Introduction to Fatigue in Riveted Joints and Adhesively Bonded Joints

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Introduction

A new hands on approach in laboratory experimentation at the undergraduate level in the mechanical engineering curriculum presents comparison of the mechanical properties: including *Tensile Strengths, Ultimate Strengths, Elongation and Fatigue Life* at ambient temperature, between specimens fastened by r*ivets* and specimens fastened by an adhesive. The reduction or elimination of mechanical fasteners in the joining of the two parts provides the following benefits: increased strength and service life, improved distribution of stress and load throughout joint, reduced weight, reduction of personnel to manufacture and manufacturing time. This experimentation is divided into three laboratory sessions each approximately 2 hours in length.

Laboratory Session One

During this session, students are introduced to the concepts of fastening materials together and their characteristics. Students then prepare specimens applying different joining methods using rivets and adhesives. When two parts are joined together they form a joint. There are many types of joints such as the ones shown in Figure 1[1].

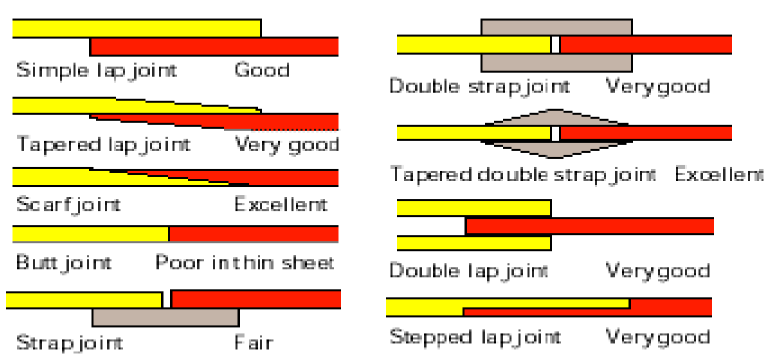

Figure 1. Various Types of Joints

When constructing joints, the type of fastener used must be considered. Some of the basic considerations used in riveted joints are the following:

- The fasteners must completely fill in the connecting holes.

- The applied load is carried equally by each of the fasteners.
- The stresses are distributed evenly over the cross sectional area of the joint.
- The flange width or the distance from the edge of the material where the fastener is placed must be sufficient enough to ensure that there is enough material to contain the fastener head and material.
- Fasteners must be spaced to avoid contact with other fasteners.
- Proper preload in the clamp up must be achieved.

The '*rivet*' is one of the oldest and most reliable fasteners. In earlier times, cherry hot rivets were forged by blacksmiths, placed into pre made holes in mating parts, water was poured onto these parts, thus cooling the rivet material. As the rivet material cooled, it would fill the surrounding hole and swell to the original size. This swelling would clinch the two parts together forming a joined material. Rivets are made from several different materials; the four most common are copper, aluminum, brass and stainless steel. Typically, the strength of the joint depends on the fastener and the materials from which the joint is composed. It is advantageous from a strength standpoint to use a rivet having about the same properties as the surrounding materials. The spacing of the rivets also depends on the proportions of the members being joined. It is recommended practice to space the rivets a minimum of three times the diameter of the rivet being used and no greater than 24 times the thickness of the material being used. There are four different types of rivets used in permanent joints: Solid Rivets, Blind (pop) rivets, Punch or Self-piercing rivets and Huck bolts (screw rivets). During this testing the Solid Rivet was used. *Solid Rivets* are one piece joining elements. A hole is pre-drilled into the components being fastened. The rivet is then placed through the hole. The rivet must be of correct length as to pass through the materials being connected and allow 0.5" distance beyond to develop a head. Figure 2[1] shows how the solid rivet is placed through the pre-drilled hole of the mating parts allowing the 0.5" clearance. The rivet is then bucked or hammered using a pneumatic hammer and a bucking bar, which compresses the shank of the rivet. This compression eliminates the gap between the parts and applies a preload force. During loading of the part, this force transmits some of the load from one sheet of the joint to the other by frictional contact. A draw back of the solid rivet is that during installation it requires that both sides of the joint be accessible.

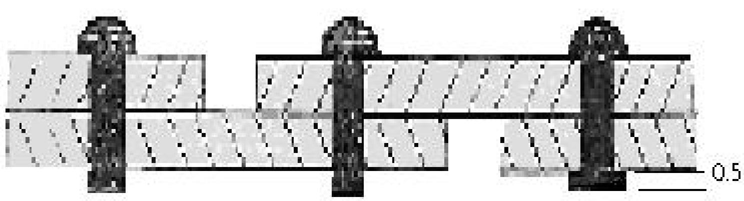

Figure 2. Solid Rivet Installation

Considerations are also reviewed before developing an adhesive joint. One must be familiar with adhesives' physical properties and its cure conditions. The cost and ability required to manufacture the component joint in the manufacturing plant must also be considered. Finally, the designer should be aware of the different loads and stresses (magnitude, duration and direction), which may be experienced by the product over its lifetime and from its environment. A well-designed joint must be as strong as the adherends themselves. Ideally, bonded joints should fail in the adherends and not in the bonded area. The types of stress that are experienced by adhesive joint are similar to the stress seen in other fasteners, like mechanical fasteners. The most common are tensile, shear cleavage and peel. Some of these may be applied in combination and other effects such as environmental stresses could be combined with the above to fatigue the joint and/or fasteners. The tensile or compressive stresses develop when forces are acting perpendicular to the plane of the joint and are spread over the entire bonded area. The outer edge or boundary of the adhesive develops high stress regions, with the majority of the load being applied here, a stress crack can form at the weakest link in these highly stresses adhesive boundaries. Unless the joint is designed correctly the crack will growth and completely fail in a short amount of time.

In a properly designed joint, the joint will have parallel substrate surfaces and have axial loading. The adherends must also have enough rigidly to distribute the load evenly over the entire area of the bonded region. The selection process for the *Adhesive* is difficult since there are over 500,000 different adhesives to date. Each one has different characteristics and uses. The data for each must be reviewed from the adhesives functional and operational criteria to its environmental effects and durability. These criteria have been formulated based on design experience and testing. Some examples of the criteria are Young's Modulus, the Shear modulus and the materials Ductility. One can gain useful knowledge from this data as an example: a toughened adhesive is good for increasing static strength, but may decrease the fatigue life and creep under sustained load, where a brittle adhesive may be better for increasing the fatigue life.

A definition for "Adhesive" is – a substance capable of holding two surfaces together in a strong and permanent manner. The theory of adhesion has no set standard on which to base a perfect model. There are several theories of adhesion that are based on practical observations, however none are universally accepted. The designer must face the possibility that the adhesive may fail in some situations. Nevertheless, by being familiar with these theories, one has gathered information on which to expand their knowledge as to how adhesives work in joining materials in modern applications. The forces involved in holding adhesive to the substrates are all around us in nature. To understand these forces, one must first understand the forces that bind atoms and molecules together. The two most well known forces in adhesives are the cohesion and adhesion forces. Cohesive forces hold the adjacent molecules of a single material together, while adhesive forces hold two materials together at their surfaces. When an adhesive fails, the type failure is categorized as an adhesive or cohesive failure. An example would be similar to peeling a piece of cellophane tape from a sheet of glass, if the tape peeled cleanly from the glass and none of the adhesive film remained on the glass adherend, it would be classified as an adhesive failure. An example of a cohesive failure would result when two materials held together by grease were pulled apart, the grease would be on both pieces of material and thus be a cohesive failure.

Testing was conducted on two different types of samples, one the baseline sample or riveted joint made from 20 gauge cold rolled steel with four solid rivets and the second type was made with the same adherend material (20 gauge cold rolled steel), however the fastener used was a methacrylate adhesive. This adhesive is a two-part adhesive designed for thermal bonding of thermo-plastics, metals and composite assemblies. It has a working time of 4 to 6 minutes and achieves 75% of its ultimate strength in 15 to 18 minutes after application. It is widely used due to its reduction of surface preparation requirements, high tensile strength (2.70-3.00 ksi) and high cohesive shear strength (2.10-2.25 ksi) and high fatigue endurance. It also has a wide working temperature range of -67^0F to 250^0F.

Riveted Joint Sample Preparation

The specimens were made from 20-gauge cold-rolled steel with red oxide primer. This material was sheared into 4.5" x 6.0" panels. Two panels were arranged such that an overlap exists between the two panels. These panels are then clamped and held in place for drilling. Four 3/16" holes are drilled into the clamped sample as illustrated in Figure 3. Two of the holes are aligned 3/8" from the edge of the inside overlap at 1-1/4" from the side. The next two holes are aligned with the previous two at a separation distance of 2.0" from the first holes.

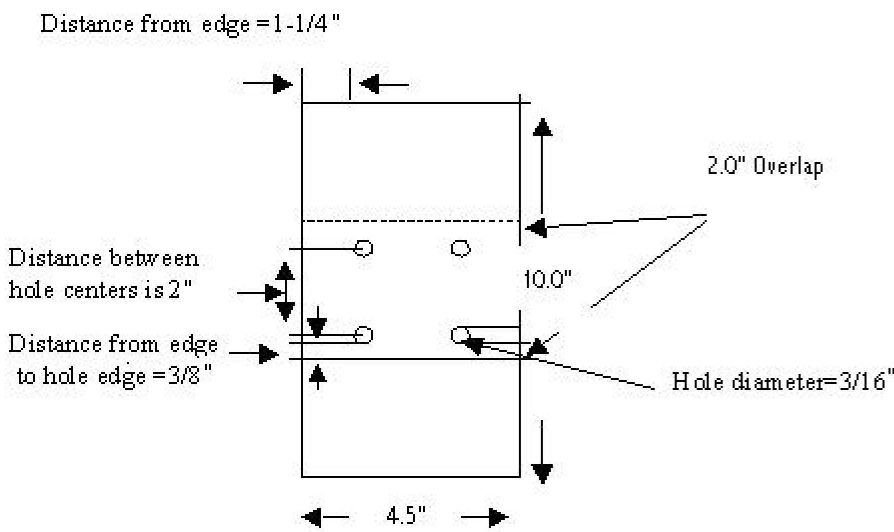

Figure 3. Riveted Joint Specifications

For mechanical fastening, surface preparation only requires that the samples be deburred and cleaned well. The holes are deburred and the four 3/16" x 3/8" Solid Rivets are placed into the four holes. The rivets are set or driven leaving approximately 3/8" head on both sides of the sample. The physical properties of the 20-gauge cold rolled steel are as follows: the value for Young's Modulus is 30 Ksi and Poisson's Ratio is 0.30. Four samples were constructed as simple lap joints using the solid rivets mentioned above.

Adhesively Bonded Joint Sample Preparation

The adherend used for the adhesive joint was made from the same 20 gauge cold rolled steel material; however, the 6.0" length of the material was slightly changed to encompass the additional thickness of the adhesive. The change was made in the overall length of the adherend, where the 6.0" length was changed to 6-3/8", see Figure 4. The additional 3/8" was then formed at a 7-degree angle from the other 6-3/8 inches.

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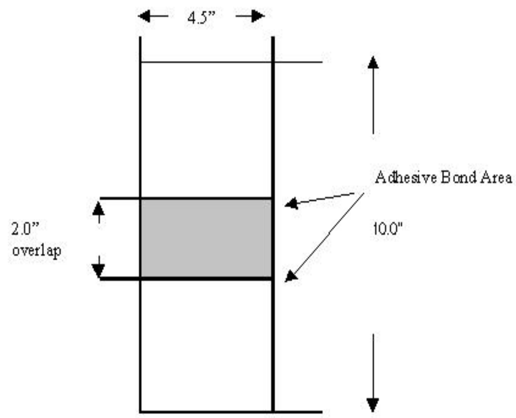

Figure 4. Adhesive Joint Specifications

Here the new adherend was 4.5" x 6-3/8" with the same 20 gauge sample thickness and an adhesive thickness of 0.030" thickness. Sample preparation was also different in the case of the adhesive joint. Once the panels were sheared and deburred, a scrim line was scribed onto the rear of each panel as a template where the adhesive must be applied and where the mating part would then be aligned. The panels were then cleaned. The cleaning process consisted of removing any dirt or debris with a wet cloth, next the panel was cleaned with MEK (Methyl-Ethyl-Keytone) which is a solvent that is used to remove any grease, film or chemicals from the surface and pores of the material.

A pneumatic adhesive dispenser was then used to mix and apply the two-part adhesive onto the panel. The physical properties for the adhesive are the following: Young' Modulus $\approx$ 75KSI-100 Ksi and Poisson's Ratio $\approx$ 0.35[3]. Since this adhesive has a 4-6 minute work time, the next step of panel alignment was conducted with diligence. The edge of the second panel was aligned onto the scribed line on the panel and the adhesive was applied. The two panels were pressed together, compressing the adhesive and spreading it over the bond area with the excess extruding out the ends of the joint until the 0.030" thickness was obtained uniformly throughout the joint by use of the 7-degree angle of the adherend as a guide. A 10-pound compression clamp was placed over the overlap area on each side of the sample to apply pressure during the curing stage. Four adhesive joint samples were constructed, two to be tensile tested and two to be used for fatigue testing. The four adhesive samples were taken and placed in a bake oven at 265°F for 17 minutes to accelerate the cure process and determine if the elevated temperature affects the tensile strength. The samples were then allowed to set until the next session, the following week.

<u>Laboratory Session Two</u>

Static Tensile Testing

The second lab session instructs students on how to perform static tensile testing on the fabricated samples from the previous session. Two of the four specimens made from the rivets and two of the four made from the adhesive were obtained for static tensile testing. Students were then trained in how a tensile test is programmed into the Tensile machines computer software and it operates the hydraulics. Safety training was also explained for test setup, installation of samples, application and use of machinery.

Tensile Test Equipment

The tension test is conducted on an MTS 880 110kN Load frame with an Instron® 8500 Plus Series Controller. The hydraulic grips on the machine have a 67.5 kip capacity. The system calibration certificate is reviewed to determine when it was last calibrated per ASTM E4-99 specifications and its load cells are also verified and certified per ASTM Standard E74-95 and is traceable to NIST. The Instron® Control Software contains existing software programs to conduct tension testing once control parameters have been entered. The software requires that a cycle time and type of load cycle to be entered for the test. In the tension test, the ultimate strength of the sample is determined by pulling the specimen to failure.

Previously, samples were constructed from the 20 gauge cold rolled steel and tensile tested to determine the ultimate strength of the homogenous material, the average material strength was approximately 6,600 lbs. The strength of the joints made from the material should not greatly exceed the strength of the parent material; however, a safety factor was used to be sure that the joints would fail during the tension test. The system was set into load control, where when the sample fails or breaks and the force drops below a predetermined value, the system will shut down. This is also a safety function. The upper limit was set to 8 kips. The time for a complete cycle was set to 960 seconds or 16 minutes. Since the test was to pull the sample apart, a smooth ramp up was not required. Therefore, a triangular shaped waveform was chosen as the input waveform. A cycle consists of a ramp up to the 8 kip value, a ramp down and another ramp up to return to the original or zero position. However, when the sample breaks the load value will go zero and the system will stop the test, thus really only one-fourth of the cycle or 4 minutes will be used. The data acquisition system for the Instron® System records the load from the tensile force that was pulling the specimen apart, the displacement of the grips and the time elapsed during the test from start to failure. The sample rate of the data acquisition system was set to 10 hertz.

ASTM E8-00b Standard Test Methods For Tension Testing of Metallic Materials was followed for the tension testing procedure. All tension tests were conducted at ambient room temperature. Each sample is aligned into the jaws or grips and centered on the mid axis of the machine for repeatability. The grip pressure is applied and the preset tension test software program is recalled and initiated. The sample is pulled to failure and the data is recorded into an appropriately named file corresponding to that particular tension sample for later use. The failed specimen is removed and another specimen is tested. This process continues until all riveted joint specimens are tested. The same software program and test method is used for tension testing of the adhesively joined samples with only one modification. The strength of the adhesive samples had already been determined to be stronger than the riveted samples from preliminary tensile testing. Therefore, the upper limit is changed from 8 kips to 10 kips. The purpose of the test is to determine if the adhesively bonded joint will survive the same tests and situations as the riveted joints. Once the above modification is made, the adhesive joints are placed into the grips and testing is done until all samples have been tested.

The data from the riveted and the adhesive joint tension testing is then reviewed as to the method of failure. A statistical analysis is performed to determine the standard deviation and mean of each group. The static tensile testing of the riveted joints illustrates mean force of 4,458 lbs., whereas the adhesively bonded joints gave a mean force of 8,971 lbs. These results illustrate that the adhesive joint is approximately 55 % stronger than the riveted joint. The failure mode of the riveted joints occurs when the rivet head puckers, pulls and elongates the surrounding area of the steel adherend around the rivet head. The adhesive joint failure modes occur through adhesive and cohesive failures of the adhesive and material failures in the steel itself [4].

<u>Laboratory Session Three</u>

The third session introduces the students to dynamic fatigue testing. The same tensile machine as is used in Laboratory Session Two is used here. The students were divided into three groups and each student is instructed on how fatigue testing is performed. This information encompasses machine setup, sample mounting, safety and software development for a fatigue test. Each fatigue test lasts approximately one day for the riveted joints and up to three days for the adhesively bonded joints. A fatigue test applies cyclical loading of forces onto a material or sample as would be seen in the life of the material or part. These loadings help the designer understand how a material or part will react or endure certain forces or loads. There are several approaches or methods to fatigue testing. The method used for the fatigue testing of this class utilized the HALT approach. The HALT (Highly Accelerated Life Testing) method uses percentages of the yield of the baseline joint or material as the upper and low limits for the tension-tension fatigue test. This approach decreases the amount of time for failure to occur during fatigue testing.

All fatigue tests were conducted at ambient room temperature. Each sample is aligned into the jaws or grips and centered on the mid axis of the machine for repeatability. The grip pressure is applied. The preset software program is recalled and initiated. The sample is cycled until either failure occurs or the number of cycles is exceeded. The number of cycles and loads are recorded into an appropriately named file corresponding to that particular fatigue sample for later use. The failed specimen is removed and another specimen is tested. This process continues until all riveted joint specimens are tested. A group of samples of the baseline sample or in this case the riveted joint is fatigue tested. The mean number of cycles obtained from the fatigue tests of the riveted joints then becomes a baseline for comparison with the adhesive joints. Since the number of cycles for fatigue failure of the riveted joint was unknown, the fatigue test was set to run for 1.5 *million cycles* or until failure of the specimen occurred. None of the riveted specimens reached this *1.5 million-cycle* requirement. The mean number of cycles for the fatigue testing of the riveted joints was 404,297 cycles. Since the mean for the riveted sample turned out to be so low the 1.5 million specification was again used for the adhesively bonded joint specimens. Fatigue testing is now begun on the adhesively bonded specimens. The adhesive joints did meet the *1.5 million-cycle* requirement during their fatigue testing.

Conclusions

This new type of hands-on experimentation generated a large amount of interest from undergraduate students to perform research in the general area of fatigue and fracture. During the three sessions, the students constructed, tested, analyzed and conducted statistical analysis of their data for the specimens. They also were allowed to make assumptions on methods of failures in the joints. The students were made aware of the process used for comparing two types of similar but differently constructed joints. The hands-on instruction and use of the tensile and fatigue machine gave practical experience for future industry or research work.

Bibliography

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