



**FAILURE INVESTIGATION OF T-JOINT BONDED WITH
HYSOL E-214 HP UNDER ELEVATED TEMPERATURE**

by

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LIST OF ABBREVIATIONS

FE	Finite Element
FEM	Finite Element Method
FEA	Finite Element Analysis
UTM	Universal Testing Machine
ASTM	American Society for Testing and Materials
ISO	International Standards Organization
RT	Room Temperature
DCB	Double-Cantilever Beam
SLJ	Single Lap Joint

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LIST OF SYMBOLS

ε	Strain
E	Young's modulus
T_g	Glass transition temperature
ν	Poisson's ratio
l	Length
T	Temperature
t	Adhesive thickness
ε	Tensile strain
A	Cross-sectional area (m ²).

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Penyiasatan Tentang Kegagalan Hubungan Perekat Bersendi-T Menggunakan Hysol E-214 HP Pada Suhu Ternaik

ABSTRAK

Katil lapisan terbendalir merupakan komponen utama bagi sistem penghasilan baja di dalam loji baja. Sejak kebelakangan ini, kimpalan adalah sambungan biasa yang digunakan untuk memasukkan plat tertebuk ke struktur rangkanya. Walau bagaimanapun, teknik ini boleh mengakibatkan kegagalan kerana suhu operasi yang tinggi semasa proses penghasilan baja. Isu ini telah menyebabkan mesin penghasilan baja dihentikan operasi seketika dan hal ini mengganggu proses pengeluaran baja. Oleh itu, kajian telah dijalankan untuk membangunkan teknik penyambungan alternatif dengan menggunakan ikatan perekat yang dapat menahan suhu operasi pengeluaran baja. Secara umum, teknik ikatan perekat telah menunjukkan keupayaannya sebagai kaedah alternatif kepada sambungan konvensional seperti perivetan, kimpalan dan pengikat mekanikal dalam pelbagai aplikasi. Perekat yang digunakan untuk aplikasi struktur perlu menunjukkan keupayaan suhu tinggi untuk mengekalkan sifat mekanik mereka pada suhu operasi yang dikehendaki iaitu 95 °C. Di samping itu, perekat perlu cukup kuat untuk mengikat plat tertebuk. Tujuan penyelidikan ini adalah untuk mengenal pasti sifat-sifat mekanik perekat yang mempunyai rintangan suhu yang baik sambil memberikan kekuatan ikatan yang tinggi kepada perekat bersendi-T. Untuk tujuan ini, kesan ketebalan perekat pada kekuatan perekat bersendi-T pada suhu tinggi telah dianalisis. Di samping itu, struktur bersendi-T dimodelkan, disimulasikan dan dianalisis untuk penilaian tegasan bagi meramalkan kekuatan perekat bersendi-T pada ketebalan pelekat yang pelbagai. Ujian tegangan dilakukan untuk mendapatkan sifat mekanikal bahan perekat (modulus Young, tegangan alah dan lengkung tegangan-terikan) yang dibuat dalam bentuk spesimen pukal. Suhu ditetapkan dalam lingkungan suhu bilik hingga 125 °C. Lima sampel perekat bersendi-T dengan ketebalan perekat yang berbeza juga diuji tegangan menggunakan mesin ujian semesta pada suhu tinggi untuk memperoleh kekuatan perekat sendi-T. Berdasarkan hasil eksperimen, 0.5-1.0 mm adalah ketebalan perekat yang berkesan untuk perekat bersendi-T pada suhu antara suhu bilik hingga 125 °C. Kekuatan bersendi-T tertinggi ialah 1.500 MPa diperoleh pada suhu bilik selepas merujuk kepada semua julat ketebalan perekat. Kekuatan sendi-T sedikit berkurangan dari suhu bilik hingga 100 °C. Walau bagaimanapun, kekuatannya berkurangan dengan ketara pada suhu 125 °C dengan nilai purata 1.065 MPa. Berdasarkan keputusan yang diperoleh, menunjukkan bahawa suhu dan ketebalan perekat bersendi-T adalah parameter utama yang mesti dipertimbangkan dalam reka bentuk perekat bersambung. Ramalan unsur terhingga untuk kekuatan bersendi-T adalah dalam persetujuan yang baik dengan keputusan eksperimen bagi kegagalan tegasan. Atas dasar ini, adalah disyorkan bahawa perekat ini adalah penting untuk digunakan dalam plat tertebuk dalam katil lapisan terbendalir. Kajian lanjut boleh dilakukan untuk mengenalpasti faktor-faktor lain yang menyumbang kepada kekuatan bersendi-T untuk memilih perekat terbaik bagi aplikasi penyambungan plat tertebuk.

Failure Investigation of T-Joint Bonded with Hysol E-214 HP Under Elevated Temperature

ABSTRACT

Granulator fluidization bed is a main component of fertilizer granulator system for the fertilizer plant. In recent cases, welding joint is the regular joint that used to affix the perforated plate to its frame structure. However, this technique can lead to joining failure due to high operating temperature during the production process. This issue also caused the granulator to shut down and interrupted the fertilizer production process. Thus, the investigation of the present work was intended to develop an alternative joining technique by using adhesive bonding that can withstand the fertilizer production operating temperature. In general, adhesive bonding technique has shown its capability as an alternative to the conventional joining method such as riveting, welding and mechanical fastening in various applications. The adhesive used for structural application needs to exhibit high-temperature capabilities in order to maintain their mechanical properties for the intentional service temperature of 95 °C. In addition, the adhesive needs to be strong enough to adhere the perforated plate. The aim of this research is to identify the mechanical properties of adhesive that has good temperature resistance while providing high bond strength to the adhesive T-joint. For this purpose, the effect of the adhesive thickness on the strength of adhesive T-joint at elevated temperatures was analysed. Additionally, the T-joint structure were modelled, simulated and analysed for stress assessment to predict the strength of adhesive T-joint at the various adhesive thickness. The tensile tests were conducted to obtain the mechanical properties of the adhesive (the Young's modulus, the yield stress and the stress-strain curve) that was fabricated in the shape of bulk specimens. The temperature was set within the range of room temperature (RT) to 125 °C. Five samples of the adhesive T-joint with different adhesive thickness were also tensile tested using universal testing machine at elevated temperature to acquire the adhesive T-joint strength. Based from the experimental outcomes, 0.5-1.0 mm is an effective adhesive thickness of adhesive T-joint for temperature ranging from RT to 125 °C. The highest T-joint strength of 1.500 MPa was obtained at RT would refer to all ranges of adhesive thicknesses. The T-joint strength was slightly decreased from RT until 100 °C. However, the strengths reduced significantly at temperature 125 °C with the average value of 1.065 MPa. The presented results indicate that the temperature and adhesive thickness of T-joint are the key parameters that must be considered in the bonded joint design. The finite element prediction for T-joint strength is in good agreement with the experimental failure stress results. On this basis, it is recommended that this adhesive is significant to be applied in perforated plate in fluidization bed reactors. Further research could be undertaken to identify other factors which contribute to T-joint strength in order for selecting the best adhesive for application of perforated plate joining.

CHAPTER 1 : INTRODUCTION

1.1 Background of the study

Historically, mechanical joining techniques involved nails, screws, bolts and rivets, while adhesive bonding inadequate compared to normal adhesive for binding the book, paper, woodworking, and packaging process (Robert D Adams, Lucas, & Andreas, 2011). The glue is based on the animals, rubber from the wood and tree resins. In 19th-century in Europe, due to the technical and systematic interest, the adhesion properties were improved by the researcher. Trial and error experimentation for bonding development was researched to obtain the empirical evidence results. From years to years, many innovations for adhesive have been developed due to the rises in demand for the adhesive joint application.

1.2 Introduction to adhesive bonding

There will be established intermolecular forces between two substances. This force is called adhesion process (Robert D Adams et al., 2011). By definition, the adhesive could be explained as a material which when coated into surfaces of materials is able to join them together and oppose separation. Adhesives produce from synthetic polymers have been familiarized since 1900. Nowadays, there are many burgeoning fields, including industrial, aerospace, vehicle, metallic and fusion that uses of adhesives and sealants. It is hard to envisage manufactured goods in the household, industry, transportation, or anywhere else for that matter that does not use the adhesives

in some way. On the other hand, it is required knowledge in various sciences field to achieved desirable outcomes dealing with the adhesive bonding technology (Petrie, 2000).

Besides that, all industries are more interested to use adhesive bonding due to its advantages compared to another joining technique. The advantages are high strength to weight ratio, the stress distribution is uniform, the stress concentration is reduced, design flexibility, a high load-carrying potential provided by a larger load-bearing area, damage tolerance, shock loads absorption and fatigue resistance (Akhavan-Safar, da Silva, & Ayatollahi, 2017; Armstrong, 1997; Dorn & Liu, 1993). This is the main reason why adhesive joint is preferable to use.

In contrast, the used of riveting only limited for lap joints, costing to make drilling for bores and rivets, leave the effect into structure materials. The weight of the structural material and preparation costs also increases by using welding in joining application (Kožuh, Kralj, & Cvirn, 1997). In addition, some application is not suitable for welding technique such as aircraft fuselage manufacturing. The part is made from alloy AlZuMgCu that is more suitable for adhesive bonding. Else, there are no limitations for type of joint that can be applied the adhesive joint such as single lap joint, T- joint and butt joint.

Sometimes, materials or parts were operated in high-temperature, high-pressure, high speed or highly- erosive environment. Thus, the adhesive behaviour towards the applied situation needs to be characterized in order to get a properly designed joint.

Another important parameter that needs to be emphasized is the effect of the adhesive thickness at the different temperatures on the joint strength (Harris & Fay, 1992).

Updated sealants and adhesives would be the accredited key for attaining targets of worldwide sustainability through developments in polymer science and technologies, developments in multi-component formulations and hybrid, innovative equipment and curing techniques. Nonetheless, the effect of the temperature on the adhesive properties change is the main challenge for high-temperature applications. An experimental and numerical approach needed to be researched in order to increase the data for structural engineering application.

1.3 Fluidization Bed Granulation

In a fluidized bed granulation, particulates are constructed by dispersing the liquid binder in powder feeds. Granulator fluidization bed is a main component of the urea granulator system in fertilizer plant to produce granular products for tablet production (Tsujiimoto, Yokoyama, Huang, & Sekiguchi, 2000). Figure 1.1 shows the schematic diagram of urea granulator chamber.

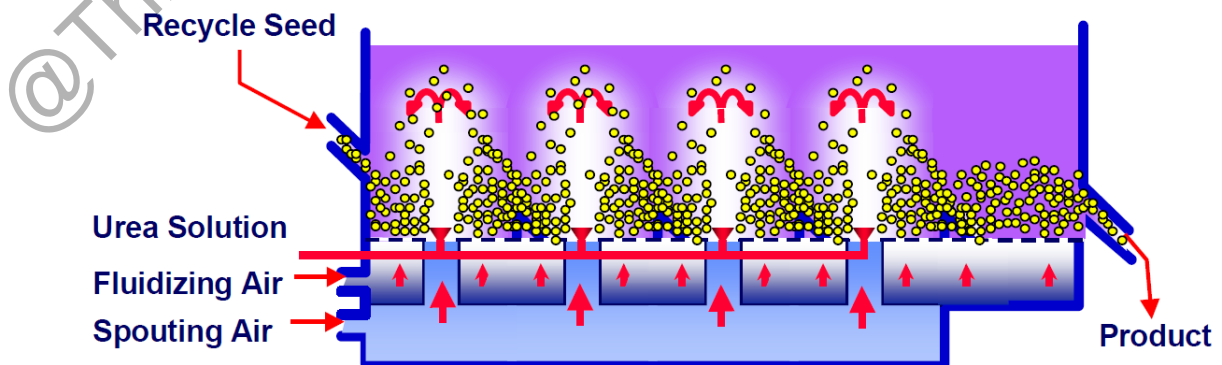


Figure 1.1: Urea granulator chambers (Renato, 2008)

Perforated plate and frame structure are usually held together using spot welding techniques. Nevertheless, this technique has produced an unreliable finished result. Spot welding technique constitute in using specific amount of heat and welding speed to avoid excessive metal melting (304 L Stainless Steel) due to a thin perforated plate, i.e. 1.25 mm. Moreover, fluidization bed is exposed to operating temperature of 95 °C. So, the adhesive used must exhibit high temperature tolerances in order to retain its mechanical characteristics and their structural integrities at the intended services temperature (resist thermal breakdown at elevated temperature).

1.4 Problem Statement

Since 1999, Petronas Chemicals Fertilizer Kedah Sdn. Bhd. (PCFKSB) experienced a lot of granulator upset, mainly due to failure of fluidization bed. In 2009, PCFKSB suffered major setback after perforated plate replacement. In 2011, company loss about RM 8.7 million because of the recurring problem. Each day, during the production of granular urea, fluidization bed operates at temperature of 95 °C. Thus, frequent exposure to the temperature of 95 °C will lead to the failure of fluidization bed. This failure may result in granulator immediate shutdown, which reduces production of urea and requires a welding specialist with high level of skill and experience for this specific application. The perforated plate is very thin that is about 1.25 mm. The welding part is weak due to limited heat that can apply during the welding process. The excessive heat input during welding might resulted in holes.

Figure 1.2(a) shows the perforated plate in good condition while Figure 1.2(b) show the perforated plate lifted off due to the failure of the joint. This issue has to halt

the fertilizer production and inflicts a financial loss to the company. The company needs to hire a skilful welder to repair the lifted off the perforated plate. An alternative jointing technique by using adhesive bonding able to joint dissimilar material, fast and cheap joining technique, eliminates galvanic corrosion, good vibration damping properties, uniform mechanical stress distribution along the joint and good fatigue resistance. Some modification is also needed from the previous study.

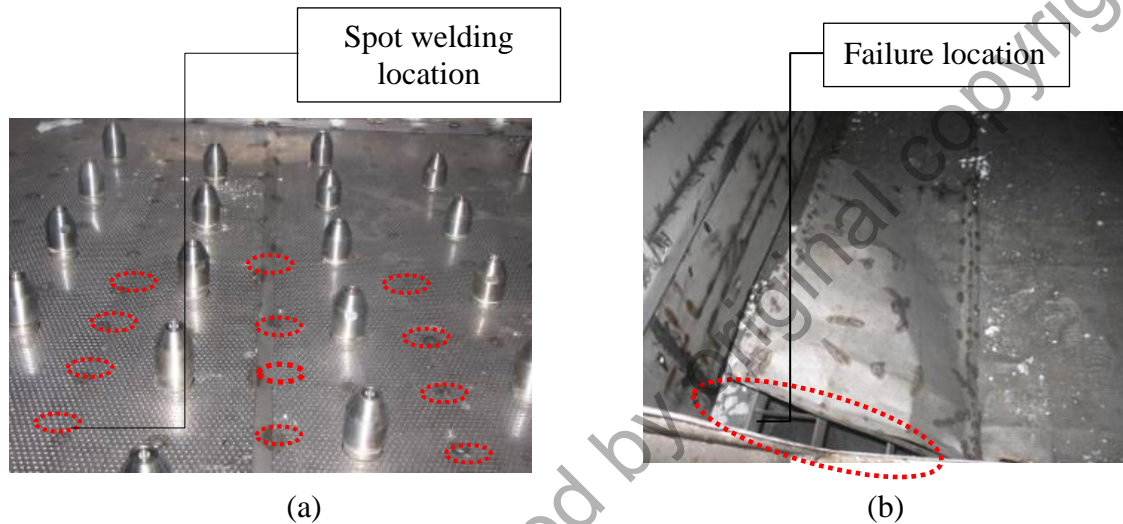


Figure 1.2: (a) Perforated plate in good condition; (b) Perforated plate lifted off due to joint failure

Required load for this specimen also important in order to have load target to aim for. Actual loading in Urea Granulator Fluidization bed was calculated as in Table 1.1. Therefore, target load for this experiment is 963 N or 1000 N for easy reference.

Table 1.1: V-39-01 Granulator force calculation

	L(mm)	W(mm)	Area (mm ²)	Area (m ²)
Area	261	289.5	75559.5	0.07556
Air Pressure (N/m ²)			12747.6	
Force (N)	963.2			

1.5 Research Objectives

The purpose of this research is to discover the adhesive suitability for high-temperature application. The objectives of this research are as follows:

- i) To evaluate the tensile strength of bulk and adhesively bonded T-joints specimens in tension loading at elevated temperatures.
- ii) To analyse the effect of adhesive thickness on the strength of adhesively bonded T-joint at elevated temperatures.
- iii) To predict the strength of T-joint using adhesive joint by finite-element analysis.

1.6 Research Scope

- i) This study focused only on the effect of testing temperature and adhesive thickness towards the strength of adhesives bonding.
- ii) Experiments were conducted with T-joint specimens, fabricated from the perforated plate on the fluidization bed in a fertilizer granulator chamber.
- iii) The material for workpieces used in experiments was 304 L stainless steel.
- iv) The adhesive T-joint were tested at five different temperatures; RT, 55 °C, 75 °C, 100 °C and 125 °C.
- v) The high temperature adhesive used was Hysol E-214 HP.

- vi) The thickness set up for adhesive thickness were 0.5, 1.0, 1.5 and 2.0 mm for the T-joint specimens.
- vii) The strength predictions for T-joint with different adhesive thickness were analysed by finite element (FE) simulation.

1.7 Thesis organization

This thesis was divided into five chapters, namely Introduction, Literature Review, Methodology, Results and Discussion and Conclusion. Chapter 1 covers the detail about the introduction to the project. This chapter discussed about project background, problem statement, and also the scope. Introduction presented giving a confident about the purpose of this study.

Chapter 2 of the thesis presents the review from books, journal, conference paper and other sources was done to support and collecting the detail information. This chapter explored the study of adhesives joint existed in research and commercial sector, focusing on the review of the general adhesive properties, type of material joining, the effect of the temperature on the adhesive properties, the type of the joint failure and the effect of the adhesive thicknesses on the adhesive joint. Furthermore, in-detail comparisons of existing material bonding technique with the adhesive's joint technique were discussed. At the end of this chapter, the review of FE analysis was presented.

The methodology of this study was deliberated in Chapter 3. The experimental procedure and feature analysis technique that being used for this research were described in details. All the specimen preparation method, the equipment and machine,

the testing procedures along this project, and FEA were presented throughout this chapter.

Chapter 4 reported the results and discussion found in this project. This chapter also included the discussion from the obtained results that are already tested by using several equipment such as Universal Testing Machine (UTM). The comparisons between the experimental and numerical results for T-joint were discussed. The last chapter presents the conclusion and the recommendation of this project.

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CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

This chapter reviews the information or knowledge gathered on past researches, problems, current and existing solution regarding this project. Apart from that, the theoretical of adhesive bonding will be discussed. Furthermore, several techniques utilized in anticipating bonded joints failure will be deliberated as well throughout this chapter. Moreover, related literature on FEA approach which using numerical analysis will be explained further in this chapter.

2.2 Adhesive and Adhesion

An adhesive is a material used to hold two surfaces together. An adhesive must wet the surfaces, adhere to the two surfaces, develop strength after it has been applied, and remains stable. Adhesion is specific interfacial phenomena. There are three main theories of adhesion: adsorption, electrostatic and diffusion. The adsorption theory or model explains the phenomenon of adhesion based on concepts such as contact angle, wet ability and surface tension. Meanwhile, the electrostatic theory resembles the phenomenon of adhesion to a condenser, where the electrostatic charges of opposite sign attract each other causing the adhesion between the adhesive and substrate. The diffusion model explains the concept of adhesion by the compatibility between polymers and the movements that occur in the polymer chains.

All probably apply to most adhesives. The raw materials for both naturally occurring and synthetic adhesives are mainly polymeric materials. There is a huge range of adhesives available and appropriate adhesive for the specific materials being joined must be chosen correctly to ensure good adhesion. Synthetic adhesives can be applied quickly, give good adhesion to a variety of substrates, and it also cost-effective. Adhesive bonding offer many advantages but at the same time it has a few disadvantages too. Majors of the advantages and disadvantages of the adhesive bonding are summarized in Table 2.1.

Table 2.1: Adhesive's advantages and disadvantages

Advantages	Disadvantages
The heat does not affect the adherent	Heat limit the stability
The stress is distribute uniformly	The properties of the bond-line may be altered after long-term use
Large surfaces can be possibly joined	In many cases cleaning and surface preparation of the adherents is necessary
Different materials can be possibly joined	Requirements for specific production to must be met
Very thin adherents can be possibly joined	To fix the joint, niche clamping devices are usually required
Does not have crevice corrosion	The testing of non-destructive quality can be carried out to a certain possibility
Does not have contact corrosion	
Excellent damping properties	

2.3 Adhesive Properties

Adhesive property is one of the basic processes in adhesion where it heavily influencing the strength of the joint (Rudawska, 2012). Joint performance (operating environment, load), adhesive type, substrates type, cost, aesthetics, health necessities, application, manufacturing process and pre-treatments are several important aspects in selecting adhesives in the fabrication process. Other than that, testing and validation are required in order to verify process quality (Robert D Adams et al., 2011).

There are many adhesives used in the structural applications such as epoxies, silicones and cyanoacrylates. Table 2.2 presents the selected properties for the different types of adhesive. Epoxies adhesive are temperature resistance and high strength. Silicones are known as an excellent sealant for low-stress application and very high temperature resistance, meanwhile, cyanoacrylates has ability in fast bonding for plastic and rubber but it has poor resistance to moisture and temperature. In general, curing temperature at a specific temperature or at room temperature for certain time is required in order for an adhesive to reach its utmost effectiveness properties.

Table 2.2: Selected properties of adhesives

Type of adhesive	Description	Service Temperature (°C)	Cure (°C)
Epoxy	User-friendly, cheaper, low cure temperature, high strength and heat resistance.	-40-100 (*180)	One part epoxies need to cure at a certain temperature. Meanwhile, epoxies for two parts can be cure at RT or accelerated with temperature curing.
Silicones	Very high temperature resistance, low strength and long cure time, excellent sealant for low stress application, the ability to bond or seal materials of many natures.	-60-300 (350**)	Room temperature
Cyanoacrylates	Poor resistance to moisture and temperature but fast bonding capabilities to rubber and plastic.	-30-80	Fast cure upon exposure to moisture at room temperature (second or minutes)

Note *with different filler material,
**intermittent

American Society for Testing and Material (ASTM) and International Standards Organization (ISO) have been established to analyse and verify adhesive properties via experiment. Throughout this standard, the basic testing of material has been provided. For instance, tensile test, shear tests, compression and dynamic test are the most common methods utilized in determining the adhesives properties. This test is simple and can be measured easily by using a standard testing machine. Z. Chen, Adams, & Da Silva (2011) and I. Basirom, Afendi, Daud, & Majid (2014) have investigated the mechanical properties of an adhesive using bulk tests. From the results,

it can be said that data obtained from bulk tests are true mechanical properties of the adhesive. This is because the bulk is free from any stress concentration.

Fundamentally, elastic material properties, i.e Young's modulus and Poisson's ratio and failure strength are the main parameters acquired from the tensile test. It is notable that as the temperature increases, the mechanical properties of the adhesive, i.e ultimate strength, elasticity modulus, and stiffness are decreased. As the temperature is further increases, it would result in changing of adhesive behaviour, which is from brittle to ductile (Straalen.I.J.v, 2001). This solidified to rubbery transition for adhesive can be related to glass transition temperature.

Numerous studies on the effect of temperature on adhesive behaviour have been conducted. Park & Liechti (2003) has performed a tensile experiment on a urethane structural adhesive at different temperature i.e (50 °C, 60 °C and 70 °C). The experimental results have demonstrated that stress-strain behaviour is dependent on the temperature. Meanwhile, Sharon, Dodiuk, & Kenig (1989) have studied the influence of temperature on the mechanical properties of adhesive. It has been found that the yield stress and modulus decrease with increasing temperature.

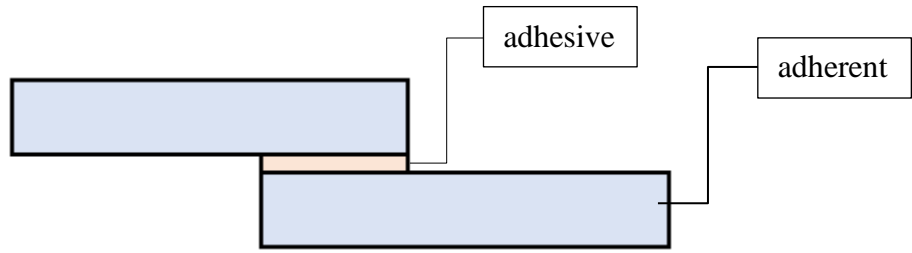
Apart from that, Carlberger, Biel, & Stigh, (2009) has investigated the effect of temperature on cohesive properties of an epoxy adhesive. They reported that the temperature from -40 °C to 80 °C is not affected fracture toughness, where the glass transition of the epoxy adhesive investigated is 90 °C meanwhile the peak stress in peeling loading decreased monotonically with increasing temperature within this temperature range. At glass transition temperature, T_g there is a rapid reduction in both

modulus and strength when temperature increases, and causes the adhesive to no longer carry a substantial load.

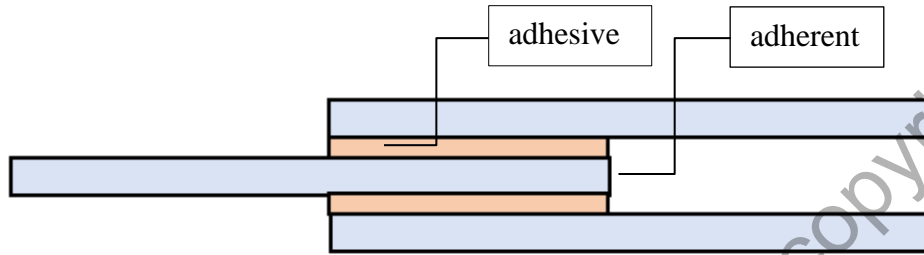
2.4 Adhesive Joint Configuration

Adhesives are being used intensively in many industries such as machinery, medical, dental, automotive, marine, home appliances, construction, toy and aerospace industry. However, information of adhesive properties particularly in complex structural elements is scarce (Lee, Pine, & Jones, 2001). There are many types of joint such as butt joint, single strap joint, step lap joint, double lap joint and etc. The most common types of adhesive joining studied are shown illustrated in the Figure 2.1.

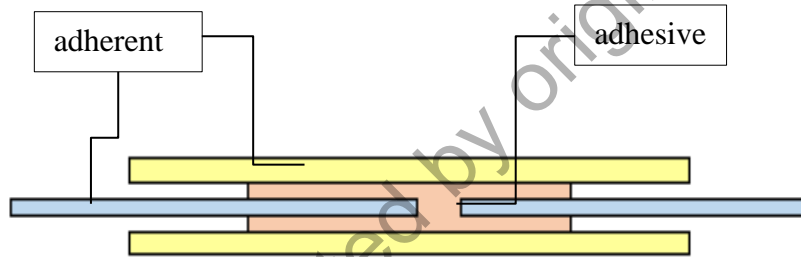
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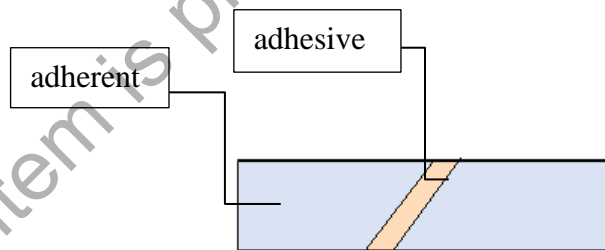
(a) Single lap joint



(b) Balanced double lap adhesive joint



(c) Unbalanced double lap joint



(d) Scarf joint

Figure 2.1: The illustrates the typical adhesive joint configuration (SatyanarayanaGupta & Veeranjanyulu, 2017)

Since structural adhesives do not involve with bolts or rivets, therefore, it provides significant potential for lightweight design, but it causes a weight penalty and as stress concentrations which lead to potential weak spots in the structure. However, de-bonding of adhesive joint components is the primary concern in designing process. The geometry of the joint and the mechanical properties of adhesive and adherent give effect to stress distribution. Hence, the most preferable validation case for material model in adhesive joints is adhesive T-joint structure (Wissling & Hahn, 2007; Jousset & Rachik, 2014). Meanwhile, for a given type of load, the strength of joint type is depended on stress distribution within the joint.

T-joint configuration which mainly involving the perforated surface of the adherent has shown good performance in many applications. Robert D Adams et al., (2011) said that this T-joint configuration involving perforated surface is very useful for the usage of the perforated plate where it can reduce weight and become more effective in areas such as automotive industry. Therefore, various T-joint have been investigated in order to improve its strength and weight reduction (Toftegaard & Lystrup, 2005; Apalak, Apalak, Gunes, & Sinan Karakas, 2003 ; Khalili & Ghaznavi, 2011; M.D.Aydin & S.Akpinar, 2014).

Previous study by Lucas F M Silva & Adams (2002), has conducted an experiment on variety of metallic T-joints strength in order to determine the main parameters that affect the strength that depending on different manufacturing method. The strongest T-joint was the joint with two support gussets. It was reported that the failure may cause by the plastic hinge generated by the yield of the base sheet. In addition, the influence of geometrical parameters on stress distribution in the adhesive

layer of T-joint has been studied by Akpınar, Aydın, & Özel, (2013) . It has been found that the behaviour of two types of adhesive T-joints namely single (Type I) and bi-adhesive T-joint (Type II) were found to have lower stress concentration in adhesive layer, which leads to a higher joint strength. Although the joint configurations involve additional support to the sandwich structure, however, this approach can be used to determine the stress concentration by creating the geometry path along the adhesive layer.

2.5 Joint Strength

In adhesive joint strength, the static strength is most common strength that taken into consideration. This is presumable because one of the elementary requirements of an adhesive joint is to achieve desired static strength. Static strength (immediate strength), conventionally referred as strength, is defined for specific force exerted over the time period of several to a couple of dozen seconds. It is also referring to the stress that needed to push or pull an object or to hold the object. Meanwhile, dynamic strength needed to keep a load moving over a long period. From the prospective of the operations of such joints, this information is important in determining the strength values and types of loads with the joint can be subjected and therefore, can be used safely. Apart from the joint strength, adhesive joint is analysed with respect to long term (Derewonko, Godzimirski, Kosiuczenko, Niezgoda, & Kiczko, 2008) and dynamic strength (X. Chen & Li, 2010). Moreover, in the previous work, the most common type of joints conducted are single lap joints (Abdo & Aglan, 1997; Liu et al.;1998; Grant, Adams, & da Silva, 2009), double lap joints (Diaz, Hadj-Ahmed, Foret, & Ehrlicher, 2009) and T-joint (Nurhashima et al., 2014).

In order to produce a proper adhesive that meets desired strength as well as dimensional and shape repeatability, several factors such as material, technology and structural, as well as future operations of a tested joint are taken into account. The correlation between those factors and adhesive joint strength has been extensively investigated in the literature. For instance, cure conditions (applied pressure, time, temperature and curing agent) and the joining forming conditions (e.g., temperature, humidity and seasoning conditions) has been conducted by Czederski et al., (2012), Godzimirski, Kozakiewicz, Łunarski, & Zielecki (1997), Grant, Adams, & Lucas (2009), Moussa, Vassilopoulos, De Castro, & Keller (2012) and He (2011) have discussed several factors that affect the strength of the adhesive joint. The several factors that have been investigated are type and value load, temperature, loading time, mechanical of applied adhesive, failure stress values, joint dimensions (adhesive layer width, length, and thickness, adherent thickness), physical properties of adherent, for example, Young's modulus.

2.6 Failure Load for T-joint

A few previous researchers have tested T-joints by means of tensile test. Almost all results indicate less strength compared to another type of joint such as lap joint or butt-joint. This is primarily because of T-joint adhesive bonding area is lesser than lap joint. By using perforated plate, even lesser bonding area was observed in this T-joint specimen. Prior to experiment, estimated tensile strength or failure load must be obtained to examine the feasibility of this specimen. Hence, several values from previous researchers were obtained. The following failure load, kN were recorded by previous researchers as tabulated in Table 2.3. The lowest tensile value was 0.45 kN and

the highest was 175 kN. Based on their experiments, geometry used by Lucas et al., (2008) was closely similar with this current research. Hence, tensile strength between 0.5 and 1.5 kN was expected.

Table 2.3: Reported failure load of T-joint in literature.

No.	Researchers	Paper Title	Failure Load (kN)	Adhesive
1	Lucas F.M. da Silva, R.D. Adams (2002)	The strength of adhesively bonded T-joints	1.0	ESP110 (Permabond)
2	S. Guo , R. Morishima (2003)	Numerical analysis and experiment of composite sandwich T-joints subjected to pulling load	18.9	3M 7823
3	V. Marcadon, Y. Nadota,, A. Royb, J.L. Gacougnollea (2006)	Fatigue behaviour of T-joints for marine applications	0.45	vinylester adhesive
4	S.M.R. Khalili, A.Ghaznavi (2011)	Numerical analysis of adhesively bonded T-joints with structural sandwiches and study of design parameters	175	Crestomer 1152PA
5	Ping Hu,Qi Shao, WeidongLi , XiaoHan (2012)	Experimental and numerical analysis on load capacity and failure process of T-joint: Effect produced by the bond-line length	2.09	ESP110 (toughened, single-part paste epoxy which has 30% aluminum powder as a filler to increase the modulus)

2.7 Glass Transition Temperature

In order to obtain high strength adhesive structural joint, an effective operating temperature of the adhesive should be known properly. Essentially, the most important factor that needs to be considered is the glass transition temperature, T_g for epoxies/ polymers. At specific temperature region, transition of the polymer from glassy and hard material to a rubbery material and soft is occurred, which called as glass transition temperature, T_g . Practically, the preferable operating temperature for structural joint or products which using adhesive to assemble the subtracts should be lower than T_g . Meanwhile, softening of the polymer/ epoxies will be occurred when the operating temperature exceeds the T_g . (Mette, Stammen, & Dilger, 2016) mentioned that the shear strength of the adhesive joint is simultaneously a drastic drop after passing the T_g while (Lucas F M Silva, A.Öchsner, & Robert, 2011) said that the structural adhesive expected to operate or function below their T_g .

In order to determine the glass transition temperature, Souza & Reis, (2013) noticed that T_g analysis can be performed based on three different analysis; Differential Scanning Calorimetry (DSC), Dynamic Mechanical Analysis (DMA) and thermogravimetric analysis (TGA). M. D. Banea, Silva, & Campilho, (2012) has studied the effect of epoxy adhesive and single lap varies with temperature. From their observation, the lap shear strength experiences a drastic drop when temperature is above the T_g . While, the modulus magnitude of the polymer drop and soften at T_g region. When the applied temperature to the joint exceeds the T_g , the polymer becomes rubbery and the mechanical properties could improve significantly with the consideration of operational limit temperature (Sperling, 2006).

2.8 Relationship between Adhesive Joints Strength and the Temperatures

Over past decades, numerous studies related to the temperature effect on the strength of adhesive joints have been investigated. In designing the adhesive joint structures, the most paramount importance parameter is temperature. This is because, the thermal effects lead to a joint strength reduction (Apalak et al., 2003; Srivastava, 2003; Al-Samhan & Darwish, 2005). It is noticeable that when the temperature increases, the adhesive mechanical properties e.g. elasticity modulus, ultimate strength, and stiffness (Sahellie & Pasternak, 2013) is changing. Moreover, increasing the temperature will causes changes in failure modes of a bonded connection, i.e. cohesive to adhesive failure (Straalen.I.J.v, 2001).

Glass transition temperature, T_g is the crucial factors that related with the temperature of polymers. As the temperature increases, the strength and modulus of the adhesives decrease while the ductility is increases below the glass transition temperature, T_g . It can be said that the ideal adhesive joint strength for high and low temperatures can be attained if the loaded applied to the joint is designed at temperature range.

Various frameworks' studies have been proposed to observe behaviour of the adhesive joint that varies with temperature. L. F. M. da Silva & Adams, (2007); L. F. M. da Silva & Adams, (2005) have explored the mixed of low and high temperature adhesive joints to increase the strength and improve stress distribution. In order to investigate the probability structural adhesive joint used in the automotive industry to

substitute spot welding, the experimental work was performed. The temperatures that have been selected for the test were ranging from -55 °C to 200 °C.

Similarly, the single lap joint and T-joint specimens were undergone the test at temperature -40 °C, 20 °C and 90 °C in order to evaluate joint strength over temperature variation (Grant, Adams, & Silva, 2009). It has been proved that increasing temperature adversely affects adhesives behaviour, mechanical shear properties and failure mode. Besides, increasing temperature that leads to the decreasing the shear strength attributes to the adhesive strength degradation within the temperature. For instance, Adamvalli & Parameswaran (2008) has determined the lap joint strength at temperatures of 25 °C, 50 °C, 75 °C and 100 °C. It has been found the decreases in failure load with increasing the temperature. According to Lucas F. M. da Silva & Adams (2005); M. Banea, Silva, & Campilho (2012), it can be concluded that strength of adhesive is declined with increasing temperature as the thermal stresses are high and vice versa.

It is well known that as the temperature increases, the mechanical properties of the adhesive such as ultimate strength, elasticity modulus, and stiffness are decreased. Moreover, increase of temperature would result in change of behaviour of the adhesive which is from brittle into ductile. However, increasing temperature could lead to the failure modes of a bonded connection from cohesive into adhesive failure (Straalen.I.J.v, 2001). This failure mode of the adhesive is represented in the form of load-displacement plots that was measured through the tensile test. The graph obtained from the test has proven that overall adhesive phase and behaviour can be observed until it failed when the maximum load is applied. Furthermore, it has been found that

the stress and strain are drastically reduced after reaching the T_g value of adhesive (Afendi, Teramoto, & Bakri, 2011).

2.9 Types of Adhesive Joint failure (Modes of Failure)

Another significant main concern in the adhesive joint is a failure mode criterion. The types of the failure were considered in order to obtain a full conception of the studied adhesive properties and joint. There are three main failure modes, which categorized as follows:

- Cohesion failure which is characterized by failure mode of the adhesive itself.
- Adhesion (interfacial/adhesive) failure occurs on the interfacial surface between adherent and the adhesive layer, and fracture surfaces are moderately smooth.
- Adherent failure occurs between the surface and the second adherent, (Panigrahi, 2009).

Figure 2.2 shows mechanism of adhesive failure. The specimen's failure modes are visually evaluated after tensile, bending or shear experiment is performed. Generally, high strength of the adhesives that has a stronger interface with the adherent usually demonstrates cohesion bond failure (Lucas F M da Silva et al., 2011). Similarly, the cohesion failure modes can be observed with the existence of voids, which diminish the obtainable bond overlap length below a critical size. In the revised for adhesion bond failures, residual adhesive is remaining at any location on one surface only. The failure will be found at the interface between the adhesive and the adherent. This is

typically caused by contamination during manufacture, inadequate surface preparation, and usage of expired adhesive or deficient temperature control through manufacture. In spite of that, the adhesion (interfacial) failure indicates low surface energy and low strength of the adhesives.

Adherent failure occurs when the substrate failed instead of the adhesive. In metals, this adherent failure is occurred when the adherent yields. An adherent failure indicates that adhesive is stronger than adherent in the joint being tested. This is a desirable situation in practical design, but not when the determination of adhesive behaviour is being studied. In some cases, both cohesion and adhesion failure can be occurred at the same time, which is due to the partial degradation of the interface. These failure modes are usually known as mix-mode failure.

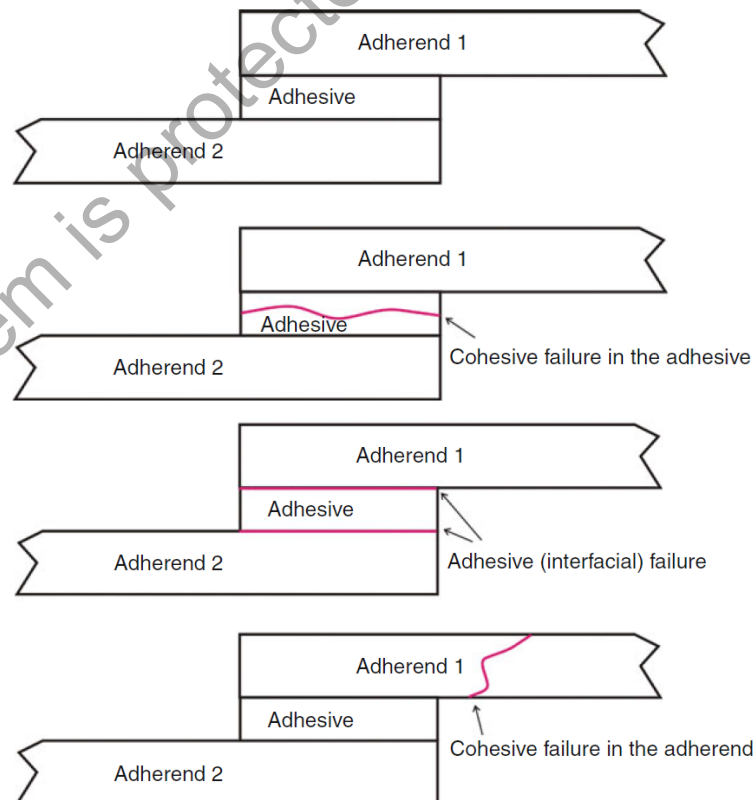


Figure 2.2: Examples of cohesive and adhesive failures of bond lines (Lucas F M da Silva et al., 2011)