Towards enhancing peel strength of adhesively bonded joints

W Ameen, S M Darwish and A AlSamhan
Industrial Engineering Department, Advanced Manufacturing Institute King Saud University, Saudi Arabia
E-mail: Darwish@ksu.edu.sa

Abstract. The evaluation of strength as well as failure behavior of adhesively bonded structures is essential to further improvement of their applicability. Since adhesively bonded structures are very poor in resisting peel loading, designers of these joints usually avoid subjecting these structures to peel loadings. However, in some circumstances, designers fail to avoid peel stressing in their designed structures. The aim of the present work is to enhance peel resistance of adhesively bonded structures in order to confront inevitable situations that bonded structures are subject to peel loading, without adding extra weight to the design.

1. Introduction

It is found that strength and failure behavior of adhesively bonded structures depend much on mechanical properties of adhesive material and stress concentration in bonded structures [1]. Usually, adhesive manufacturers offer a wide range of adhesives with variable mechanical properties. However, the selection of an adhesive depends on the materials to be bonded (adhered), surface treatment methods, bonded structures, working environment and types/magnitude of applied loads. Moreover, stress distribution plays a significant role in achieving a strong adhesive bonded structure.

Peel testing allows users to understand the strength of adhesive structures and evaluate joint strength, such as maximum and minimum peeling forces and average peel force. Peel resistance, which refers to the required load to peel bonded adherent parts, can be calculated as average peel load per bond line width dimension [2]. According to ASTM D1876-01 Standard Test Method [2], average peeling force per unit width is issued to measure the peel strength. The average peeling is taken from the force-displacement diagram after the initial peak reading. It has been found that adding fillers to the adhesive mastic results in a change in the composite material properties (mechanical, physical and chemical properties). Nowadays, Nano fillers become more attractive to many researchers, due to its great improvement in composite material properties compared with other fillers due to their small size and large surface area. Nano-reinforcements are able to provide unique combination of properties, which cannot be reached for conventional fillers in micrometer range size. Hence, it is possible to design the adhesive in the Nano scale by adding nanoparticles such as nanoclays, carbon nanotubes (CNT) or carbon nano fibers (CNF) and others in the adhesive matrix [3]. Due to the large surface area of the nano-sized particles, only a small amount can lead to significant changes in the resulted properties of the nano-composite adhesives [3]. The effect of adding nanoclay to epoxy adhesive on shear strength was investigated, using single lap joints. Different percentages (1%, 3% and 5%) of nanoclay filled epoxy adhesive were tested, under both static (tensile) and dynamic (impact) loadings. The results showed that the adhesive joints with 1% nanoclay particles had the maximum shear loadings. It was found 7% strength enhancement compared with plain adhesive results [4].
Experiments were conducted to study the enhancement of joint strength by adding zirconia nanoparticles to epoxy matrix [5]. Three percentages of nanoparticles are considered, i.e., 0.5%, 1% and 1.5%. The tests showed that the mechanical properties improved with the percentage of zirconia nanoparticles increasing up to 1% and declined with the percentage further increasing to 1.5%. Similar studies were carried out for the strength enhancement by adding alumina nanoparticles to epoxy adhesives [6] using four percentage levels (0.5%, 1%, 1.5% and 2%). The results found that the alumina nanoparticles improved the shear strength of the bonded joints by 60%, at optimal filler percentage of 0.5%. In order to investigate the effect of adding carbon nanotubes on the strength of epoxy resins, different studies have been conducted. Bonded similar substrates of carbon/carbon (C/C) and carbon/carbon-silicon carbide (C/C–SiC) composites using pure epoxy resin and 3% filled adhesive of multiwall carbon nanotubes (MWCNTs) were used to study the strength enhancement of overlap joint. The experimental results showed that the MWCNT filled epoxy resin bonded C/C–C/C and C/C–SiC–substrates have a higher strength than those bonded with plain epoxy adhesive. Furthermore, it has been reported that the overlap joints having dissimilar adherents (C/C–SiC) provide higher bonding strength compared with similar adherent substrates (C/C) for both plain and MWCNTs filled adhesives, since particles loaded composite materials increase the toughness and resist the formation of cracks [7]. The effect of MWCNTs filled adhesive Epoxy 862 with four levels of percentages on joint strength is also studied. The four levels of percentage are 0.1, 0.2, 0.3 and 0.4%. From the overall experimental results, it is clearly observed that the joint strength reaches the maximum with 0.3% of MWCNTs with 26% strength enhancement [8].

According to the above literature, it was observed that most of the research was carried out for enhancing only the shear resistance of single overlap joints. For this reason, the current study will focus on enhancing T-peel strength using MWCNTs filled adhesive, in order to prepare adhesively bonded joints to cope with inevitable peel loadings.

2. Strength of adhesively bonded T-peel joints
Several research works have been conducted to investigate the effect of T-peel joint geometry (e.g., adhesive thickness, adherend thickness, flange radius, and spew fillet) on enhancing the peel strength. Matsui [9] compared the peel strength of T-peel joint with different bonding line adhesive thickness. The results pronounced an increase in strength of the peel joint with the increasing bond line thickness (adhesive layer thickness).

Numerically the effect of joint geometry and properties (adhesive fillet, adherend thickness, flange radius and adherent material properties) on different Von Misses stress distribution within the adhesive layer were considered in the study [10]. The parametric investigation showed that Von Misses, peel and axial stress concentration increase with the decrease of adherend thickness, adhesive fillet and adherend material stiffness. In addition, it has been found that the effect of flange radius is less pronounced [10].

The finite-element analysis was conducted to evaluate the effect of adherend thickness dissimilarity on the peel strength of spot-welded and weld-bonded T-peel joint. The finite element (FE) model assumes isotropic adhesive materials, cohesive failure mode, while neglecting the adhesive contact boundary condition. The results show that dissimilarity of thickness magnifies the stress concentration located at the boundaries of the weld nugget. Furthermore, the stress concentration located in the thinner adherends of the joint is higher than that in the thicker adherends. The introduction of an adhesive layer between dissimilar thickness joints, with the spot weld nugget results in the improvement of the peel strength of spot-welded through reducing the associated level of stress concentration (by nearly 84%) [11].

Numerical methods were also used to study the effect of spew fillet ratio ((f/RO)×100) (0, 25, 50, 75 and 100%), on the T-peel joint stiffness. The results show that the spew fillet parameter of T-peel joint has a significant influence on the T-peel stiffness. For example, it has been found that the T-peel stiffness increases by 11 times for 100% spew fillet ratio compared with non-spew fillet model using modified shell solid element [12]. Based on the literature review, the following conclusions can be
drawn:

- Peel resistance of the bonded and weld-bonded joint is very low.
- Little attention has been paid to strengthening the peel strength for bonded joints.
- Mixing nano particles or nano carbon tubes with plain adhesive results in the enhancement of shear strength of bonded joint.

The current research focuses on the enhancement of peel strength of adheavely bonded 2024 aluminum alloy joints. The technique covers introducing carbon nano-tubes to plain adhesive for performance enhancement of T-peel bonded joints.

3. Experimental work

3.1. T-peel specimens

The peel specimens of the present work were manufactured according to ASTM [D1876-01], as shown in figure 1.

![Figure 1. T-peel specimen ASTM [D 1876-01].](image)

3.2. Peel joint substrates preparation

Aluminum alloy of grade 2024-T3 was used for the experimental study. This alloy provides high ratio of the strength to weight and good fatigue performance, so it is often used for aircraft body structure especially fuselage and wing structures [13]. The chemical composition of the specimens is obtained using spectra machine as listed in table 1.

![Table 1. Chemical composition of aluminum alloy (2024-T3).](image)

| Component | Al  | Cu  | Mg  | Fe  | Other |
|-----------|-----|-----|-----|-----|-------|
| Wt.%      | 93.1| 4.45| 1.45| 0.136| 0.864 |

The T-peel joint adherents were manufactured with thickness of 1.6mm and flange radius of 6mm [1].

3.3. Plain adhesive bonded specimen preparation

The specimens having unfilled adhesive were prepared by washing the bonding contact surfaces with distilled water, and then polished with 200 and 400 grade abrasive papers, and finally wiped by an acetone agent to remove any pollutants [14, 15]. Epoxy adhesive (type Araldite 2011) was selected for the current study based upon its performance [15-17]. The adhesive was prepared by manually mixing the resin and hardener with weight ratio of 100:80, respectively [15]. In order to ensure a uniform thickness (0.3 mm) of applied adhesive layer, a special fixture (adhesive applying fixture, see figure 2) was designed and manufactured using CNC milling machine.
After applying the adhesive on the surfaces of the metal substrates, the specimens were held in the suitable position until the adhesive bonded joint was safe for handling (2 hours) using holding fixture.

Finally, the specimens were transferred to the oven for curing purpose. The curing temperature and time were set according to the manufacturer recommendations, that is, 120 °C and 60 minutes, respectively [15, 17], and figure 3 shows the prepared T-peel joint.

3.4. MWCNT filled adhesive specimen preparations
In the present work, MWCNT was used to enhance the strength of T-peel bonded joints with varying percentages (0, 0.1, 0.4, 0.5, 0.6 and 1%) of MWCNT adhesive, and tensile test facility was utilized to prepare and test them in order to allocate the optimum percent of MWCNT adhesive that ensures the highest joint strength. Tensile test was carried out for Aluminum alloy 2024-T3, specimen having plain epoxy adhesive and MWCNT filled adhesive in order to obtain the mechanical properties.

MWCNTs were obtained from Hanwha Nanotech Corporation with average diameter of 9.5 nm and length of 1.5 μm of 99% purity. Different percentages of MWCNTs were respectively mixed with adhesives to obtain the optimum strength enhancement of T-peel joint. Figure 4 shows the scanning electron microscope (SEM) image of MWCNTs.

The adhesive resin is mixed with MWCNT, for 5 minutes using electric shock device in order to ensure uniform distribution of the MWCNTs on the surface of resin. Furthermore, to achieve a homogenous mixture, a magnetic stirrer was used to steer the mixture for 10 hours, at 200 rpm at a
temperature of 50 °C. It is worth noting that the mixing procedure with MWCNTs was established when adhesive temperature increased to 50 °C.

The hardener resin was added to it and then mixed manually to obtain the required adhesive mixture to be used for the T-peel joints. Optical microscope was used to inspect the homogeneity of MWCNTs distribution on adhesive (see figure 5).

Based upon the literature review [4, 8], MWCNT mixing percentages were selected as follows: 0.1%, 0.4%, 0.5%, 0.6% and 1% of adhesive weight.

3.5. Adherends and adhesive materials properties

The mechanical properties of both adherends and adhesive materials are evaluated in order to measure their specifications. The mechanical properties of sheet metal 2024 Aluminum were obtained through tensile testing according to ASTM standard E8-S1 (cutting along rolling direction) in order to be tested on Instron Tensile test Machine (see figure 6 and table 2).
Figure 6. ASTM standard E8-81 tensile test specimens.

Table 2. Tensile test specimen dimensions.

| Symbols | Description                      | Dimension |     |
|---------|----------------------------------|-----------|-----|
| L       | Overall length                   | min 200   |     |
| A       | Length of reduced section        | min 57    |     |
| G       | Gage length                      | 50±0.1    |     |
| W       | Width                            | 12.5 ± 0.2|     |
| B       | Length of grip section           | min 50 [2]|     |
| C       | Width of grip section            | 20 [0.750]|     |
| R       | Radius of fillet                 | min 2.5 [0.500]| |
| T       | Thickness                        | thickness of material | |

Five standard specimens were prepared and tested to obtain the average mechanical properties values. The experimental stress strain curves and measured material properties are shown in figure 7 and table 3, respectively.

Figure 7. The stress strain curves for five samples.
Table 3. Measured mechanical properties of aluminum alloy 2024-T.

| Material Code | Peak Load (KN) | E-Modulus (MPa) | Yield Point (MPa) | Ultimate Tensile Stress (MPa) | Mass Density (g/cm³) | Tangent Modulus MPa Et |
|---------------|----------------|-----------------|-------------------|-----------------------------|----------------------|------------------------|
| AA2024-T3     | 9.72           | 73.100          | 358.16            | 486.12                      | 2.78                 | 830.0                  |

3.6. Mechanical properties of plain and MWCNTs filled epoxy adhesive materials

In order to measure the properties of the used adhesive materials (Araldite 2011), standard ASTM D3763 tensile test specimens with overall dimensions (127×12.7×4 mm and gauge length 25 mm) were fabricated using specimen casting method, where a dumbbell-sharp cutter was used for manufacturing the mold cavity from wax (see figure 8).

![Figure 8. Dumbbell-sharp cutter metal tool and wax cavity.](image)

The cast specimens were then placed in an oven in order to melt the wax and to achieve the curing time required by adhesive material. The cured specimens were then subject to tensile testing in order to obtain the mechanical properties of the adhesive; the results are shown in figure 9 and table 4.

Figure 10 shows the tensile test specimen for MWCNTs filled adhesive with 0.5% percent composition. The results obtained from Instron tensile machine are shown in figure 11 and table 5.

![Figure 9. Stress strain curve of plain adhesive obtained from Instron machine.](image)

Table 4. Mechanical properties of plain adhesive.

| Peakload (KN) | E-Modulus (MPa) | Yield Point (MPa) | Ultimate Tensile Stress (MPa) | Mass Density (g/cm³) | Tangent Modulus MPa Et |
|---------------|-----------------|-------------------|-----------------------------|----------------------|------------------------|
| 1.16          | 437.5917        | 16                | 36.73                       | 1.0350               | 188.2                  |
The peak peel load increased from 1.16 KN to 1.97 KN in case of MWCNTs filled adhesive compared with plain adhesive results. Furthermore, it was reported that the yield strength also increased from 16.0 MPa in case of plain adhesive to 34.63 MPa in case of MWCNTs filled adhesive.

3.7. Strength measurement of the plain and MWCNT filled joints
To ensure the consistency of the results, tests were repeated three times, for each case, Instron Tensile testing machine (Series 3369H) with load capacity up to 50 KN was used for peel testing of all experiments. The tests were carried out at a crosshead speed of 5 mm/min as recommended [13]. Figure 12 shows the T-peel joint test setup on the Instron Machine and the experimental results analysis with provided software (Bluehill® 2).

Figure 13 shows the cohesive failure of T-peel bonded joint, while figure 14 shows the load displacement plots for three tests specimens.

4. Results and discussions
From figure 14, it can be observed that the average of 3 peak loads of the three samples is 300 N. The average peeling load is 52.3 N and the peel strength is 2.08 N/mm. (After being divided by bonding
line width, is used to obtain the T-peel strength. The same procedures and preparation conditions were followed to evaluate MWCNTs filled adhesive T-peel bonded joints.

![Figure 12. T-peel test setup.](image)

![Figure 13. Tested specimen after peel test.](image)

![Figure 14. Load displacement curves for three plain adhesive bonded peel joints.](image)

Table 6 shows the recorded values of the T-peel strength for unfilled and filled specimens with different MWCNTs percentages.

One-way ANOVA was used to show whether different MWCNTs percentages have significant effects on the peel strength or not. The data has been tested and successfully verified for normality as shown in figure 15. From ANOVA results (figure 16), it has been observed that MWCNTs percentages significantly affect peel strength (p-value = 0 < 0.05).
In order to determine the optimum percentage of MWNCTs that provides the highest peel strength, average strengths were calculated and plotted as shown in figure 17. It can be observed from this figure that T-peel strength increases with the increase of MWNCTs percentage up to 0.5%, and then decreases when the MWNCTs percentage further increases. It is worth mentioning that the trend obtained in the experimental results is identical to what was reported in literature [8].

It can be also observed that addition of 0.5% of MWCNTs has resulted in 23% increase in peel strength T-peel joints with MWCNTs filled adhesive.

Table 6. Peel strength T-peel joints with MWCNTs filled adhesive.

| MWCNTs Percentage (%) | T-peel joint strength N/mm |
|------------------------|----------------------------|
|                        | Sample 1 | Sample 2 | Sample 3 |
| 0 (Plain adhesive)     | 2.084    | 2.144    | 2.016    |
| 0.1                    | 2.268    | 2.192    | 2.220    |
| 0.4                    | 2.300    | 2.336    | 2.364    |
| 0.5                    | 2.596    | 2.548    | 2.564    |
| 0.6                    | 2.504    | 2.492    | 2.484    |
| 1                      | 2.380    | 2.292    | 2.388    |

Figure 15. Residual plots for peel strength.

Figure 16. ANOVA test results.
The peel strength of bonded joints of 2024 aluminum alloy. The method covers application of carbon nano-tubes filled adhesive on T-peel bonded joint. It is worth noting that mixing 0.5% MWNT with adhesives enhances the strength of the T-peel joint without increasing the structure weight. The average-peeling load for the MWNTs filled adhesive T-peel joint increases by 23% compared with plain adhesive joints.

Acknowledgments
The project was financially supported by King Saud University, Vice Deanship of Research Chairs.

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