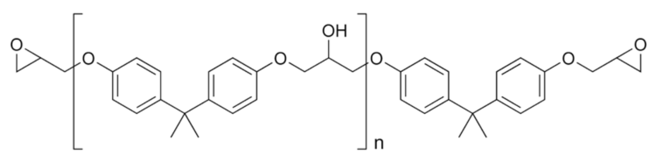

Figure 5: Bisphenol A Molecule

Adhesive selection type cannot begin until the geometry and loads on a joint are understood. Increasing surface area of the bonded components and reducing areas of built-up mechanical stresses are both key design considerations to maximize the success of an adhesive joint. Special consideration

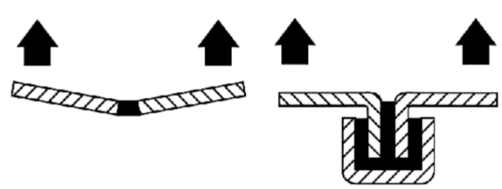

Figure 6: Cleavage Joint Redesign

should also be placed on keeping the adhesive itself free from moisture during its lifetime, which prolongs degradation. Adhesives also perform better under pure tension/compression or shear loads. Peel and cleavage loading scenarios would load the bond in directions not along its strongest axis. Joints can instead be redesigned, such as in Figure (6), where a cleavage loading location (left) is switched to only tension/compression and shear loads on the adhesive (right) [6].

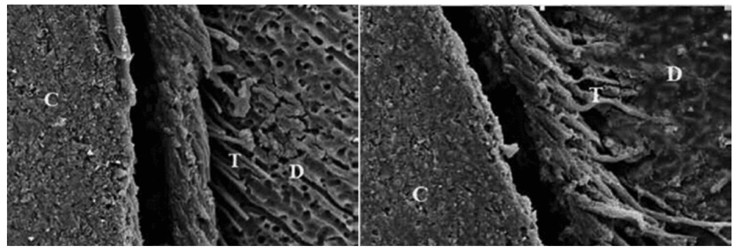

Figure 7: Adhesion Before/After Treated Surface

Using adhesives can sometimes be difficult. Not only are there numerous types of adhesives with widely varying properties, but the surface quality of the adhered parts must also be treated for the process. As expected, an adhered joint will be stronger with more contact area. The area between the surface and the adhesive can be significantly increased by roughening the surface through either sand blasting or with abrasive material, therefore increasing the overall contact strength. Varying grits of abrasives can be used depending on the desired output, with glass beads offering a smoother finishing compared to a harder material such as silicon carbide. Surfaces can also be chemically treated, which acts as a catalyst when binding to the adhesive. Figure (7) displays an SEM image of before (left) and after (right) a chemically treated surface, with a larger zone of interaction between the adhesive and surface, increasing strength [7].

Prospects for Future Development

Of the three fastening methods discussed, adhesives are currently the fastest developing, with research into high temperature and durable options. Many adhesives are inherently at a disadvantage when it comes to temperature range because they are polymer based, but some ceramic substrates are being developed. NASA and Boeing have made substrates by mixing high silica borosilicate with boron oxide. A metallic additive of silicon tetraboride, silicon hexaboride, boron silicide, and boron allow the ceramic to solidify and adhere. [8] This method can be used at up to 1000°C in some cases, but more research is needed to increase the adhesive's mechanical strength before use in aerospace.

References

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