Experimental Stress Analysis of Some Adhesively Bonded Joints

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Abstract: *The* ***benefits and wide use of adhesive jointing in industrial fabrications and general purposes were revisited. Survey indicated various types of existing adhesives which were not all good or backed up with design information for every specific engineering application. Here in, the analysis provides on the basis of yield stress failure criterion practicable insights into bond-cure strengths of different common similar-metal joint types of three common metals-mild steel, aluminum and bronze by two widely available cheap adhesives-super glue and araldite. DIN 50 125 standard samples of the metals were systematically used to make 40^0-angle aluminum-to-aluminum scarf joints, 47^0-angle steel-to-steel scarf joints, steel-to-steel butt joints and bronze-to-bronze overlap joints using separately each adhesive according to its manual. Analysis of tensile test stress-strain information obtained with the super glue joints, gave contrasting adhesive yield stresses for the joints as 7.540N/mm^2, 6.987N/mm^2, 10.186N/mm^2 and 13.462N/mm^2 respectively. The corresponding values with araldite were 8.488N/mm^2, 9.920N/mm^2, 10.540N/mm^2 and 14.316N/mm^2 respectively. Torsion tests with similarly butt-jointed aluminum-to-aluminum by super glue and araldite produced lower yield shear stresses of 4.497N/mm^2 and 5.496N/mm^2 respectively in comparison to the values by tensile loading of the lap joint.***

Keywords: Common adhesive joint types, cheap and widely available adhesives, common metals, common loadings, yield stress failure criterion design information

1. Introduction

1.1 Background to the study

A joint is a surface or point at which mechanical or structural parts are held together with capability to transmit stresses [1, 2]. Joining materials is our daily need but a technological problem to contend with to optimally satisfy the various needs. Different methods of making mechanical joints include: welding, brazing, soldering, riveting, bolting, adhesive bonding, etc. Industrial designers and technologists are often faced with the problem of choosing among the methods for various tasks due to feasibility question to reliably, economically and durably meet various levels of stress loads to be encountered [2, 3]. Choice of a method for a desired application is influenced mainly by its comparative benefits over the others. Adhesive jointing can generally be used for low and medium stress applications compared to the strength of the bonded components. Some of the method's comparative advantages that attract its choice over the other methods include:

1) It permits the joining of materials which are impossible or impracticable to join by other methods, such as honeycomb for face sheet, thin sheets, ceramics parts, composites of dissimilar materials, etc.
2) It maintains the structural sophistication of a part by not requiring stress concentration holes for riveting or bolting, and preventing corrosion of metals due to improperly removed brazing fluxes.
3) The entire joined area is united by adhesive to produce a continuous load-bearing joint. Also the localized compressive forces under the heads of mechanical fasteners are eliminated.
4) It both seals and joins in one operation to form liquid and vapor-tight joints.
5) It eliminates the labor costs for countersinking screws and bolts for flushness, or the grinding and sanding after welding. This produces the smooth surface desired in service.
6) It requires minimal heat. Temperatures involved are usually between 65^0C and 77^0C. As a result, distortion due to thermal expansion and contraction is eliminated.
7) There are in existence several types of adhesives and emerging adhesives that can be exploited to join wide range of materials.
8) Advances in adhesive jointing technologies developed over the years have enabled durable joints of high strength to be made in many cases by bonding metal to metal, metal to non-metal, and non-metal to non-metal.
9) It is used to produce joints that are electrically insulating and prevent electrolytic corrosion of conductor metals [3-6]

These and other such merits have made adhesive bonding find increasing applications in a number of industries. For example, it is extensively used in the aircraft and aerospace industries to bond stringers to fuselages and other applications involving ailerons, landing gear doors, wing flaps and other control surfaces; and attaching composite materials to metal components. It is particularly becoming more prevalent in the Air force and Naval systems such as satellites, missiles, weapons and ships. For example, the B-5B which was cited as first military aircraft was extensively adhesively-jointed structurally. Also, about 80% of the F-1 aircraft is made of adhesively jointed sandwiched structures. The C-5, F-5 and Boeing 700 series aircrafts also contain adhesively jointed structures [2, 7].This wide use in the aerospace industry is attributed to the fact that adhesives lend themselves to design for minimum weight and fair strength as well as fabrication and joining of dissimilar materials. Their use also results in substantial cost savings through improved service life of the bonded structure. Another important industry that applies adhesive jointing is the automotive industry where aluminum alloys and plastics are used for car bodies so as to lower weight because of increased pressure to improve the fuel economy of vehicles. In addition, automakers are using adhesives to address noise and vibration issues, and provide smooth surface finish and to eliminate the need for expensive secondary operations prior to painting. The industry uses adhesively bonded joints in structural application like attachment of stiffeners to bonnets and boot lid, joining outer skin to frames, bonding hem flanges, stiffening window posts and attaching reinforcement ribs to bulkheads. Other areas that adhesive jointing finds application are in dentistry, medicine, electrical appliances such as bonding shafts to bushings in motors and armatures and coil bonding, optics and packaging, office furniture such as assembling desks and file cabinets, sports equipment such as assembling bicycle frames and golf clubs, bonding magnets to base plates of hard disk drives, among others [2, 7-9]. These wide uses of adhesive bonding however require care and practice to optimize effectiveness, serviceability and durability of joints by it. This is because the level of suitability of adhesive joint for various service applications is influenced by several parameters such as properties of the adhesive, method of application of the adhesive, film thickness of the adhesive, service joint strength required, availability and cost of the adhesive, geometric configuration and sizes of the components being joined, type and level of surface cleanliness of the components to be jointed, environmental factors and biodegradability of the adhesive, and type of joint configuration [2]. The common adhesive joints are butt joint, lap joint, and scarf joint. The common types of loads the joints experience in service include tensile, shear, peel and cleavage with the tensile and shear more common with metal structures. Under axial tensile loading of adherent pairs, the joints are subjected to tensile stress, tensile stress, and shear stress respectively [10-12].

1.2 Significance of the study

Adhesives can be classified as instant, ultraviolet, sealing, retaining, locking, hot melt, pressure-sensitive, and structural adhesives based on the method of curing and service purposes. Structural adhesives are load bearing adhesives. They are the adhesive types used to build products as varied as office furniture, boats, trains, cars, aircrafts to name a few. There are approximately ten adhesive families commonly referred to as structural adhesives: acrylic, anaerobic, cyanoacrylate, epoxy, hot melt, methacrylate, phenolic, polyurethane, solvent cement and tapes [13.].As a result of advances in adhesive jointing technologies developed over the years, durable joints of high strength can be made by bonding metal to metal, metal to non-metal, and non-metal to non-metal with some of these adhesives [1- 3]. Of all the large family of adhesives available today, cyanoacrylates (super glue) and epoxy adhesives (araldite)are the most famous and widely used. The success of super glue is based on its fast drying rate with ease of adhesion on a wide range of materials and outstanding strength achieved with relatively thinner films of the adhesive. These features make super glue the most common glue used in secondary joints and widely used in the general consumer market to repair broken pieces such as ceramics, plastics or metals in a simple and reliable way. It is also used to assemble prototype electronics, flying model aircraft, and as retention dressings for nuts and bolts. Its effectiveness in bonding metal and general versatility has made it popular among modeling and miniatures hobbyists.It does not fill spaces unlike epoxies, and a very thin layer bonds more effectively than a thicker one that does not cure properly. Its unopened shelf life at room temperature is about 12 months and one month once opened. By contrast, epoxies are common and well-known structural adhesives. They offer a high degree of adhesion to all substrates except some untreated plastics and elastomers. They satisfy all necessary conditions to serve as ideal adhesives. They have various properties which make them very suitable for joining various materials together. Some of these properties include excellent resistance to oil, moisture and many solvents, low cure shrinkage and high resistance to creep under prolonged stresses and a wide range of service temperature from -100^{O}C to 100^{O}C.They are widely commercially available as liquids, pastes, films and solids. Primarily, they comprise of epoxy resins and curing agents [7-9].

A good design of adhesive joint for a critical load-bearing application requires knowledge of the ultimate strength of the adhesive joint and an understanding of its failure properties [2, 3, 14]. Altering the geometry of a bonded joint with adhesives invariably alters the stress and strain distributions within the adhesive layer. These differences can have a profound effect on the stress concentrations and consequently the load capacity of the joint. It is therefore important to appreciate the consequences of changing geometric and material parameters. In order to predict cohesive or adhesive failure loads, a criterion is needed that will define when a critical level of stress or strain is reached in the adhesive to initiate rupture. The yield failure criterion can be used in conjunction with calculated stress and strain distributions within the critical regions of the bond to predict the onset and progression of failure of the joint.

Mild steel, aluminum and bronze are cheap, durable, ductile and common metals we use every day in wide applications. Their average yield stresses in tensile loading are 220, 130 and 150MPa respectively. The corresponding values in torsion loading are 160, 125 and 140MPa respectively. It is therefore evident that common and cheap effective adhesives such as superglue and araldite can be beneficially used to join these metals into serviceable structures for some applications but relevant practicable information has been scarcely found from the literatures on operational stress levels of joints with the metals by the adhesives [2, 11, 15, 16].

2. Literature Review

Literature reviews shows that appreciable work has been done by many researchers on stress analyses of adhesively bonded joints of a number of materials using several analytical methods of calculating stress distributions in the joints. For example: stress analysis and failure prediction of adhesively bonded single-lap laminates joints subjected to the tensile loading was conducted by Yinhuan Yang [17] on the basis experimental results and considering five kinds of failure modes. He performed failure prediction of the lap joints with adherent thicknesses of 3mm and 2mm and defect in the adhesive layer under uniaxial tensile loading by progressive failure analysis method. He implemented the numerical analysis of composites adhesive joints in ANSYS Parametric Design Language (APDL) with commercial finite element codes ANSYS. The error of computational and experimental failure loads was 3.0%. Stresses in a standard metal-to-metal adhesive-bonded lap joint were analyzed by Adams and Peppiat [18] using a two-dimensional finite-element method. They made comparisons with previous analyses and paid particular attention to the stresses at the ends of the adhesive layer with the adhesive spew treated as a triangular fillet. They found the highest stresses to exist at the adherents' corner within the spew. They also obtained good agreement between some practical results and the finite-element. A local yielding failure criterion was introduced to estimate the static strength of structural single lap adhesive joints under tensile loading by Ibrahim Kocabas *et al* [19]. Their criterion was based on a simple 2D nonlinear elastic-plastic finite element analysis implementing both material and geometrical non-linearity. They found that their predictions based on the proposed criterion had good agreements with similar previous works. The stresses in adhesive bonded Tee joints, subjected to two linear and one bending moment loads were analyzed by W. Li, *et al* [20] using finite element method. They assumed that the adhesive and adherents had linear elastic properties. They also investigated the influences on the stress distributions of the overlap length, adhesive thickness and the fillet of the angle plate. They found that experimental results were in good agreement with those of the finite element analysis.

It is however noteworthy that although stresses and strains, often determined by such linear elastic analysis are useful for general points design purposes, such as seeing trends; accurate failure load prediction is still the most ultimate goal. It is generally regarded that such linear elastic analyses are inadequate to predict joint failure because they generally incorporate some assumptions that may only be approximate but not accurate prediction of the actual attendant stress levels [21].

3. Aim

The aim in this paper was to experimentally have some practicable insights into effects of changing material type and joint design on yield strength as failure criteria using adhesively bonded aluminum-to-aluminum, mild steel-to-mild steel and bronze-to-bronze joints by each of super glue and araldite using the common types of joint loadings.

4. Methodology

DIN 50 125 standard mild steel, aluminum, and bronze samples were used with super glue and araldite to produce the test joints. With the aid of a vice and hack saw each sample was cut at its middle perpendicular to its axis to get pair samples to be jointed. The cut ends of the pairs were further prepared and jointed to form specimen types with configurations shown in Fig 1.

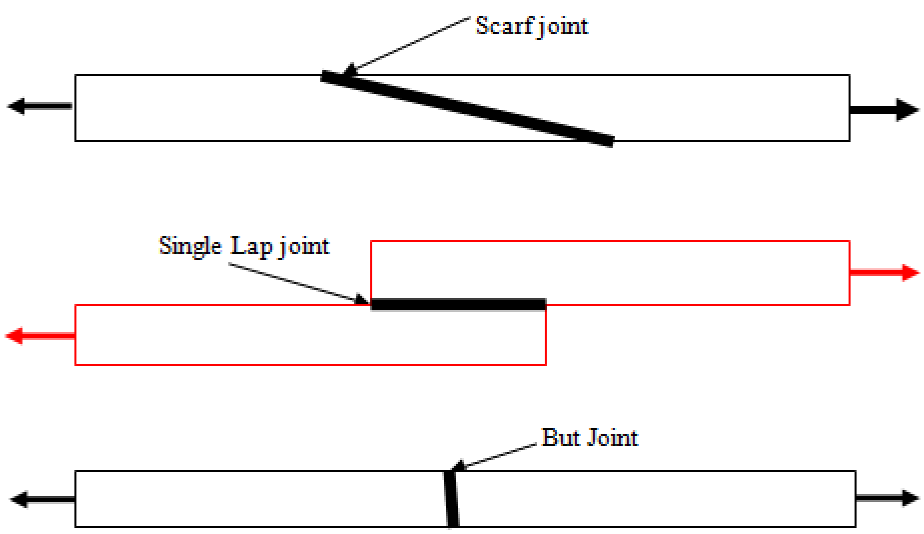

Figure 1: Joint types used for the specimens

Two aluminum pair ends were cut 40^0 inclined to the axis of the samples for 40^0-angle scarf joints. Two steel pair ends were cut 47^0 inclined to the axes of the samples for 47^0-anle scarf joints. Two other steel pairs were left as-cut perpendicular to the axis of the samples for butt joints, and lastly two bronze pairs were cut to form overlap joints. All the cut sample surfaces were then similarly cleaned by abrasion with smooth files followed by the fine 400-grade sand paper, washing with detergent and rinsing with clean water. Fresh ethanol was finally used to clean the surfaces. The clean-dry surfaces to be bonded were then inspected at an optical magnification of 10 using Amazon-made optical glasses to check the presence of any surface finish irregularity that could interfere with the bond integrity of the joint. Where these were observed, the samples were cleaned again and rechecked until satisfactory surface quality was achieved. The aluminum-to-aluminum samples were scarf-jointed by applying a thin layer of super glue adhesive directly from its tube onto the prepared bonding surfaces of the samples and slightly pressing the samples into matching contacts. The steel-to-steel sample pairs were similarly butt-jointed and bronze-to-bronze pairs lap-jointed with the super glue. After bonding, the adhesives were in principle with their manuals allowed to cure for 24 hours at ambient environmental conditions in the laboratory before testing each joint by a similar method. The tests were carried out by carefully assembling the ends of each jointed sample in the threaded chucks of the WP 300 material testing equipment for tension and compression as shown in Plate 1.Varying tensile loads were gradually incrementally applied on the joints through the adherent pairs until the joints failed and corresponding loads noted and strains read from the dial indicator. With the scarf joint of 40^{O}, the adhesively bonded area was elliptical with a major axis of length 9.85mm and minor axis of length 6.00mm and computed area of $\frac{\pi}{4}(9.85)(6.0) = 46.417\text{mm}^2$. The applied stresses were computed as each applied corresponding load divided by the area. With the scarf angle of 47^{O}, the adhesively bonded surface was elliptical in shape with a major axis of length 9.78mm and minor axis of length 6.0mm and computed area of $46.0872 mm^2$. For the butt joint, the bonded area had a diameter of 6mm according to DIN 50 125-sample and computed area of $\frac{\pi}{4}.6^2 = 28.2743\text{mm}^2$. The bronze-to-bronze overlap joint had an overlap length of 3.12mm and6.0mm-width of bonded surface and bonded surface area of 18.72mm^2. The procedure was similarly conducted using araldite. The adhesive was also prepared in accordance with the manufacturer's manual by mixing the resin with the hardener in the recommended mix proportion of 50 parts resin to 50 part hardener and thoroughly stirring to give a white homogenous liquid.

The torsion test was carried out with 6mm-diameter and 233mm-length specimens in accordance to procedure with the testing apparatus. The specimens were similarly prepared and butt-jointed in pairs with each adhesive as in the tension test. The tests were carried out using the DIN WP 100 apparatus for testing deflection and torsion as shown in plate II. The maximum torsion stress ($\tau_{\max}$) from each torsion moment was determined according to the apparatus's manual as;

$$\tau_{\max} = M_t/W_p \quad \ldots\ldots\ldots\ldots\ldots 1$$

Where M_t was the applied torsion moment equal to the product of the applied force (F) and the lever arm length (a) and W_P was the polar modulus of the section area of the specimen and was given by;

$$W_p = \frac{\pi d^3}{16} \ldots\ldots\ldots\ldots\ldots \ldots\ldots 2.$$

$$\tau_{\max} = \frac{16mga}{\pi d^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots 3$$

Where, 'g' was the acceleration due to gravity ($9.81\frac{m}{s^2}$), 'd' was the diameter of the specimen, and 'a' was 100mm. In that way, the torsion stresses and strains (deflections) were determined for each applied torsion moment.

All the obtained sets of results were reported graphically with the respective pair averages for the specimens at each test condition. The reports were used to deduce the yield stresses at the respective yield points. Where ever there was no clear yield point, the yield stress was deduced at the intersection of a 0.2% offset strain line parallel to the linear portion of the actual stress-strain graph and the graph itself [2].

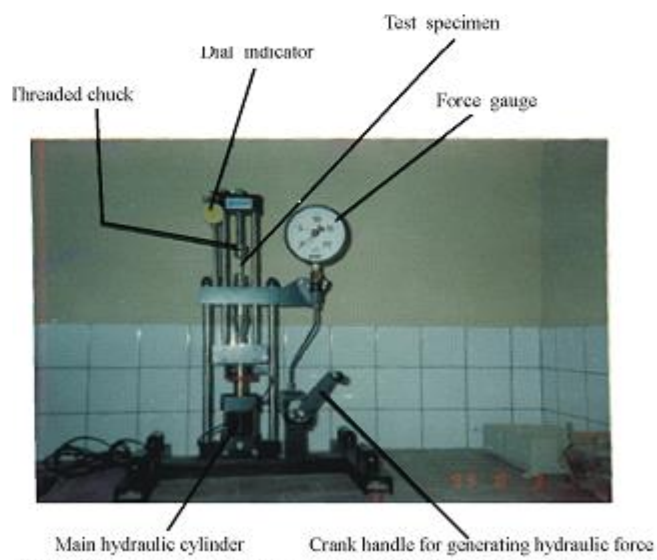

Plate I: Experimental Set up for tension testing on Adhesively borded joint with the WP 300 Apparatus for tension and compression (DIN).

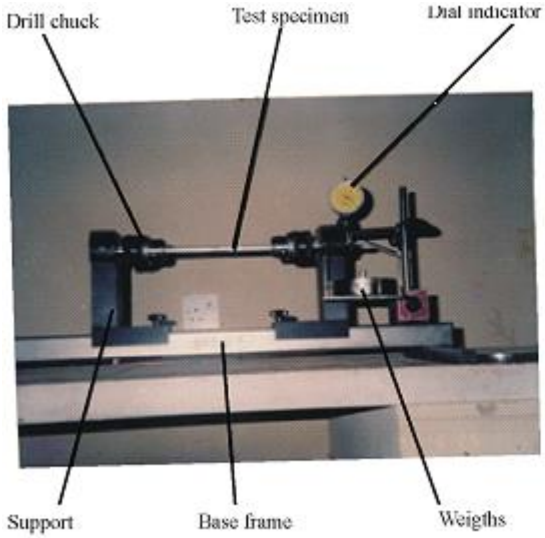

Plate II: Experimental set up for torsion test with the WP 100 apparatus for deflection and torsion (DIN).

5. Results and Discussion

The tension test results as obtained by Allison [2] with the 40^{O}–angle aluminum-to-aluminum scarf joint, 47^{O}-angle steel-to-steel scarf joint, steel-to-steel butt joint, and bronze-to-bronze overlap joint by super glue were as shown in Figs 1, 2, 3 and 4 respectively and by araldite as shown in Figs 5, 6, 7, and 8 respectively. The torsion test results with aluminum-to-aluminum butt joint by super glue, and araldite were as shown in Figs 9 and 10 respectively [2, 3].

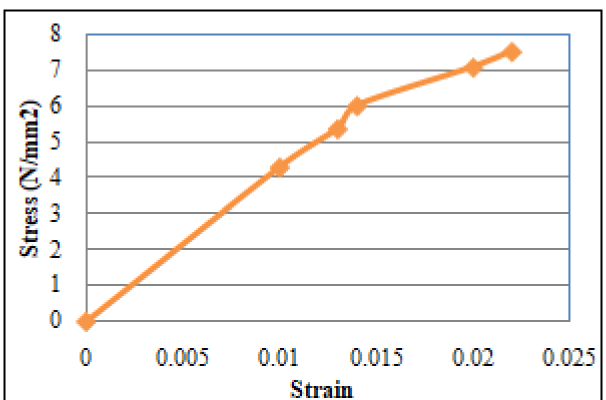

Figure 1: Tension test with 40^{O}-angle aluminum-to-aluminum scarf joint by super glue

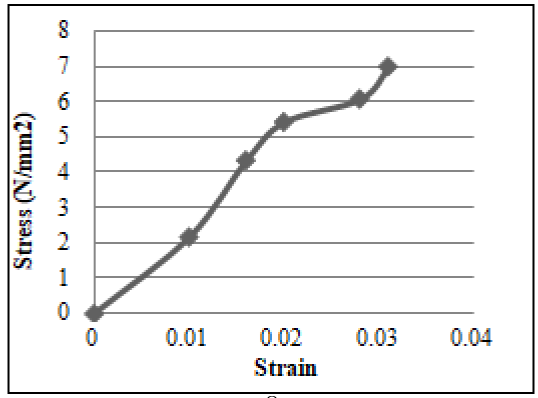

Figure 2: Tension test with 47^{O}-angle mild steel-to-mild steel scarf joint by super glue

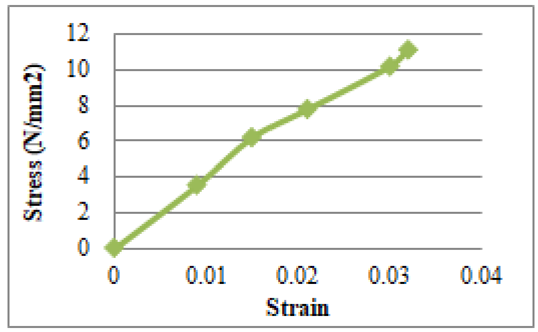

Figure 3: Tension test on steel-to-steel butt joint by Super glue

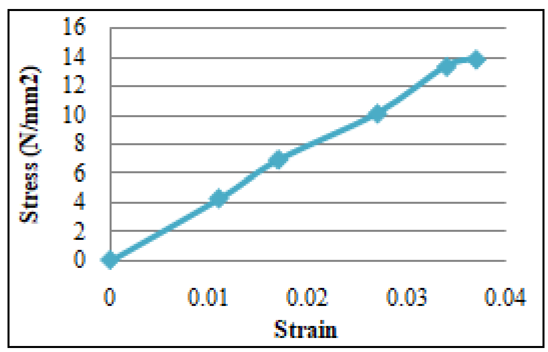

Figure 4: Tension test with bronze-to-bronze overlap jointby super glue

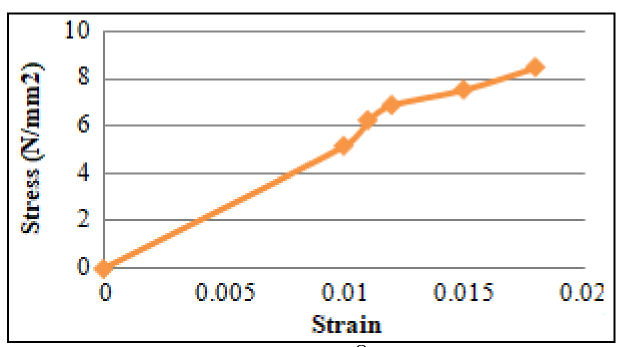

Figure 5: Tension test with 40^{O}–angle aluminum-to-aluminum scarf joint by araldite

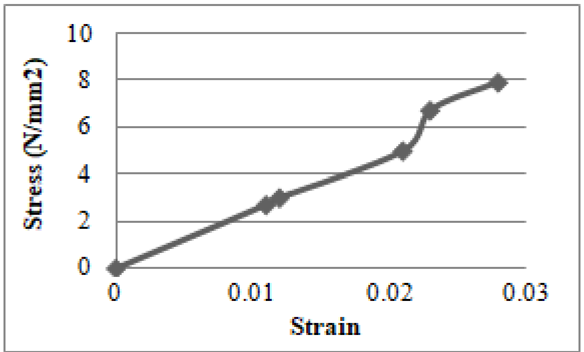

Figure 6: Tension test with 47^{O}-angle mild steel-to-mild steel scarf joint by araldite

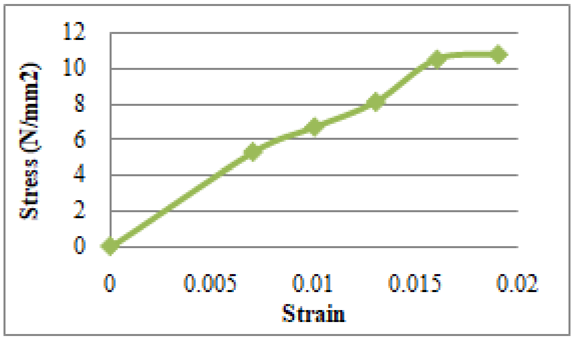

Figure 7: Tension test with steel-to-steel butt joint by araldite

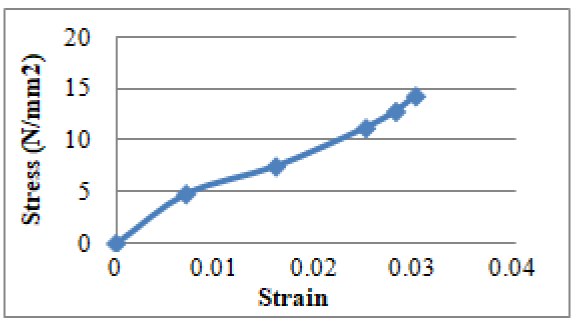

Figure 8: Tension test with bronze-to-bronze overlap jointby araldite

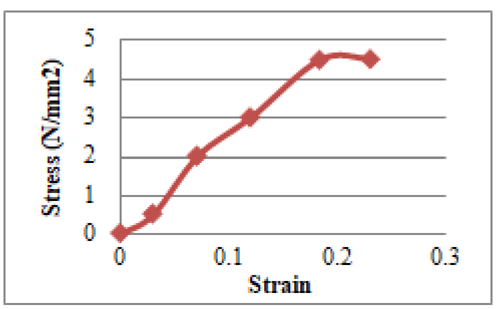

Figure 9: Torsion test with aluminum-to-aluminum butt joint by super glue

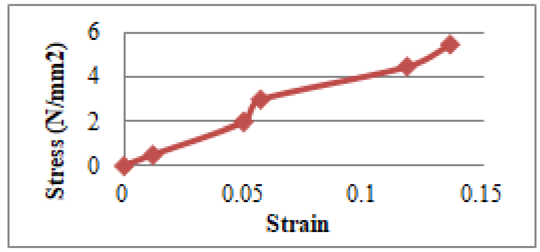

Figure 10: Torsion test with aluminum-to-aluminum butt joint by araldite

6. Discussion of Results

From the tension test results with aluminum-to-aluminum scarf joint by super glue, shown in Fig 1, it can be seen that the stress-strain relationship for the joint was linear from stress of 0 up to 4.20N/mm^2. The joint yielded when the stress reached 7.540N/mm^2.The tension test result with the other joint types showed comparable behaviors with the adhesive as can be observed from Figs 1- 4. From Fig 2, it was apparent that linear relationship existed between stress and strain from stress of 0 to 2.40N/mm^2. Thereafter, the joint yielded at a stress of 6.987N/mm^2.The difference in the yield tensile stresses between the aluminum-to-aluminum scarf joint and steel-to steel scarf joint was attributable to difference in their bonded areas due to the scarf angles of 40^{0}and 47^0 respectively as well as effects of adherent metal makes on adhesion of the adhesives. From results for the steel-to-steel butt joint shown in Fig 3, it can be observed that the applied stress on the joint was proportional to strain from the stress of 0 to 4.20N/mm^2. The joint yielded at a stress of 10.186N/mm^2.For the case of results with the bronze-to-bronze overlap joint shown in Fig 4, the stress values between 0 to 4.25N/mm^2 depicted linear relationship with strain. The joint yielded at a shear stress of 13.462N/mm^2.

The tension test results of joints by araldite shown in Figs 5-8 also exhibited comparable behaviors with one another as can be observed. The 40^0-angle aluminum-to-aluminum scarf joint shown in Fig 5 depicted linear stress-strain relationship from stress of 0 to 5.15N/mm^2. The joint yield-failed when the stress reached a value of 8.488N/mm^2.As can be observed from result for the steel-to-steel scarf joint shown in Fig 6, stress-strain relationship was directly proportional to one another from stress of 0 to 3.10N/mm^2. The joint yielded at a stress of 7.920N/mm^2. From result of the steel-to-steel butt joint depicted in Fig 7, it is also clear that the joint stress was proportional to the applied strain. The limit of proportionality of the relationship was 4.00N/mm^2. The joint yielded at a stress of 10.540N/mm^2. For the bronze-to-bronze overlap joint shown in Fig 8, a linear stress-strain relationship existed from stress of 0 to 4.40N/mm^2.The joint yielded at a stress of 14.316N/mm^2.

From torsion test result with aluminum-to-aluminum butt joint by super glue shown Fig 9, it can be deduced that proportional stress-strain relationship existed from stress of 0 to 1.05N/mm^2. The joint yielded at a shear stress of 4.497N/mm^2.

From results with similar joint by araldite shown in Fig 10, linear relationship existed between stress and strain from stress of 0 up to 1.20N/mm^2. The joint yielded at a shear stress of 5.496N/mm^2.It is thus clear from the foregoing that the yield shear strength values are much smaller than 7.540N/mm^2 and 8.488N/mm^2 for the tension tests of the same joint type by super glue and araldite respectively. This is a presupposition that the joints are stronger in tension than in torsion.

Guma [22] studied experimentally the strength characteristics of 1mm-diameter 40^O-scarf-jointed aluminum-to-aluminum wires with araldite using the same DIN WP 300 testing facility for tension and compression, and the DIN WP 100 facility for testing deflection in torsion. The joint strengths he obtained for both cases indicated strong and reliable joint for medium and low stress applications only compared to the original strength of the aluminum wire. The joint was found to be stronger in tension with yield strengths of 32.72N/mm^2 and weaker in torsion with yield strength of 10.2N/mm^2. It can thus be appreciated that the strengths of the 1mm-diameter 40^O-angle scarf-jointed aluminum-to-aluminum wires with araldite in tensile and torsion loadings were much greater than our respective values of 8.488N/mm^{2}and 5.496N/mm^2 from the 40^O-angle scarf-jointed aluminum-to-aluminum with the DIN 50 125 and the 6mm-diameter samples of the metal. This apparently presupposes that increase in diameter or dimensional sizes of the jointed metal structures with the adhesives will decrease their fracture strengths and vice versa.

7. Concluding Remark

The consequences of changing geometric and material parameters on the stress and strain distributions within the adhesive layer and consequently the load bearing capacity of a joint were recognized. The yield failure criterion was used to determine experimentally when a critical level of stress or strain is reached in the adhesive to initiate rupture of a sample of common similar metal joints of three common metals-mild steel, aluminum and bronze by two widely available cheap adhesives-super glue and araldite. DIN 50 125 standard samples of the metals were systematically used to make 40^0-angle aluminum-to-aluminum scarf joints, 47^0-angle steel-to-steel scarf joints, steel-to-steel butt joints and bronze-to-bronze overlap joints using separately each adhesive according to its manual. Results from the tension test of the joints by super glue indicated contrasting adhesive yield strengths for the joints as 7.540N/mm^2, 6.987N/mm^2, 10.186N/mm^2 and 13.462N/mm^2 respectively. The corresponding values with joints by araldite were 8.488N/mm^2, 9.920N/mm^2, 10.540N/mm^2 and 14.316N/mm^{2}respectively. Results from torsion tests with 6mm-diameter butt-jointed aluminum-to-aluminum rod samples by super glue, and araldite indicated comparatively lower yield strengths of 4.497N/mm^2 and 5.496N/mm^2 respectively in comparison to the values by tensile loading of the lap joint. Correlation with previous research results by Guma [22] evidently show that increase in diameter or dimensional sizes of the metals will decrease the fracture strength of the joint types by the adhesives and vice versa. The results provide some practicable design or research information for consideration on tensile or torsion loading of the metal joints by the adhesives.

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