PULL-OUT TENSION AND FLEXURAL CAPACITY OF ADHESIVELY JOINTED STEEL PLATES UNDER DIFFERENT TEMPERATURE

by

Siti Nur Hanani bt Sulong

Dissertation submitted in partial fulfillment of
the requirements for the
Master of Science
(Civil Engineering)

JULY 2008

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

Title of thesis **Pull-out Tensile and Flexural Capacity of Adhesively Jointed Steel Plates under Different Temperature**

I, SITI NUR HANANI SULONG

hereby allow my thesis to be placed at the Information Resource Center (IRC) of Universiti Teknologi PETRONAS (UTP) with the following conditions:

1. The thesis becomes the property of UTP.
2. The IRC of UTP may make copies of the thesis for academic purposes only.
3. This thesis is classified as

☐ Confidential

☒ Non-confidential

If this thesis is confidential, please state the reason:

____

The contents of the thesis will remain confidential for __________ years.

Remarks on disclosure:

____

Endorsed by

SITI NUR HANANI SULONG

No 10, Jalan Bandar U14,
Bandar Universiti Seri Iskandar
31750 Tronoh,
Perak, Malaysia

Date : 24/7/2008

Assoc Prof Dr Nasir Shafiq
Associate Professor
Civil Engineering Department
Universiti Teknologi PETRONAS
Bandar Seri Iskandar, 31750 Tronoh
Perak Darul Ridzuan, MALAYSIA

AP DR NASIR SHAFIQ

Civil Engineering Department,
Universiti Teknologi PETRONAS,
Bandar Seri Iskandar
31750 Tronoh,
Perak, Malaysia

Date : 24/7/2008

UNIVERSITI TEKNOLOGI PETRONAS

Approval by Supervisor

The undersigned certify that they have read, and recommend to The Postgraduate Studies Programme for acceptance, a thesis entitled

Pull-out Tension and Flexural Capacity of Adhesively Jointed Steel Plates under Different Temperature

submitted by

Siti Nur Hanani Sulong

for the fulfillment of the requirements for the degree of

Masters of Science in Civil Engineering

24/7/2008
Date

Signature :

Assoc Prof Dr Nasir Shafiq
Associate Professor
Civil Engineering Department
Universiti Teknologi PETRONAS
Bandar Seri Iskandar, 31750 Tronoh
Perak Darul Ridzuan, MALAYSIA

Main Supervisor : AP Dr Nasir Shafiq

Date : 24/7/2008

Co-Supervisor 1 :

Co-Supervisor 2 :

TITLE PAGE

UNIVERSITI TEKNOLOGI PETRONAS

Pull-out Tension and Flexural Capacity of Adhesively Jointed Steel Plates under Different Temperature

By
Siti Nur Hanani Sulong

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

AS A REQUIREMENT FOR THE

DEGREE OF MASTERS OF SCIENCE IN

CIVIL ENGINEERING

CIVIL ENGINEERING
BANDAR SERI ISKANDAR,
PERAK
JULY , 2008

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

Signature :

Name : Siti Nur Hanani Sulong

Date : 24/7/2008

ACKNOWLEDGEMENTS

First of all, praised be to Allah the Almighty for His blessing and the guidance given to the author in completing her research project as a requirement for the degree of Masters of Science in Civil Engineering. The author would like to express her heartfelt gratitude to her honorable supervisor, Assoc. Prof. Dr Nasir Shafiq for his advices and constant guidance during the course of this research. He has always been eager to listen and discuss various aspects of the project. Furthermore, his comments on the drafts of this thesis have improved its quality of presentation considerably.

The author also would like to express her deep appreciation to the staff of Postgraduate Studies Programme. Special thanks for those people who has helped directly or indirectly during the period of study. It includes the technologist, Mr. Johan Ariff B Mohamed and Mr. Meor Asniwan B Meor Ghazali, the Final Year Project students, Miss Fahima and Miss Ezura who have helped very much in accomplishment of this research project.

Finally, the author would like to take this opportunity to thank her parents for the love and support they had given to her during the entire life and in the period of this research. Especially, author would like to thank her husband who has always encouraged and helped in the execution of lab works. Author also wants to thank all good friends and colleagues who have helped the author many times during her stay in the university.

ABSTRACT

Adhesive bonding has established a remarkable interest in civil construction industry because of its proven success and wide application in aerospace and automotive industry. In fact, the application of adhesive has existed in construction of civil engineering facilities since 1960s in which the major application dominated by the segmental construction, externally-bonded reinforcement, structural repairs to concrete and also non-structural application. However, lack of design code and comprehensive research related to the use of adhesive bonding in load-bearing connections made this method of joining less attractive. Therefore, this experimental research was conducted to study the pull-out tension and flexural capacity of adhesively jointed steel plates. The effects of some of the critical variables on the performance of adhesive joint were investigated namely the overlapping length, curing temperature and joint configuration particularly single-lap joint, single-strap joint and double-strap joint. Only one type of commercially available structural adhesive namely Sikadur®-30 was used to join the 100mm wide steel strips. It was observed from the test results that the stiffness and load carrying capacity of adhesive joints subjected to pull-out tension increases with decrease in overlapping length. Investigation the effects of the curing temperature; it was noted that at 45°C the adhesive was fully cured. On the other hand, the double-strap joint has shown much higher loading capacity under all loading conditions such as pull-out tension and bending. It has performed best amongst the three other types of joint designs investigated. The available results of this research study is a primary effort in order to establish the future research studies for adoption of adhesive joints as structural connection in the global construction industry.

ABSTRAK

Sambungan berperekat telah menarik perhatian industri pembinaan sivil disebabkan oleh kejayaan dan aplikasi yang meluas dalam industri angkasa dan industri permotoran. Sebenarnya, penggunaan perekat telah wujud dalam pembinaan kejuruteraan sivil sejak 1960-an dimana aplikasinya yang utama dipelopori oleh pembinaan bersegmen, tetulang luaran, pembaikan struktur konkrit dan juga aplikasi bukan struktur. Walaubagaimanapun, kekurangan kod amalan dan kajian yang terperinci berkenaan dengan penggunaan sambungan berperekat untuk sambungan tanggung-beban menjadikan kaedah penyambungan ini kurang diberi perhatian. Oleh yang demikian, kajian bereksperimen ini telah dijalankan untuk mengkaji kapasiti tegangan tarikan dan lenturan sambungan pelat keluli berperekat. Kesan-kesan pembolehubah ke atas sambungan berperekat seperti panjang tindihan, suhu pengerasan dan rekabentuk sambungan terutamanya sambungan bertindih (*single-lap joint*), sambungan temu satu "strap" (*single-strap joint*) dan sambungan temu dua-"strap" (*double-strap joint*) telah dikaji. Hanya perekat Sikadur®-30 telah digunakan untuk menyambung kepingan keluli berukuran 100mm lebar. Daripada keputusan ujian, diperhatikan bahawa kekerasan dan kapasiti tanggungan beban sambungan perekat yang dikenakan tegangan tarikan adalah meningkat dengan pengurangan panjang tindihan. Dalam kajian kesan suhu pengerasan, didapati bahawa perekat telah betul-betul mengeras pada suhu 45°C. Di samping itu, sambungan temu dua-"strap" telah menunjukkan kapasiti bebanan lebih tinggi apabila dikenakan tegangan tarikan dan lenturan. Sambungan ini juga adalah yang terbaik antara ketiga-tiga jenis reka bentuk sambungan yang telah dikaji. Keputusan daripada kajian ini adalah usaha permulaan untuk mewujudkan kajian-kajian di masa hadapan ke atas penggunaan sambungan berperekat sebagai sambungan struktur dalam industri pembinaan global.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Background

Structural steel constructions are fabricated with wide range of joining technique such as bolting, welding, riveting and other forms of mechanical fastening. However, when such connections are exposed to harsh environment and/or abnormal conditions in service they tend to deter or loose a part of their resisting capacity. The main intention of this research was to introduce an alternative jointing technique of structural steel members that enables their connections to sustain the possible shocks of harsh environment and the abnormal conditions exist during service.

Technique of adhesive bonding has successful record of its application in varieties of industries such as aerospace and automotive, due to which it has great potential to be applied in civil engineering application and being used in reinforced concrete construction for joining the segments in segmental bridge constructions. It is also being used for concrete repair in external bending of composite strips. Few examples of application of adhesive-bonded segmental construction are the bridge over the Seine, at Choisy-le-Roi in Paris, S-shaped Byker viaduct in the UK and M180 Bridge at Scunthorpe. In this technique, concrete hollow blocks or segments are bonded together using epoxy adhesive and pre-stressed in order to form monolithic long span bridges. The epoxy adhesives is the only adhesive that have been used so far because they display excellent adhesion to concrete with high mechanical resistance and proven long term durability (Moavenzadeh, 1990).

There are some steel bridges in the U.S those were built using adhesive connections together with additional bolts to enhance their safety. However, at that time of construction of such bridges, analytical techniques for designing adhesive connections were not available; therefore construction and design of such bridges were merely based on physical model tests. It is interested to note that all such bridges still exist and functioning without showing any sign of severe damage and/or distress hence, it is the evidence of long lasting behavior of the adhesive joints application in over 40 years old bridges (Pasternak et al, 2004).

Since the development of a series of novel adhesives by Dr Norman de Bruyne during the Second World War at the company which became to be known as Ciba, the qualities of adhesives have been greatly improved (Adam & Comyn, 2000). There are many types of adhesive available in the market, which are being used for variety of applications. Each type of adhesive has several advantages as well as drawbacks for its application. Despite the wider application of adhesives in automobiles and aircraft industries, currently it is quite difficult for designers to accept adhesives connections to be applied in structural steel construction because of the lack of design codes and guidelines and also the fears of premature and unpredictable failure.

It can be anticipated that adhesive joints can offer substantial performance and economic advantages in comparison to other conventional methods of joining particularly mechanical fastening. It is required that engineers and the manufacturers should acquaint with the knowledge regarding the mechanism, design calculations and long-term resistance as well as the working of the sticking surfaces. It is essential that the designers should be familiar with qualitative overview of the factors that influence adhesion and control the joint performance in order to make rational judgments concerning the selection and use of adhesives.

As a result of recent advances in the science and technology of adhesive and the adhesion couple with the demands which requires the combination of thick bondlines, ambient temperature curing and the need to join dissimilar materials with a relatively high strength joint, adhesive bonding technique may be presented as a potential alternative for future construction.

1.2 Engineering Application of Adhesives

Adhesives have been applied widely in engineering sectors such as aerospace, civil engineering, automotive and marine and offshore. In order to improve the level of confidence, it is important to understand how the adhesives are applied for metal fabrication.

1.2.1 Aerospace

The application of adhesives to metal fabrication was initially adopted by the aircraft industry. The safety and reliability is given paramount attention, because the adhesives are used to bond critical parts in commercial and military aircraft and helicopters, spacecraft, rockets, missiles and the US Space Shuttle. This technology was adopted to replace mechanical fasteners due to the need to extend aircraft life and to reduce costly maintenance. Previously, riveted joints were commonly used, but the rivet holes as points of weakness that cause cracks to occurs, and metal fasteners to corrode or loosen are no longer attractive technique of connections. Furthermore, nowadays aircraft are designed to include a large amount of composite materials and the fabrication of honeycomb sandwich panels frequently involves connecting dissimilar materials for the skin and core, therefore adhesives are the choice (Mays & Hutchinson, 1992). Since aerospace structures need to be reasonable light, the use of adhesives reduces the weight of the structure and at the same time improving the stiffness and strengths of connections.

The potential of bonding for variation of styling due to possibility of combining different material with galvanic corrosion prevention also make this technique in very high demand. It is evident in the construction of aircraft such as Boeing 747, McDonnell Douglas DC10, Lockheed Tristar and the Swedish military aircraft JAS Gripen. For the case of JAS Gripen (Figure 1.1), epoxy and cyan ester were used in which the epoxies used for aerospace applications are considerably stiff as shown in Figure 1.2 (Täljsten, 2005).

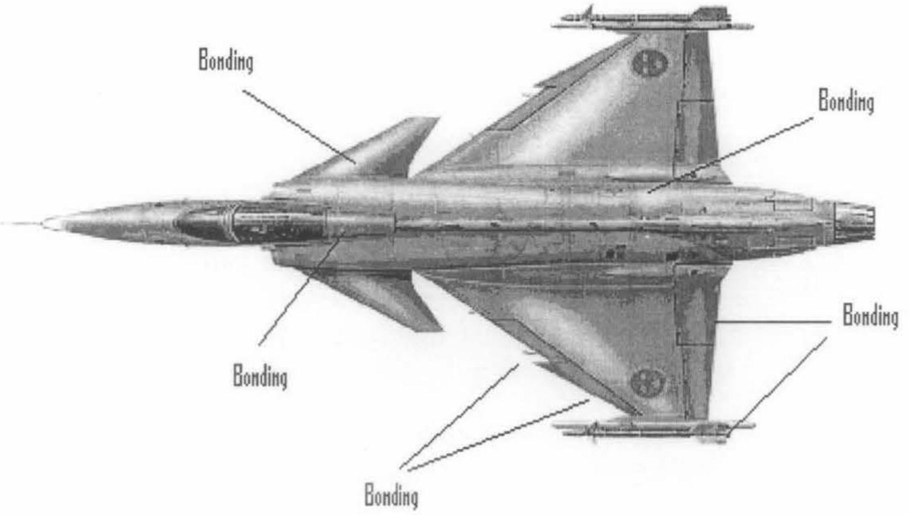


Figure 1.1: The Swedish Military Aircraft JAS Gripen Bonded Parts (Täljsten, 2005)

1.2.2 Civil engineering

Construction industry adopted the application of adhesives in non-structural, semi-structural as well as structural connections. In non-structural application it has been used in industrial flooring, water-proofing membranes on concrete bridge decks, surface repair of spalled concrete, the injection and sealing of cracks in concrete, and bonding new concrete to old. In semi-structural application, it has been employed in steel fixings in concrete, rock or masonry, self-levelling epoxy grouts for the support of heavy machinery, and segmental pre-cast pre-stressed concrete structures such as bridges, in which epoxides have been used for nearly 30 years as stress-distributing and waterproof medium in joints. In structural application, it has been used in glulam, bonded external plate reinforcement for strengthening existing concrete structures, bonded composite steel/concrete bridge decks, structural steelwork connections and sleeved steel bar and rebar connectors (Mays & Hutchinson, 1992).

Studies were also conducted on the strengthening of the civil engineering facilities with the application of *Carbon Fiber Reinforced Plastic* (CFRP) bonded to the structure using structural adhesive particularly epoxy. Ishii et al (1999) evaluated the fatigue endurance of adhesively bonded CFRP/metal for single and single-step double-lap joints. Colombi & Poggi (2006) studied the effectiveness of the use of CFRP plates in the reinforcing of steel elements commonly used in structural steelwork.

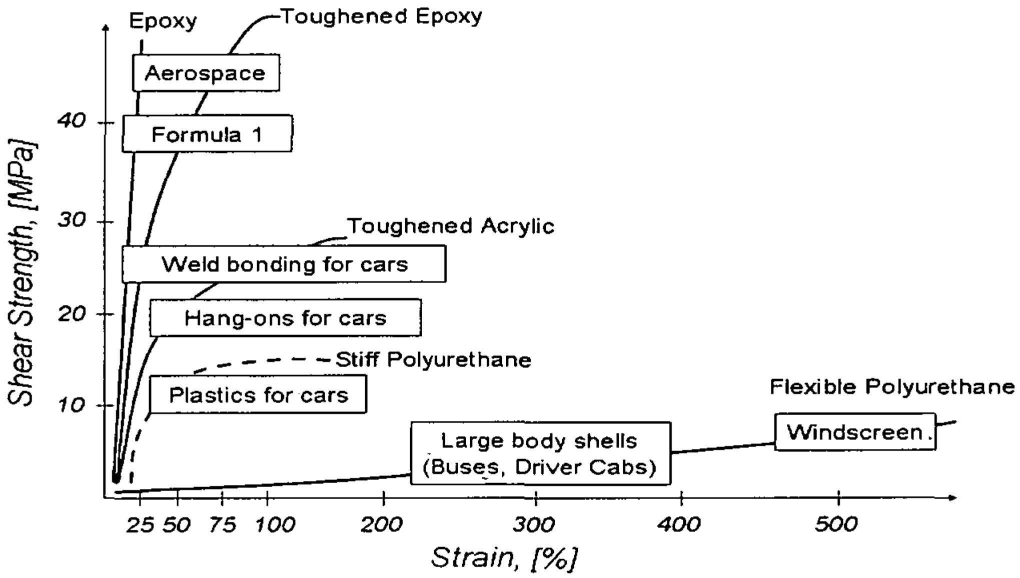


Figure 1.2: Shear versus strain for different bonded parts in the automotive industry (Täljsten, 2005)

1.2.3 Marine and offshore

In marine and offshore construction, casein and then formaldehyde based resin have been used as adhesives, in later years, polyester resins were introduced in the marine industry. Due to the advance development of technology, the boat-builders used GRP (glass reinforced plastic) craft which used resins for laminating, stiffening and the fabrication of sandwich panels, and for bonding attachments. Traditionally, the shipbuilding industry used welding as the primary process for joining different structural parts in a ship. However, this process results in induced stresses during the fabrication stage which in turn lead to distortion in the shape of structural components and of course, the ship itself.

Considerable efforts to mitigate these problems have increased the production costs. One additional problem, in the case of aluminum, is the significant reduction in the fatigue load capacity in welded structures (Kecsmar, 2003). As a consequence, either the structural topology has to be designed to cope with increased stress levels or the scantlings of the structure have to be enhanced. In either case, there is an increase in the weight of the structure. Since structural weight needs to be minimized, especially in high speed, high performance ships, there is a need to investigate alternative joining techniques for aluminum structures; adhesive bonding is one of them (Clark, 1996 and Cantrill et al., 2004).

Adhesive bonding offers the opportunity to replace welding of steel structures, to reduce distortion, effectively eliminate residual stress and to improve fatigue performance when compared to welded connections. Avoidance of hot-work leads to safer construction practices in hazardous environments. Adhesive bonding of composites provides well-distributed loading and maximizes the utilization of the adherent materials. Typical adhesives in the marine industry are polyesters which are less expensive than epoxy and are widely used in other industrial applications. Polyester, however, is chemically weaker than epoxies and experiences a high degree of shrinkage. Vinyl ester, which provides higher strength, modulus of elasticity, and elongation than polyesters is still less expensive than epoxy are often preferable to polyesters. For bonding to metallic parts epoxies are typically used.

1.2.4 Automotive

Adhesives technology has been employed in the automotive industry since its beginning. The early metal-to-metal adhesives application was to overcome the low strength gap-filling inter-weld sealers and to contribute to the overall strength of the assembly. Recent developments in synthetic technology have resulted in a very wide range of adhesive materials available to the design engineer (Mays & Hutchinson, 1992).

In Figure 1.2, shear strength versus strain diagram for various adhesive types used in the automotive industry is shown. From this diagram it is clear that bonding is widely used in the automotive industry both for structural- and non-structural parts (Täljsten, 2005). Adhesives are used to bonding stiffeners to bonnet and boot lids, attaching trim, for thread-locking, for gasketing in the engine and for components such as headlamps, radiators and brake linings and etc in addition, mass-produced vehicles are increasingly being fabricated with coated steels therefore adhesive bonding is very attractive method in order to minimize damage to the surface coating (Mays & Hutchinson, 1992).

The drivers for the automotive industry are lightweight structures, use of mixed materials, long term performance, crash performance and also styling and design. The adhesive application can improve the stiffness and strength of a joint while reducing the weight. Furthermore adhesive application allows the realization of combining different structural materials such as FRP, metals, glasses and ceramics. It is quite clear that many parts of different materials have to be brought together through bonding, sometimes together with rivets. In many situations this is preferred to welding. Similar to aerospace bonding, galvanic processes can be delayed or prevented when adhesives are used, in particular when different materials are joined together. Improvement of crash performance is possible by the use of substrates and adhesives with a high potential of energy absorption. Finally, diversity of styling and design are possible due the possibility of combining different materials and components and joining them together by bonding. Adhesives for automotive and industrial bonding are modified acrylics/methacrylates which provide high strength and elongation properties and also bond to thermoplastics. Other adhesives are polyurethanes, which are tough and have a high abrasion resistance and good adhesion at low temperatures. Silicones are also used for bonding to glass, plastics or other rubbers (Täljsten, 2005).

1.2.5 Civil engineering versus other industries

In order to extend the application of adhesive bonding techniques in construction industry, it shall be worth to review the experience gained in other industries such as aerospace and automotive. In general, construction industry is different than other industries in which the projects are specifically commissioned and built in situ. It is distinguished as compared to vehicles and aeroplanes, which are produced on mass scale, built first and sold later, employed pre-fabricated components and can also be assembled economically under cover. These factors pose questions on relevance of previous adhesive research and practical experience (Mays & Hutchinson, 1992).

Though there are few design tools and recommendations available for general applications of adhesives, for the design and specification stage, the engineering application generally involve the use of adhesives in very thin bondlines; 0.002 to 0.008 in. (0.05 – 0.20 mm) (Fisher, 2005). Whereas in civil engineering applications, the adhesive is generally used as gap-filling material as well as being a stress transfer medium and the adhesive often being used in thick bondlines. The level of dimensional precision is also far lower than those in other industries which further compound the problems. This is again poses questions on the validity of any existing design tools developed for other industries (Mays & Hutchinson, 1992).

The choice and availability of adhesives for civil engineering applications is also limited as the manufacturers have naturally tailored their products to support the aerospace and general manufacturing industries. There are only a very few products developed specifically for bonding steel and concrete and results in limited choices. Quality control in adhesive bonding is required very high emphasis. However, the outdoor nature and scale of construction projects can possibly deter the surface pre-treatment techniques generally used. And yet, the simple grit blasting and degreasing methods can also be very difficult in remote locations or in adverse weather conditions (Mays & Hutchinson, 1992).

Many civil engineering structures are generally designed for a service life of 100 years, during the entire life span they may be subjected to extreme temperature conditions, moisture variation and probably have to sustained cyclic loading. On the other hand, the operating conditions in other industries may be quite different, and the life span of particularly vehicle or aircraft is unlikely to exceed twenty years. Therefore, the engineers or designers must ensure the adhesive joints remains capable of performing its intended role throughout the design life (Mays & Hutchinson, 2005).

1.3 Problem Statement

As discussed in a number of literatures that there is very limited knowledge for the use of adhesive bonding in civil engineering application particularly in structural steel construction. There have been reported few applications of adhesive connections in steel bridge construction, however they were solely designed on the basis of experimental studies because of the absence of design tools, guidelines, specifications and standards.

Still the traditional connections such as welding and bolting have been widely used in structural steel construction, yet there are many issues and concerns may be raised particularly regarding the fatigue behavior, stress concentrations and long term durability.

On the basis of above facts there is a great need for detailed investigations of several modes of adhesive connections in structural steel that could be led to the formulation of design guidelines for adhesive connections.

1.4 Objectives and Scope of Study

Based on the problem statement and aim of this study, following objectives were formulated;

1) To determine the effective and optimum design of adhesives joints under the mode of pull-out tension and bending based on the chosen variables.

2) To assess the influence of some of the critical variables on the performance of adhesives joints, such as:
    a. joint configuration (strap and/or lap)
    b. overlapping length
    c. curing temperature

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

The main focus of this chapter is to review the available literature regarding the use of adhesive connections in construction and other industries. The literature review was also aimed at the connection design, effects of controlling parameters on the performance of connections, issues and problems in the use of traditional connections, etc.

2.1 Adhesives

Adhesives are substances that are capable of holding materials, and the part they comprise, together by surface attachment forces arising from the formation of secondary chemical bonds (Messler, 2004). Adhesives may be classified as either organic or inorganic materials in a number of different ways; for example by origin, by method of bonding, by end use or on a chemical basis (Mays & Hutchinson, 1992). Table 2.1 gives an overview of a general classification of organic adhesives. Focus will be placed on the structural adhesives; however some different adhesives discussed in general terms below.

Animal glues are made from the protein extracted from the bones, hide, hoofs and horns of animals by boiling. The extract is cooked to form a gelatin material. The gelatin can then be reliquified with heat, which gives it quick setting properties. Its major use has been in the wood and furniture industry. Animal by-products from meat processing have been the source of supply for this type of glue. Fish glue is also protein-based glue made from the skins and bones of fish. An exceptionally clear adhesive can be made from fish and was the first adhesive used for photographic emulsions for photo film and photo resist coatings for photoengraving processes.

Casein glue is made from a protein isolated from milk. The extraction process creates an adhesive that is waterproof. Its first use was in bonding the seam of cigarette paper (Täljsten, 2005).

Glues made from *vegetable* starch, which is a carbohydrate extracted from vegetable plants such as corn, rice, wheat, and potatoes are probably better known as paste. Major uses of these materials include bonding of paper and paper products (such as bookbinding, corrugated boxes, paper bags, wallpaper paste) and as a sizing in textiles. The laundry uses starch on our shirt collars, to stiffen and give shape to the shirt. Cellulose adhesive is made from a natural polymer found in trees and woody plants; it is the adhesive used on the cellophane wrapper on cigarette packs and the adhesive on decals placed on windows (Täljsten, 2005).

Elastomeric adhesives are based on both natural and synthetic polymers that exhibit superior elongation and toughness. These polymers can be thermosetting or thermoplastic. Because of these properties, elastomeric adhesives are used exclusively for nonstructural applications such as vibration damping, impact absorption, sealing. And accommodating mismatched thermal-expansion coefficients, and for joining elastomeric adherends to one another or to another material (Messler, 2004). Rubber-based adhesives are used in a wide variety of applications such as: contact adhesive for plastic laminates like counter tops, cabinets, desks and tables. Self sealing envelopes and shipping containers use rubber cements. Solvent based rubber adhesives have been the foundation of the shoe and leather industry. Furthermore, silicone adhesive is a rubber-like polymer called polydimethylsiloxanes. Silicone rubber adhesives are made from a complicated process that turns elemental silicon metal made from sand (silica) into a rubbery polymer. Because of its exceptional properties, silicone adhesive has been used in some exotic applications such as the soles of the boots worn by the first astronauts to walk on the moon (Täljsten, 2005).

Table 2.1: Organic adhesive classification (Mays & Hutchinson, 1992)

Group	Type	Source	Use
Animal	gelatin casein albumen	mammals, fish milk blood	can labels plywood, block board
Vegetable	starch cellulose acetate cellulose nitrate	corn, potatoes, rice cellulose	paper, packaging leather, wood, china
Mineral	asphalt/bitumen	earth's crust	road pavements
Elastomeric	natural rubber synthetic rubber	tree latex synthetic	carpet making tyre, fabrics, bookbinding
Thermoplastic	PVA polystyrene cyanoacrylates liquid acrylic	synthetic synthetic synthetic synthetic	wood and general model making plastics, metals, glass, rubber structural vehicle assembly
Thermosetting	formaldehyde-(urea/phenol) unsaturated polyesters epoxy resins polyurethane	synthetic synthetic synthetic synthetic	chipboard and plywood glass fibre, resin mortars structural, especially metal-to metal semi-structural uses with plastics, metals, wood and sandwich panel construction

Thermoplastics adhesives are based on polymers that can be repeatedly softened by heating and stiffened by cooling. The thermoplastic polymers on which these adhesives are based consist of long-chain molecules that do not cross-link between chains to form rigid aggregates during curing. Thermoplastic adhesives are single-component systems that harden either by simply cooling from a melt or through the evaporation or absorption of an organic solvent or water used to thin the adhesive initially (Messler, 2004).

As a group, thermoplastic adhesives exhibit limited strength, especially as the temperature is increased. Hence most thermoplastic adhesives have been nonstructural. However, more recently developed varieties, and most of the *hot melts* are definitely suited to structural applications (Messler, 2004).

Unlike thermoplastics, *thermosetting adhesives* do not melt or flow on heating but become rubbery and lose strength. The molecular chains present in thermosetting adhesives undergo irreversible cross-linking during curing (Mays and Hutchinson, 1992). Thermosetting adhesives are based on the thermosetting polymers. While they require a chemical reaction to cure, they are available as so called "one-part" and two-part" systems. In one part systems, the chemical catalyst or hardener necessary to cause the chemical reaction leading to cross-linking is premixed into the adhesive base. It will remain without causing any reaction with the base until the reaction is activated or triggered by some external energy such as heat or light or some type of radiation. Shelf or storage life of this type is usually limited but can be extended by storing the adhesive in a cool (possibly refrigerated) and dark place. In two-part systems, the hardener or catalyst must be carefully measured and mixed into the adhesive base to initiate the curing reaction with the absence of heat or light, although heat is often used to accelerate the reaction. Once this adhesive type is mixed, working time is limited, although the self life of the separate components is usually quite good (Messler, 2004).

2.2 Structural Adhesive

Structural adhesives are distinguished from other adhesives by being high strength materials that are designed to support loads (Täljsten, 2005). They are generally accepted to be a monomer composites which polymerize to give fairly stiff and strong adhesive uniting relatively rigid adherends to form a load-bearing joint (Shield, 1985). Most structural adhesives used in construction harden by chemical reaction. Curing takes place within the bulk of the adhesive and adhesion occurs at the interface, Van der Waals forces contribute to adhesion as these are the normal attractions between atoms and molecules and chemical bonding, mechanical interlocking, diffusion, electrostatic and weak boundary layer all play a part in forming the joining of two adherends together (Hollaway, 2005). Such adhesives are often subjected to cycling high and low temperatures and aggressive environments, fluids or the weather. They are generally used for the bonding of rigid structures, although a degree of flexibility is required in the adhesive to counter the effects of movement, impact or vibration. Materials most commonly bonded with structural adhesives are metals, glass, ceramics, concrete, plastics and composites. Structural adhesives include anaerobics, epoxies, reactive acrylics, polyurethanes, reactive hot melt polyurethanes, and special formulations of cyanoacrylates (Täljsten, 2005). Structural adhesives can be both cold cured and hot cure and all are cross-linked, this renders the polymer insoluble and infusible and these characteristics greatly reduce creep of the adhesive. The cold cured polymer will cure at room temperature and should be post cured at a temperature of 500°C. To avoid brittle behavior, using additives toughens most modern epoxy adhesives. All amorphous polymers have a glass-transition temperature (T_g), below this temperature they are relatively hard and inflexible and are described as glassy and above it they are soft and flexible and are then described as rubbery. It is unacceptable for adhesives to pass from one state to another during service. Most cold cured epoxy polymer resins will have a T_g of between 500°C and 600°C and therefore will soften at this temperature when exposed, for instance, to the sun rays (Hollaway, 2005).

As structural adhesives, epoxies are the most widely accepted and used. Two-part epoxies, first developed in the 1940s (Lee & Neville, 1967), consist of a resin, a hardener or cross-linking agent which causes polymerization, and various additives such as fillers, tougheners or flexibilizers, all of which contribute to the physical and mechanical properties of the resulting adhesive. Formulation can be varied to allow curing at ambient temperature (e.g. cold-cure epoxies), which uses the most common hardeners; aliphatic polyamines, resulted in hardened adhesives which is rigid and provide good resistance to chemicals, solvents and water (Mays & Hutchinson, 1992). During the 1950's epoxies began to be used commercially in the construction industry. Tremper (1960) describes the use of epoxies in repairing concrete highways and Gaul and Apton (1959) for repair on runways and roads. Wakeman et al. (1962) describes resin injection of cracked pile caps and beams.

Epoxy resin is chosen over other polymers as adhesive agents for civil engineering because it has high surface activity and good wetting properties for a variety of substrates. It may also be formulated to have a long open time which is the time between mixing and closing of the joint. For a cured adhesive, it has high cured cohesive strength hence the joint failure may be dictated by the adherend strength, particularly with concrete substrates. Epoxy resin may be toughened by the inclusion of dispersed rubbery phase. It has low shrinkage hence residual bondline strain in cured joint is reduced. It also exhibit low creep and superior strength retention under sustained load. It can accommodate irregular or thick bondlines particularly with concrete adherends. In order to achieve desirable properties, formulation can be readily modified by blending with a variety of materials such as surfactants, fillers and other modifiers (Mays & Hutchinson, 1992). Although epoxies perform best when the adherends are properly prepared, they are more forgiving than most adhesives when it comes to cured strength, because they tolerate being applied in thick sections, helping overcome poor joint design (Fisher, 2005).

According to Pereira and de Morais (2003), where epoxy adhesives are concerned, joints strength were found to depend essentially on the level of peel stresses near the bondline edges

2.2.1 Adhesive properties

The engineer will be concerned with the behavior and performance of the selected adhesive right from the time he purchases it from the manufacturer. The properties of interest are likely to include the properties through the mixing, application and curing phases to its properties in the hardened state within a joint over the intended design life. Table 2.2 summarized the general adhesive properties (Mays & Hutchinson, 1992).

Table 2.2: Adhesive properties (Mays & Hutchinson, 1992)

Stage	Properties
Unmixed	shelf life
Freshly mixed	viscosity usable life wetting ability joint open time
During cure	rate of strength development
Hardened	strength and stress/strain characteristics fracture toughness temperature resistance moisture resistance creep fatigue

2.3 Adherend (Metallic)

Adhesive bond involving metals are typically stringer than those formed with other substrates, because of their higher surface energy, which allows them to adhere more readily with lower surface energy adhesives. The adhesive bond may initially be stronger than a comparable welded joint but not as resistant to adverse environments, possibly resulting in reduced life due to accelerated aging of the adhesive. The greater material stiffness of metals is also an advantage because it allows for use of more rigid adhesives, which generally form a stronger bond, without concern for cracking or otherwise overstressing then from flexing of the substrate.

2.3.1 Steel

Steel is the most versatile metal in traditional construction materials and the most reliable in terms of quality consistency. Structural steel acts as load bearing frames in buildings because of its strength and speed of erection. Steel is also used in conjunction with concrete in composite and combined frame and shear wall construction. Therefore, connection in structural steel is significant to maintain the integrity and stability of the structure as a whole. By its nature, structural steel is also the strongest and may be used in long span lengths with a relatively low self weight. Using modern technique for corrosion protection, the use of steel provides structures having a reliable life. Eventually, when the useful life of the structure is over, the steelwork may be dismantled and this significant residual value could not be achieved with alternative materials. There are also many cases where steel frames have been used again, or erected elsewhere (MacGinley, 1997) .

Structural steels are alloys of iron, with controlled amounts of carbon and various other metals such as manganese, chromium, aluminum, vanadium, molybdenum, niobium and copper. The carbon content is less than 0.25%, manganese less than 1.5% and the other elements are in trace amounts. The alloying elements control grain size and hence steel properties, giving high strengths, increased ductility and fracture toughness. High-carbon steel is used to manufacture hard drawn wires for cables and tendons (MacGinley, 1997).

Structural steel must possess sufficient ductility so as to give warning, preferably by visible deflection, before collapse condition are reached in any structure which becomes unintentionally loaded beyond its design capacity and to allow use of fabrication process such as cold bending. According to Hayward et al (2002), ductility may be defined as the ability of the material to elongate or strain when stressed beyond its yield limit shown as the strain plateau in Figure 2.1. Two measures of ductility are the elongation (or total strain at fracture) and the ratio of ultimate strength to yield strength.

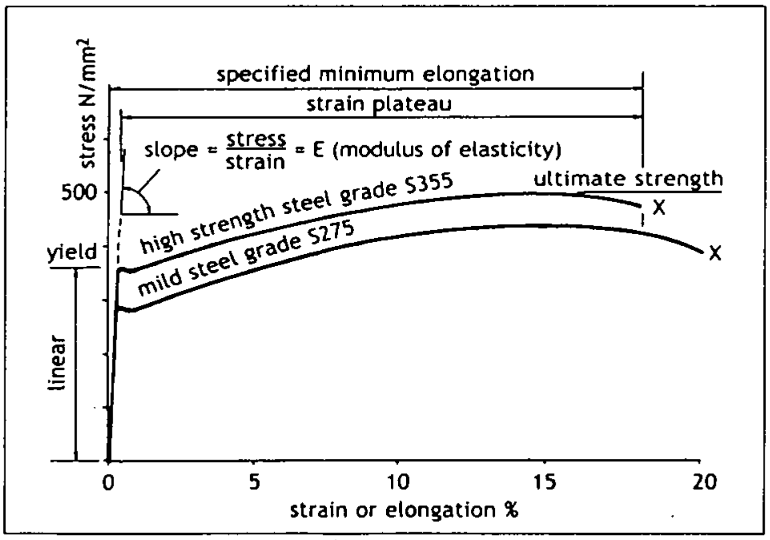


Figure 2.1: Stress-strain curves for structural steel (Hayward et al, 2002)

Generally, there are several grade of steel available in the market ranging from mild steel grade to high strength steel grade as shown in Table 2.3. Each grade will have different properties and yield strength and is used in certain industry. With the advancement of technology, higher grade steels are produced with different specification. In general it is economic to use high strength steel grade (S355) due to its favorable cost: strength ratio compared to mild steel grade (S275) that is typically showing a 20% advantage. Where deflection limitations dictate a larger member size (such as in crane girder), then it is more economic to use mild steel grade (S275) which is also convenient for a very small project or where the weight in a particular size is less than, say 5 tonnes, giving choice in obtaining material from a stockholder at a short notice (Hayward et al, 2002).

Table 2.3: Guidance on steel grades in BS 5950 (Hayward et al, 2002)

Steel grade	Thickness* less than or equal to mm	Design strength p_y N/mm^2
S275	16	275
	40	265
	63	255
	80	245
	100	235
	150	225
S355	16	355
	40	345
	63	335
	80	325
	100	315
	150	295
S460	16	460
	40	440
	63	430
	80	410
	100	400

2.4 Adhesive Bonding

Adhesive bonding is defined as a process of joining materials with the aid of a substance, acting as a chemical agent, capable of holding those materials together by surface attachment forces. The materials being joined are called the adherends, while the bonding agent is called the adhesive. The forces that enable the surface attachments arise from several fundamental sources, most of which are chemical in origin, but some of which can be mechanical or even electrostatic. These forces combined to create a mechanism which is termed adhesion, that is the sticking together of different materials. There are two types of adhesive bonding called as structural bonding and non-structural bonding. In structural bonding, the primary function of the process is to develop sufficient strength in the joint and also the set adhesive. The bonded adherend is then stressed to a point that is either the adherend or the adhesive fails. Such failure would occur by plastic yielding or fracture in either a ductile or brittle manner, depending on the type, condition, and strain behavior of the adhesive (Messler, 2004).

There are some basic requirements for the creation of satisfactory adhesive bonded connections. These include the selection of a suitable adhesive, adequate preparation of the adherend surfaces to ensure good adhesion between the adhesive and the adherends, appropriate design of the joint and a controlled fabrication of the joint itself. Some form of post bonding quality assurance is also desirable (Hollaway & Leeming, 1999)

Adhesive bonding has its advantages and some drawbacks which should be taken into consideration to achieve an adhesive bonding of high quality. The advantages and drawbacks of adhesive bonding are given in Table 2.4. With the advantages of adhesive bonding, the designer should utilize this new alternative for the development of novel design concepts and structural configuration.

Table 2.4: Advantages and drawbacks of adhesive bonding (Mays & Hutchinson, 1992 and Messler, 2004)

Advantages	Limitations
Ability to join similar or dissimilar materials	Surface pretreatments is required to achieve maximum joint strength and durability
High load-carrying capacity possible due to large (surface) area bonding	Sensitivity to peel or cleavage versus pure tension or shear
Damp vibrations and shock loads	Extremely complicated stress analysis required for critical applications
Causes little or no change to the chemistry or structure of adherends	Requires rigid process control
Suitability to very thin as well as thick adherends	Fairly long curing times frequently involved
Insulates against electricity or heat	Repair of defective joints is virtually impossible
Resists fatigue and imparts damage	Direct inspection is not possible; NDE methods are needed
Uniform stress distribution in joints resulting in improved fatigue resistance	Poor resistance to elevated temperature and fire
Weight savings over mechanical fastenings	Structural joints require proper design
Smooth external surfaces are obtained	Brittleness of some products, especially at low temperatures
Corrosion between dissimilar metals may be prevented or reduced	Sensitivity to attack by some solvents
Glueline acts as a sealing membrane	Poor creep resistance of all products at elevated temperatures
No need for naked flames or high energy input during joint fabrication	Toxicity and flammability problems with some adhesives
Capital and/or labor costs are often reduced	Equipment and jigging costs may be high
	Long-term durability, particularly under severe service conditions, is often uncertain

An adhesive bonding provides many advantages over mechanical fastening such as using rivets, screws and bolts. As compared to other assembling techniques, adhesive joints have more uniform stress distribution, lower stress concentration, better fatigue life, and corrosion resistance. However, despite all the advantages mentioned above, the difficulty in disassembly of adhesive joints for inspection of damage and lack of suitable non-destructive evaluation methods has restricted their application in critical structures where safety must be given paramount attention (Aga & Woldesenbet, 2006).

Hashim (1999) studied the important properties and limitations of structural adhesive materials particularly the durability in wet environments and the resistance to elevated temperature. He stated that the main mechanisms that contribute to strength reduction in bonded steel joints in wet environments are; interfacial attack to displace adhesive from the adherend, degradation of adhesive strength due to plasticization and corrosion of adherends. An adhesively bonded joint has a relatively high sensitivity to temperature compared with that of structural metals. Bonded structures may experience high operating temperatures, be subject to high solar gain in a hot climate or be subject to accidental fire conditions. The resistance to elevated temperature will depend mainly on the glass transition temperature of the adhesive. However, high-temperature commercial adhesives are now available and these include modified epoxies, bismaleimide and cyanate-based adhesives. They have been used in many high-temperature applications (Adams & Wake, 1984; Jeandrau, 1989; Millard, 1984; and Dixon, 1995) mainly in the aircraft industry.

2.4.1 Forces in an adhesive bonding

In adhesive joint, there are typically two substrate materials joined using appropriate types of adhesive such as epoxy or methyl acrylate. The substrates or adherends are held by some forces that provide the strength to the joints. Figure 2.2 shows the forces between two substrates bonded by an adhesive compound. When two surfaces are held together by surface forces; the phenomenon is termed as adhesion. In a bonded joint, the force required to pull the adhesive away from the surface of adherends is termed as the adhesion strength. As the adhesive is cured, it acquires an internal strength. The force required to deform permanently the cured joint is called as the cohesive strength. (Pasternak et. al., 2004)

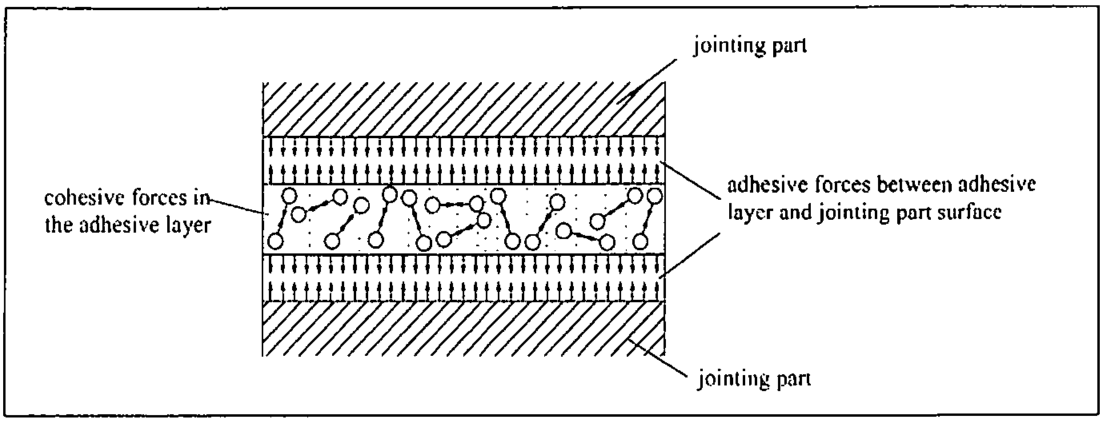


Figure 2.2: Adhesive and cohesive forces in an adhesive sealing. (Pasternak et. al., 2004)

2.4.2 Stress in adhesive bonding

A joint type that is going to be employed to produce an adhesive joint must be designed specifically for the use of adhesives. Petronio (1977) states that in order to achieve maximum success, joint design should follow several general principles, namely to stress the adhesive in the direction of maximum strength (i.e. in compression or in shear), to provide the maximum bond area, to make the adhesive layer as uniform as possible, to maintain a thin and continuous bondline and to avoid stress concentration.

Excluding compression, there are generally four types of stress that are likely to exist in an adhesive joint namely tensile stress, shear stress, cleavage and also peel stress as depicted in Figure 2.3. Adhesives are generally strongest when stressed in shear because all of the bonded area contributes to the strength of the joint and the substrates are relatively easy to keep aligned (Petrie, 1999). Shear stress results when forces acting in the plane of the adhesive try to separate the joint elements by sliding them past one another. Pure shear imposes a uniform stress across the entire bonded area, thereby using the entire joint area to carry the applied loads to the best advantage.

Thus, whenever possible, most of the loading applied to an adhesive bonded structure should be transmitted through the bonded joints in shear (Messler, 2004). Joints that are dependent on the shear strength of adhesive are relatively easy to assemble and are commonly used in practice (Petrie, 1999).

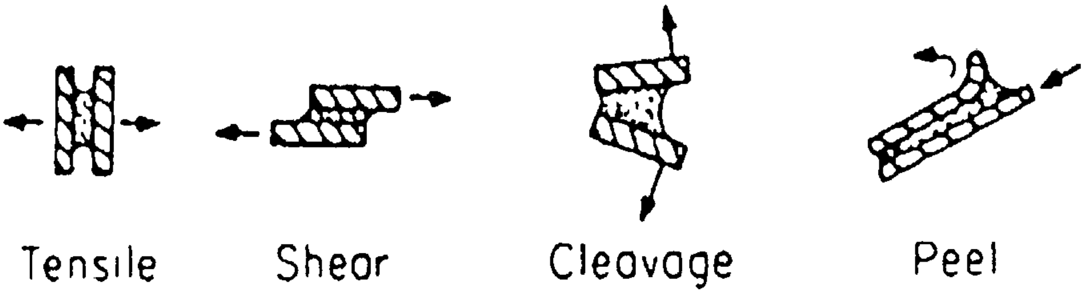


Figure 2.3: Basic types of stress common to adhesive and sealants (Petrie, 1999)

Shear stresses are measured as force per bonded area. By overlapping the adherends, one places the load bearing area in shear. A large amount of stress is localized at the ends of the overlap, while the centre of the lap joint contributes little to joint strength as illustrated in Figure 2.4. In other word, depending on the joint geometry and physical properties of the adhesive and adherends, two small bands of adhesive at each end of the overlap may provide the same bond strength as when the entire overlap area is bonded with adhesive (Petrie, 1999).

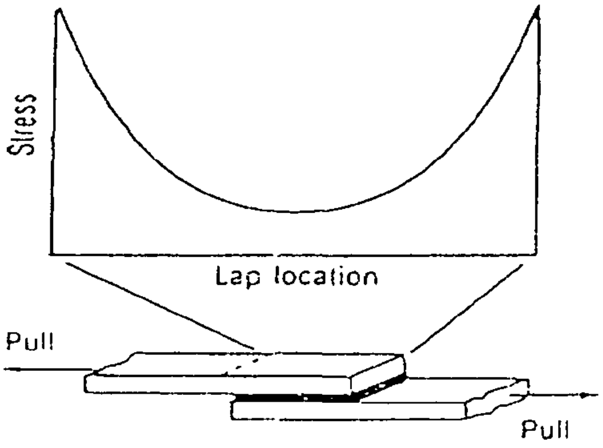


Figure 2.4: Stress distributions on an adhesive when stressed in shear (Chastain, 1974)

Lap shear strengths are directly proportional to the extent or length of the overlap, but the unit strength actually decreases with the width of the overlap. The optimum shear strength of a bonded joint is largely dependent on the shear modulus of the adhesive and its optimum thickness (Messler, 2004).

Tensile stress is developed when forces that act perpendicular to the plane of the joint are distributed uniformly over the entire bonded area. In tension, high stress regions are developed at the outer edge of the adhesive, and those edges then support a disproportionate amount of the load. When the first small crack occurred at the weakest area of one of the highly stressed edges, it will propagate swiftly and lead to the failure of the joint. To avoid this kind of situation, the joint should be properly designed by having parallel adherend surfaces and axial loads. However, in practical, bondline thickness is difficult to control and loads are rarely axial and hence result in an undesirable cleavage and peel stresses. Therefore, tensile joints should be designed with physical restraints to ensure continual axial loading and the adherends must also have sufficient rigidity so that the stress is distributed evenly over the entire bonded area (Petrie, 1999).

Cleavage and peel stresses are undesirable for adhesives. Cleavage stresses tend to perpendicularly separate bonded rigid parts from one another at an end or edge of the bond. The situation is much like splitting wood with a triangular wedge. The failure or crack propagates progressively from the end of the bond which undergoing cleavage. Thus resistance to failure is concentrated primarily at the edge or end of the bond. In some cases, cleavage stresses may be introduced at the bond ends when a lap joint undergoes tensile shear loading. Supposedly, the tensile shear loading acts to force the adherends into the same plane however, because of the overlap cleavage forces result when the adherends deform to become coplanar. Such forces can lead to failure of the bond at stress levels lower than those expected with stiff and non-deformable adherends (Schneberger, 1983).

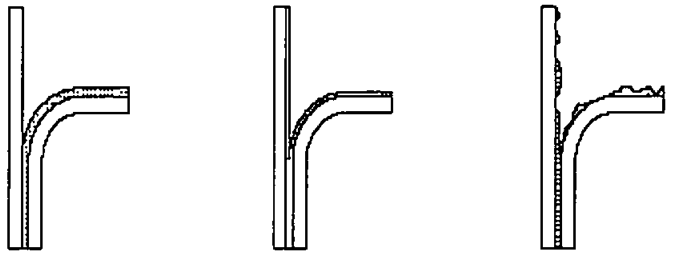
Peel stress is similar to cleavage in which the stress is concentrated at the failing edge of the bond. However this stress applies to a joint where one or both of the adherends are flexible which result in bond failure that occurs progressively at relatively low loads from the end of the bond undergoing the cleavage stress (Schneberger, 1983). Thus, the angle of separation (or the angle made by the separating adherends) can be much greater for peel than for cleavage (Petrie, 1999).

Joints loaded in peel or cleavage give lower strength than the joint loaded in shear because the stress is concentrated at only a very small area of the total bonded area. A large amount of stress is localized at the end of the bond that is bearing the load while the adhesive at the other end of the bond provides little to the ultimate strength of the joint. These two types of stress should be avoided where possible (Petrie, 1999).

2.5 Failure Modes

Generally, there are two type of forces exist in an adhesive connection which are adhesion and cohesion. Adhesion holds two materials together at their surfaces. Cohesion holds adjacent molecules of a single material together. Adhesive or sealant joints may fail either adhesively or cohesively. Adhesive crack is a failure occurred at the interface between adherend and the adhesive. It happens because of the presence of a weak-boundary layer which sometimes resulted due to improper surface preparation or adhesive selection. Cohesive crack is the internal failure of adhesive layer or sometimes in one of the adherends depending on the types of material used in the fabrication (Pasternak et. al, 2004). Ideally, the bond will fail within one of the adherends or the adhesive. This indicates that the bond strength of the jointed materials is less than the adhesive strength between them. Usually, the failure of joint is neither completely cohesive nor completely adhesive. Measurement of the success of a particular joint is based on the relative percentage of cohesive failure to adhesive failure (Messler, 2004).

The objective of any good bond design is to obtain substrate or adherend failure; that means the bond is stronger than the joining material themselves. In substrate failure, the parent materials fail either away from the joint or near the bond area by tearing away the parent materials. Another kind of desired failure mode might be the cohesive failure of the adhesive, in which the adhesive splits in the bond area but it remains firmly attached to both substrates. On the other hand, adhesive failure, where adhesive releases from the adherend, is considered a weak bond and is generally unacceptable (Mazumdar, 2002). Figure 2.5 illustrates several type of crack occurred as a result of joint failure.



adhesive crack

cohesive crack

mixture of adhesive and cohesive crack

Figure 2.5: Crack types (Pasternak et al, 2004)

2.5.1 Premature failure in adhesively bonded joints

Premature failure of adhesively bonded joints is a serious issue. There are many causes that contribute to this failure, however, the exact cause of premature failures is difficult to determine. For instance, if the adhesive fails to wet the surface of one of the adherends completely during adhesive application, the bond strength is certainly less than optimal due to the reduction in bonded area. Furthermore, adhesion is less than expected in areas where a weak boundary layer forms. Internal stresses arising from adhesive shrinkage during setting or curing, or stresses arising from different coefficients of thermal expansion, can also cause premature failures (Messler, 2004).

The types of stress acting on the completed bonds, their orientation relative to the adhesive layer, and their rate of stress application are also influencing the failure. Operating environmental factors such as temperature, moisture level (e.g., presence of water or humidity), salt or salt spray, organic solvents, and radiation can also seriously degrade the performance of adhesive-bonded joints. Table 2.5 lists the major causes of failure in adhesive-bonded joints (Messler, 2004).

Table 2.5: Major causes of premature failure in adhesive-bonded joints (Messler, 2004)

Adhesive is not compatible to adherend(s), leading to: - failure of the adhesive to wet the adherend surface(s) - adverse chemical reactions at the bonding interface(s)
Improper adherend preparation, leading to: - incomplete wetting of the adherend by the adhesive - void entrapment or gas (porosity) formation at bonding interface(s) - weak boundary layers (e.g., oxides, tarnish, reaction zones) at bonding interface(s)
Internal stresses, resulted due to: - adhesive shrinkage - differential coefficients of thermal expansion between adherend and adhesive
Out-of-plane peel or cleavage loading resulted due to improper joint design
Processing errors, resulted due to: - improper adherend surface preparation - improper adhesive application (e.g., working time exceeded) - improper curing and setting
Operating environment leads to degradation of the adhesive or adhesive-adherend interface(s)

2.6 Joint Design

A successful adhesive joint design provides the maximum strength for a given area of bond for structural efficiency. The interface area between adhesive and adherend provides the strength in an adhesive joint therefore the designer must ensure that there is sufficient contact area to provide the required strength. Furthermore, the selection of a joint design is also influenced by the limitations in production, construction facilities, production cost constraints, and desired final appearance of the part or assembly (Mays & Hutchinson, 1992).

The basis principle in adhesive joint design is that, joints intended to be adhesive bonded must be designed specifically for the use of adhesives, just as the joints intended to be mechanically fastened or welded should be designed specifically for mechanical fastening or welding, respectively (Messler, 2004). Although it may be tempting to use the joints originally intended for the other method of fastening, adhesives require special joint design to achieve the optimum properties. The practice of using the joints designed for some other method of assembly and slightly altering them to adapt to adhesives can lead to unfavorable and fatal results (Petrie, 1999)

Petronio (1977) states that for maximum success, joint design should follow several general principles, namely (1) to stress the adhesive in the direction of maximum strength particularly in compression or in shear; (2) to provide for the maximum bond area; (3) to make the adhesive layer as uniform as possible; (4) to maintain a thin and continuous bondline; and (5) to avoid stress concentration (Mays & Hutchinson, 1992).

Various design approaches have evolved following the empirical development of appropriate joint configurations from the long historical development of load-bearing joints in, and between, engineering materials.
It must however be emphasized that structural bonded joints exist in engineering disciplines other than those involving civil engineering tend to be formed with thin bondlines, often with relatively high modulus adhesives, whereas the general concern in the construction industry is with thick bondlines, often with lower modulus materials. This is very important due to the fact that the nature of the resultant bondline stress distributions of loaded joints may be significantly different (Mays & Hutchinson, 1992).

2.6.1 Factors affecting joint strength

The strength of an adhesive joint is determined primarily by the following factors: (1) the mechanical properties of the adhesive and the adherend(s); (2) the presence of any residual (internal) stresses resulted due to the processing; (3) the degree of true interfacial contact that is achieved through the adhesive application and wetting; (4) the type of loading in which the joint will be subjected to; and (5) the joint geometry. These factors are further illustrated in Table 2.6 (Mays & Hutchinson, 1992).

Srivastava (2003) showed that the adhesive bond strength increases with the increase of strain rate and decreases with increase in exposure temperature. Deb et al (2007) found out that the effect of increasing extension rate at a given temperature is generally to increase the failure load while simultaneously decreasing the joint ductility. They stated that at a high temperature, the adhesive becomes softened which is reflected in the overall joint behavior with a perceptible fall in joint strength compared to that at room temperature. At the same elevated temperature, both adhesive as well ad the joint exhibit a greater degree of strain rate sensitivity.

It is understood that the adhesive itself primarily influence the strength of the joint, however the stress that is required to split a joint is not a well-defined materials constant. When two adherends are bonded, the resultant composite has at least five elements, namely the adhesive itself, two adhesive/adherend interfaces, and two adherends. If a primer is applied to both adherend surfaces, the number of elements increases to at least nine. These elements involving a metallic adherend are illustrated schematically in Figure 2.6.

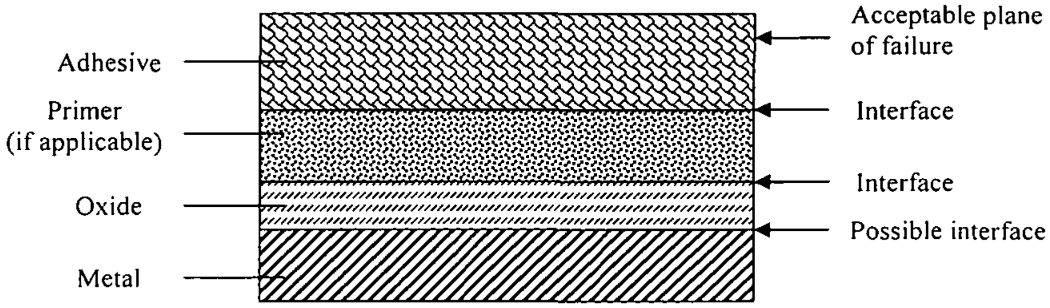


Figure 2.6: Elements of a metal adherend/adhesive interface (Mays & Hutchinson, 1992)

However, in reality adhesive joints do not consist of simple, separate, elastic materials with a clear mathematical geometry. Metal adherend surfaces are micro-rough, with oxide layers and the surfaces readily adsorb air-borne contamination. Also, the thickness and the modulus of primer layers, if employed, are often unknown, and the thickness and the properties of the adhesive layer are difficult to regulate and to determine.

Table 2.6: Factors affecting joint strength (Mays & Hutchinson, 1992)

Factors	**Causes**
Joint design	Geometrical configuration Bondline thickness
Adherends	Mechanical properties Susceptibility to deterioration Linear coefficient of thermal expansion Permeability
Adherend surface	Surface chemistry Surface topography Surface cleanliness
Nature of primer (if applicable)	Viscosity Chemical composition Mechanical properties
Nature of coupling agent (if applicable)	Chemical functionality Dilution factor in solution
Nature of adhesive	Rheology – viscosity Chemical composition Reactivity – pot life Mechanical properties Linear coefficient of thermal expansion Resistance to biodeterioration Permeability
Bonding conditions	Temperature of substrate Ambient temperature Humidity Air-borne contamination Open time Cure time Pressure
Internal stress	Cure shrinkage Temperature Environmental conditions Nature of adherends Nature of adhesive
Service/environmental conditions	Stress Moisture Temperature
Testing conditions	Strain rate Cyclic frequency Temperature

2.6.2 Joint configuration

Determining the appropriate construction of an adhesive joint involves many considerations and compromises in regard to the substrate selection, joint geometry, joint loading, and adhesive. It is also driven by the design requirements which should include a maximum load capability, loading profile, operating environment, and manufacturing limitations such as cure time and fixturing. The substrate being joined must not only provide the required strength but also have the desired adhesion characteristics. Therefore the design engineer must consider the substrate strength concurrently with the required bond strength to produce a design that includes compatible materials. Postponing the bonding issues until the design is too mature to alter the substrate can result in increased manufacturing costs and worse, premature failure of a poorly designed joint. Joint geometry and how it will be loaded in the final assembly needs also to be considered when selecting the substrate as they can often be used to offset reduced adhesion or low strength (Fisher, 2005).

The ideal joint can be achieved when the adhesive is stressed in the direction in which it best resists failure under all practical loading conditions. A favorable stress can be applied to the joint by adopting a proper joint design. Some joint designs may be impractical, expensive to make, or difficult to align. The design engineer will often have to take into consideration these factors in order to produce optimum and excellent adhesive joint performance (Petrie, 1999).

The basic geometry of an adhesively bonded joint involves the thickness of the adherends, the width of the joint, adherend overlap, and adhesive thickness (Figure 2.7). Generally, joints perform best when the adherends are thick, joint width is maximized, and the overlap and bondline minimized. They should also maximize shear and compressive loading, and minimize peel, cleavage, and tensile loading (Fisher, 2005).

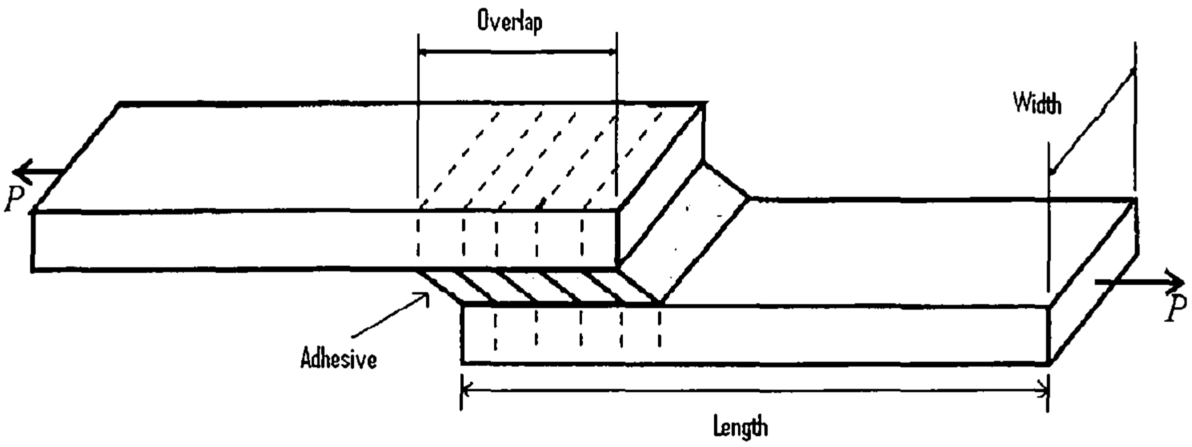


Figure 2.7: Joint geometry

Figure 2.8 indicates that stresses are concentrated at the ends of a lap bond with the result that bond strength does not increase linearly with overlap. Figure 2.9 illustrates that the effect of bond overlap on strength rises rapidly and then levels off (Schneberger, 1983). Strength can sometimes be increased by increasing the overlap length, but the relationship is not linear. Because the ends of the bonded joints carry a higher proportion of the load than the interior area, the most efficient way of increasing joint strength is by increasing the width of the bonded area (Harper & Petrie, 2003).

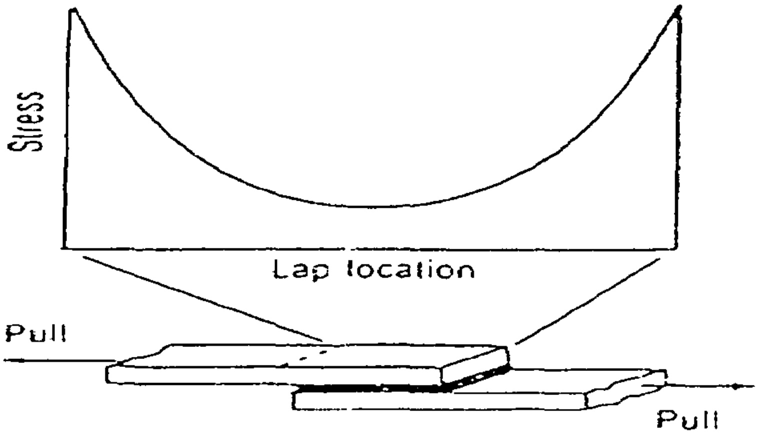


Figure 2.8: Stress distribution on adhesive when stressed in shear (Chastain, 1974)

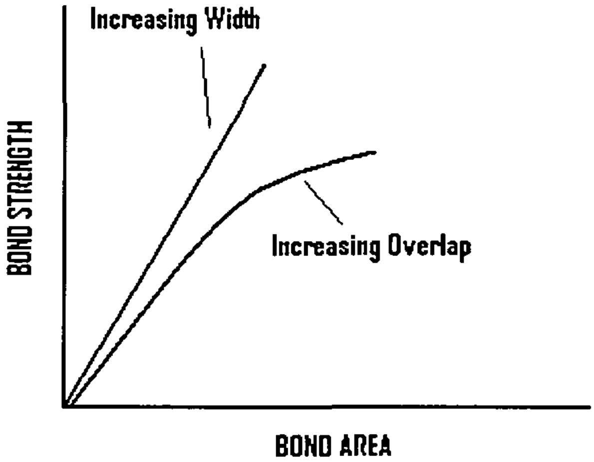


Figure 2.9: The effect of overlap and width on bond strength (Schneberger, 1983)

The joint configuration that is most practical for meeting the requirements must also include consideration of the adhesive and its curing methodology. Figure 2.10 illustrated the common joint configuration used in the industry.

Lap joint is the most commonly used in adhesive bonded joints as it is simple to make in terms of both joint element fabrication and assembly. It can be used with thin adherends to minimize structural weight, and the shear stress is almost always developed in the adhesive. However, unfortunately, bending can easily arise in simple lap joints, leading to cleavage. The double-lap joint has a balanced construction, which is subjected to bending only if loads on the double side of the lap are not balanced (Harper & Petrie, 2003). In the double-lap joint, the adhesive peel stresses are reduced in comparison to a single-lap joint and it is commonly accepted that that adhesive fails in shear (Hart-Smith, 1973).

The bevel lap joint is more efficient than the single lap joint by having beveled edges. The beveled edges allow conformance of the adherends during loading, thereby reducing cleavage stress on the ends of the joint. However, the tapering might increase the cost of manufacturing (Harper & Petrie, 2003).

Butt joint is also one of the simplest joint but also the weakest. It cannot withstand bending loads because this leads to the development of cleavage forces and stresses in the adhesive (Perry, 1958). Strap joint on the other hand, is a very simple and strong joint that does not require machining (Fisher, 2005). Strap joints keep the operating loads aligned and are generally used where overlap joints because of the adherend thickness. Like the lap joint, the single strap is subjected to cleavage stress under bending forces. The double strap joint is more desirable when bending stresses are encountered (Harper & Petrie, 2003).

Single lap joint

Butt joint

Double lap joint

Scarf joint

Bevel joint

Single strap joint

Step joint

Double strap joint

Figure 2.10: Types of adhesively bonded joints (Petrie, 1999)

The thickness of adherends also influences the bond strength. In a shear joint for example, that is made from thin, flexible adherends, there is a tendency for the bonded area to distort because of the eccentricity of the applied load. This distortion causes cleavage stress on the ends of the joint, and the joint strength may be considerably impaired. On the other hand, thicker adherends are more rigid and the distortion is not as much a problem as with thin adherends (Harper & Petrie, 2003).

Thickness of adhesive is another geometric variable that should be taken into consideration in the joint design. Thin adhesive layer offer the highest shear strength provided that there is no chance of bond starvation, where the entire adhesive has been forced out. However, a thinner bondline increases the stress concentration at the ends of the overlap (Crocombe, 1989). Excessively heavy adhesive thickness causes greater internal stresses during cure and concentration of stress under loads at the ends of a joint (Harper & Petrie, 2003). However, making the bondline thicker can sometimes reduces stress by absorbing more loads when the adhesive is more flexible than the substrate (Gaston, 2003). Analytically, it can be shown that the thicker adhesive the better is the load transfer under shear, although overall joint stiffness is decreased. Nevertheless, as the adhesive thickness increases so does the likely occurrence of bond-line porosity which decreases the shear and peel strengths markedly over the life span of the joint (Hollaway, 2005). A study by Aga & Woldesenbet (2006) shown that the debonding area decreased as bond thickness increased. This is due to the damping effect of the viscoelastic adhesive layer between the adherends.

2.7 Surface Preparation

Surface preparation is the key to bond durability and a critical element of any adhesive application. It must be considered concurrently during the selection of the substrate and adhesive so that they may complement each other (Fisher, 2005). The main objective of surface preparation is to ensure that the adhesion is developed to the extent that the weakest link in the joint is either in the adhesive or in the adherend. Any foreign materials such as dirt, grease, cutting coolants and lubricants, ink or crayon marks, visible water, obvious moisture and weak surface scales such as rust must be thoroughly removed (Messler, 2004).

This procedure is carried out to remove weak boundary layers, provide a surface which is spontaneously wettable by adhesive, and provide a surface that is microscopically rough. If they are not removed, the adhesive would not be able to reach and wet the actual adherend surfaces, and hence influence the final joint strength (Messler, 2004).

The surface preparation procedure must be safe to handle and should not be flammable or toxic to make and also economical and practical. The process should be easy to monitor and control in a production to provide fast processing time. The surface treatment should not leave a weak boundary layer and should allow for practical time between preparation and application of the adhesive. An unprepared metal surface, as it comes from the mill, has surface features resulting from rolling or forging operations and may not have the size scale necessary for good adhesive jointing. For a metal to be reliably adhesively jointed, the surface has to be changed into a clean metal or substrate and of predictable chemistry and morphology (Petrie, 1999).

The aerospace industry, motivated by the need to improve bond durability, has developed complex and detailed surface preparation techniques and fabrication procedures. However, for most of the parts, they are appropriate only for aluminum or titanium adherends. For steel adherends, grit blasting and wiping with a solvent are generally used. The comparison of surface treatments is shown in Figure 2.11. Surface preparation consists of solvent cleaning, intermediate chemical, physical and/or mechanical cleaning, and chemical treatment. These steps are better explained in Table 2.7 (Messler, 2004).

Surface Treatment	Cost	Quality
None	Inexpensive	Poor
Dry Rag Wipe	↓	↓
Solvent Degrease		
Vapor Degrease		
Mechanical Abrasion		
Plasma		
Chemical Etch		
Conversion Coating		
Anodizing	Expensive	Excellent

Figure 2.11: Comparison of surface treatment in terms of cost and quality (Petrie, 1999)

Metals are pre-treated by using physical and chemical methods. Physical methods include solvent degreasing, abrasion and grit blasting, which may be sufficient if the jointing requirements are modest. However, if service conditions are demanding, then it is likely that a chemical treatment will be necessary. Steels are usually used in many applications than aluminum or titanium and cost considerations demand respectively simple pretreatments such as grit blasting (Mays & Hutchinson, 1992).

There is no standard procedure or equipment available to ensure that the surface of pretreated substrate is clean, thus the term 'clean' would be difficult to define in this case. Since this is a very subjective terminology, the quality of the surface treatment process will ultimately depends upon rigid process controls and well-trained operators (Petrie, 1999 and Adams, 2000).

Mechanical abrasion is the most widely used surface preparation methodology, being suitable for almost all materials. Abrasion acts to remove the weak boundary layers and change the topography of the substrate therefore increasing the bondable surface area on a microscopic scale. It is further postulated that the roughened surface aids in the wetting action of the adhesive and provides a modicum of mechanical "keying" to augment the adhesive force although, there is a degree of doubt as to whether this actually occurs (Savage, 2005).

Although it has been emphasized that the surface preparation is the key to maximizing joint durability and joint quality, unfortunately, in the practice of adhesive bonding for applications in construction, surface preparation is likely to be the most difficult process to control. The choice and specification of preparation procedures should be influenced mainly by the required durability and demand simple reproducible processes. However, the location and scale of operations, the nature of the adherends, the adhesive to be used, the safety and environmental aspects, and of course the cost, all have to be taken into consideration (Mays & Hutchinson, 1992).

Table 2.7: Methods of cleaning for adhesive bonding (Messler, 2004)

Cleaning Method		Roles	Examples
Solvent Cleaning		To remove light, soluble surface contaminants	▪ Vapor degreasing ▪ Solvent wiping, immersion, spraying
Intermediate Cleaning	Chemical	To remove tenacious contaminants or loosely adhering layers of tarnish or scale	▪ Detergent cleaning ▪ Alkaline cleaning ▪ Acid cleaning
	Mechanical	To remove tenacious tarnish and/or roughen the adherend surfaces to improve adhesive grip	▪ Wire Brushing ▪ Adhesive scrubbing ▪ Grit blasting ▪ Sanding
	Physical	To remove contaminants and/or activate the adherend surfaces to facilitate chemical bonding	▪ Electrical corona discharge ▪ Flame, plasma, or laser ablation
Chemical Treatment		To produce a surface on the adherends that better accepts the adhesive	▪ Surface chemical conversion process for metal ▪ Application of dilute solution of the active agent in the adhesive as a primer

2.8 Curing

Fabrication of a successful adhesive joint is also influenced by the condition of curing process of the adhesive. If the joint is handled too soon after it is assembled the adhesive will not have had time to set up sufficiently to support the adherends, possibly resulting in separation of the joint or unseen separation of the adhesive within the joint. However, allowing it to remain fixtured for too long may unnecessarily prolong the assembly process and increase manufacturing time and expense (Fisher, 2005).

The adhesive hardening mechanisms, curing process and properties have been studied extensively. These studies indicate that during curing, the adhesive changes its phase from liquid to solid, and the molecular chain structure of the adhesive is then changed to a desired one through a chemical insertion reaction Depending on the type of the adhesives used, the curing process may be triggered and progressed by applied heat, pressure, chemical reaction, or their combinations. Raising or lowering the temperature provides the appropriate. The engineering adhesives employ chemical changes to achieve their high performance, solid state, which is irreversible and therefore, once hardening has been induced the original condition cannot be regained (Lees, 1989) .

For two part adhesives comprising a resin and a hardener, normally curing is set at room temperature or elevated temperatures such as 50°C. When two parts are mixed, a chemical reaction commences immediately and from this point the product has a limited usable life. The chemical reaction generates heat and is therefore described as exothermic. The temperature developed and the time taken to achieve it depends on the volume of adhesive used, when more adhesive is mixed, more heat is released, and if the heat cannot be dissipated because of the bulk, a shorter setting time can be anticipated as a consequence of the higher temperature reached and the higher reaction rate achieved. A lap joint in parallel, the adhesive in the joint behaves in a similar way and therefore the time to develop handling strength indicates the general cure rate at a stable temperature (Lees, 1989).

The dense cross-linking that occurs during curing in thermosetting adhesives results in good shear strength from room temperature to about 260°C, good resistance to heat with little elastic or creep deformation under loads at moderately elevated temperatures, and good resistance to organic and inorganic solvents (Messler, 2004).

2.9 Conventional Methods of Joining vs. Adhesive Bonding

Connections between metal components are required in most of the applications, which is one of the critical steps of every design. In steel structures, connections are fabricated either by the use of bolts or welds. There were also two other traditional connections; rivet and plates and cleats, which are no longer in practice. There are many advantages and limitations associated with the application of mechanical joints particularly for bolt and welding, which are commonly used nowadays. In order to minimize the deficiency of the traditional methods of joints, there is a need for an alternative technique, which may be used together with traditional methods or can be employed individually.

Practically, holes for bolts are punched, sub punched and reamed, or drilled. Punching causes the metal piece to stretch and the magnitude of stretch depends upon the thickness of the metal and the number of holes. Precautions should be taken to ensure that the bolts do not become loosen, especially in situations where fluctuating loads cause them to loose.

On the other hand, welding is a process of connecting two or more pieces of steel together by melting the metal at the joint by applying heat at high temperature. Welding is extensively used in fabricating shops where specialized equipment is available and where control and inspection procedures can be exercised, that may insure the quality of joints.

Welding technique is often cheaper than the bolting because there is a great reduction in the capacity due to the preparation and hence in welding greater strength can be achieved, the members or plates no longer being weakened by bolt holes, and the strength of the weld metal being superior to that of the material connected. In addition, welds are more rigid than the other types of load-transferring connectors. On the other hand, welding often produces distortion and high local residual stresses, and results in reduced ductility, while site welding may be difficult and costly. Figure 2.12 shows the stress distribution in welding, bolting and adhesive bonding.

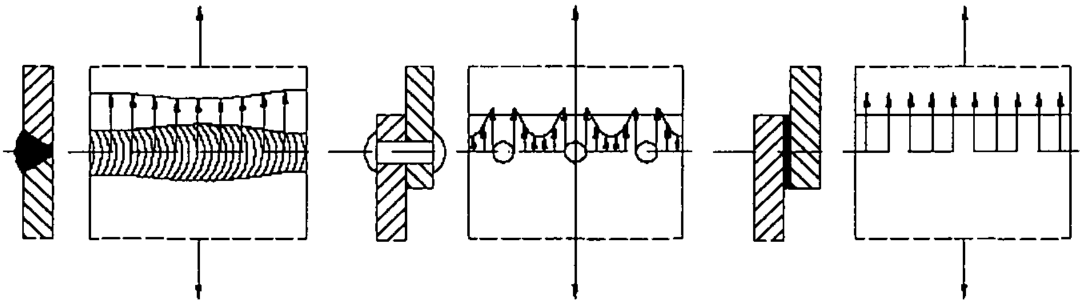


Figure 2.12: Stress distributions of welding, bolting and bonding (Pasternak et al, 2004)

Adhesive bonding is that kind of joining technique that does not change the microstructure and also causes little or no chemical alteration of the materials being joined. Adhesive bonding does not affect the properties of the material and is suitable for joining dissimilar materials. It also prevents galvanic corrosion and hence better than the mechanical joint. Although adhesive bonded joints may not be as durable as welded joints, however it may offer an excellent repair method for a temporary period of time without shutting down the plant while a new part is being constructed. Therefore, adhesive bonding is also a preferable choice as an alternative repair method especially in aqueous environment (Messler, 2004, Lian, 1998).

By using adhesive, the ultimate load and initial stiffness can be increased significantly compared to bolted connection. If the adhesive is used in a combined connection with bolting, the adhesive layer increases the stiffness and reduces the peaks of stress in combined connection (Pasternak et. al, 2004). Liu et al (2000) studied impact resistance of laminated and assembled composites. After performing the drop-weight impact test on composite samples which were joined by mechanical riveting, adhesive bonding and their combinations, they showed that pure epoxy bonding was the most efficient joining technique in assembling composite laminates together, since it gave the highest bending stiffness and resistance to perforation due to impact.

The difference between one traditional method of joining which welded joint and adhesive is bonding is further discussed in Table 2.8.

Table 2.8: Comparison between welded joint and adhesive bonding (Pocius, 2002)

Welded Joint	**Adhesive Bonding**
Local stress point	Predominantly uniform stress distribution
Joint often have to be "dressed" for aesthetic	No surface markings
Useful only for identical materials	Dissimilar materials are easily joined
High temperature resistance	Low to moderate temperature resistance
Poor fatigue resistance	Excellent fatigue resistance

Another benefit for choosing adhesive joints is that the designer has more freedom in his choice of materials. For example, joints can be made using the reverse side of coated steels without causing damage to the coating. In addition to the cost of materials, it causes significant reduction in production cost, in regards with labor and capital investment. Welding operation on the other hand requires skilled hand and hence incurs high cost.

2.10 Previous Researches

There is not much research done which is directly related to civil engineering regarding the application of adhesives to connect steel members. Generally, the studies were focused on parameters such as loading condition, types of adhesive, adhesive properties, structural configuration (overlap length, $L < 40$mm, adherend thickness, $t < 8$mm and adhesive thickness < 1mm), adherends material, durability, and environmental factors such as temperature and moisture with most of them employed lap shear joint and double-lap shear joint.

CHAPTER 3: METHODOLOGY

3.0 Introduction

This experimental work was aimed to determine the effective and optimum design of adhesively jointed steel plates under the mode of pull-out tension and bending based on the chosen variables namely the joint configuration, overlapping length and curing temperature and to assess their influence on the joint performance. The methodology for the project could be simplified as illustrated in Figure 3.1 below.

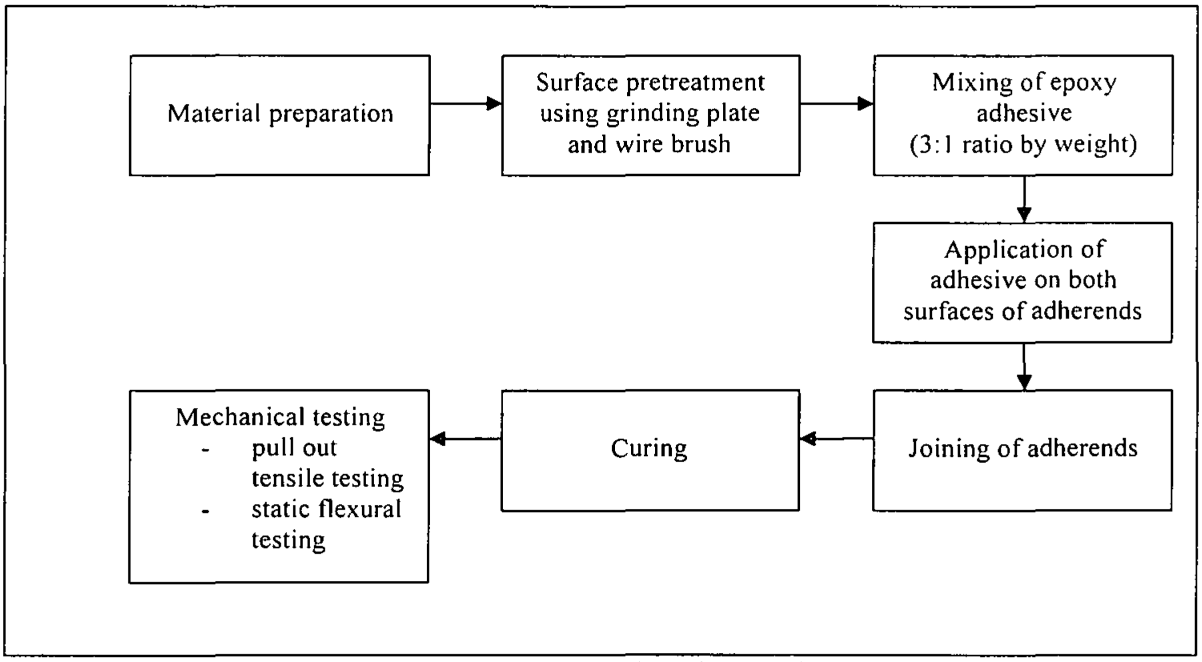


Figure 3.1: Experimental work procedures

3.1 Materials

3.1.1 Adhesive

There are several structural adhesives available in the market. The factors that influence the adhesive selection includes strength, durability, working properties, material requirements, service requirement, environmental factors, production requirements such as opening time, gap filling possibility and curing time, cost and health and safety requirements (Moavenzadeh, 1990; Messler, 2004; and Lian, 1998).

Epoxy adhesives can demonstrate lap shear strength up to 50 MPa at room temperature; with properties diminishing as service temperature is increased up to a maximum of approximately 200°C. Epoxies can be formulated to have excellent chemical resistance and have a low propensity for the absorption of moisture. However, such materials are inherently brittle with low elongations to fracture (approximately 1%) although increased fracture toughness and impact resistance can be achieved through the use of toughening agents. Epoxy adhesives have found such widespread use as a structural adhesive due to their ability to be readily modified by many different types of fillers, tougheners, flexibilizers, adhesion promoters, thixotropic agents and especially curing agents (Kinloch, 1987; Lees, 1989; and Lee & Neville, 1967).

A commercially available Sikadur® -30 epoxy adhesive from SIKA was used, which is a two-component system (an epoxy resin and a hardening agent). This epoxy is a thixotropic adhesive mortar based on a 2-component solvent free epoxy resin. The adhesive properties provided (Table 3.1) are according to manufacturer's specification (Sika, 2007).

Table 3.1: Technical data and properties of Sikadur-30 epoxy adhesive (Sika, 2007)

Color	Base (Part A) : White Hardener (Part B) : Black Part A + B : Light grey when mixed
Mix ratio	A : B = 3 : 1 (parts by weight & volume)
Density	1.65 kg/L ± 0.1 kg/L (A + B) at 23°C
Shelf life Pot life Open time	24 months from date of production 40 minutes (at 35°C) 30 minutes (at 35°C)
Sag flow	3 – 5 mm (at 35°C)
Shrinkage	0.04 %
Glass transition temperature	+62°C
Static modulus of elasticity	11200 MPa
Application thickness	Up to 10 mm
Application temperature	+8°C to +35°C
Compressive strength	90 MPa
Tensile strength	30 MPa
Shear strength	15 MPa
Bond strength (on steel)	> 21 MPa on correctly prepared surface
Maximum Service Temperature	+50°C
Coefficient of Thermal Expansion	9×10^{-5}/°C (-10°C to +40°C)
Adhesive Strength	Steel 33 MPa (sandblasted substrate)

3.1.2 Adherend

Steel adherends of grade S275 were used in all joints tested. These grade 43 (S275) steel adherends are expected to have certain strength, deformation and other characteristics that are suitable for the end use in structures, recognizing the unique condition of service

Properties of steel: (Hayward et al, 2002)

Modulus of elasticity, E = 205 X 10^3 N/mm^2 (205 Kg/mm^2)
Coefficient of thermal expansion = 12 X 10^6 per °C
Density or mass = 7850 Kg/m^3
= (7.85 tonnes/m^3 or 78.5 KN/m^3)
Elongation (200mm gauge length)
For Grade 43 (S275) = 20%

3.2 Experimental Procedures

Adherend surfaces were mechanically abraded using Bosch grinder with grinding plate and wire brush to remove weak oxide layer and to promote adhesion between the adhesive and the adherends. Adhesive was mixed according to manufacturer's specification which is 3 to 1 ratio of epoxy resin and hardener respectively, by weight. Prior to adhesive application, adherend surfaces were wiped with dry, clean cloth. Adhesive was applied on both adherend surfaces with the thickness of 5 mm for all specimens. Adherends were then joined together based on the arbitrarily chosen overlapping length which is the function of adherend thickness; 10t, 15t and 20t. To ensure the uniform adhesive thickness, supports were fabricated using the cardboard paper. The thickness of support was the overall thickness of adherend and adhesive layer. Loads were applied on the specimens during curing to ensure proper adhesion between the adhesive and the adherends.

Three variables temperature were used in this study. It is understood that this type of adhesive can be cured at ambient temperature according to the manufacturer. 45°C curing temperature was chosen due to the fact that heat is often introduced to accelerate the chemical reaction in the adhesive (Messler, 2004). However, 75°C curing temperature was also used to investigate the effect of "overcooked" adhesive on the joint strength although the glass transition temperature specified by the manufacturer as 62°C (Sika, 2007).

Single-lap joint, single-strap joint and double-strap joint were selected for joint configuration. Although much research has been done on the single-lap joint, however the effects of thick adherend (10 – 12 mm) are not yet investigated. On the other hand, the single-strap and double-strap joints are not the subject of much research.

3.3 Experimental Programme

3.3.1 Single-lap joint

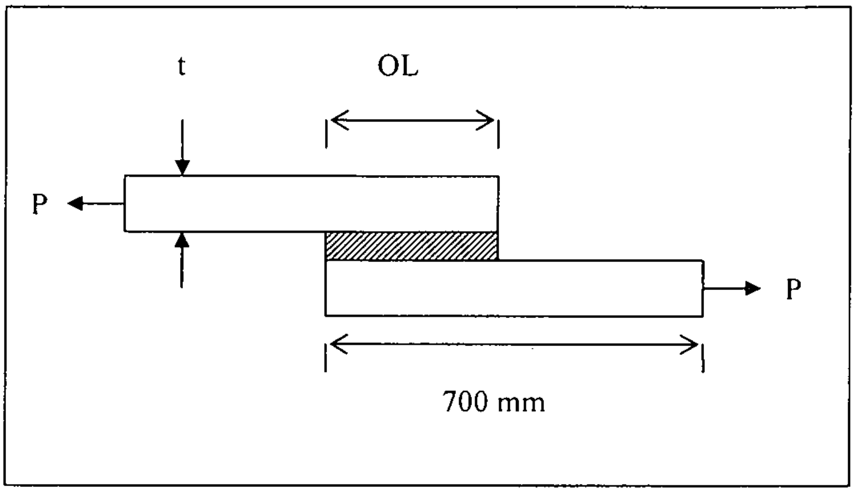


Figure 3.2: Single-lap joint cured at ambient temperature

1) 2 specimens of 10 mm plate thickness with OL of 10t; cured at ambient temperature and tested under pull-out tension.
2) 2 specimens of 10 mm plate thickness with OL of 15t; cured at ambient temperature and tested under pull-out tension.
3) 2 specimens of 10 mm plate thickness with OL of 20t; cured at ambient temperature and tested under pull-out tension.
4) 2 specimens of 12 mm plate thickness with OL of 10t; cured at ambient temperature and tested under pull-out tension.
5) 2 specimens of 12 mm plate thickness with OL of 15t; cured at ambient temperature and tested under pull-out tension.
6) 2 specimens of 12 mm plate thickness with OL of 20t; cured at ambient temperature and tested under pull-out tension.

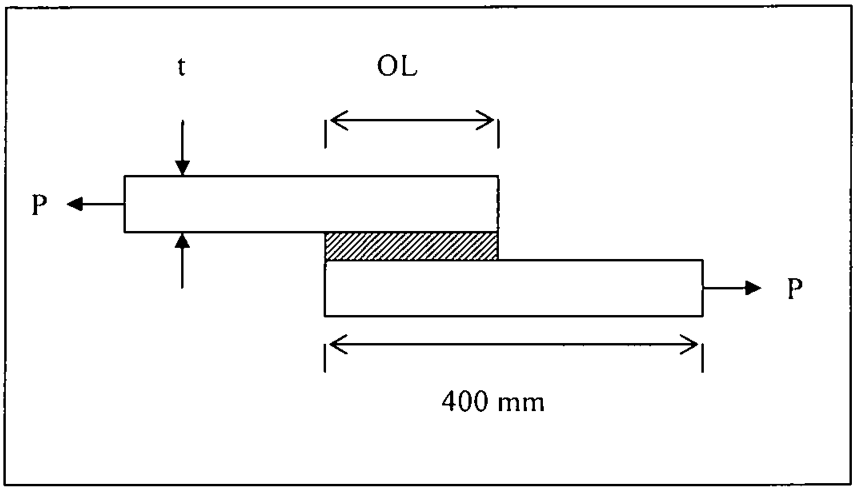


Figure 3.3: Single-lap joint post-cured at 45°C

1) 2 specimens of 10 mm plate thickness with OL of 10t; cured at 45°C temperature and tested under pull-out tension.
2) 2 specimens of 10 mm plate thickness with OL of 15t; cured at 45°C temperature and tested under pull-out tension.
3) 2 specimens of 10 mm plate thickness with OL of 20t; cured at 45°C temperature and tested under pull-out tension.
4) 2 specimens of 12 mm plate thickness with OL of 10t; cured at 45°C temperature and tested under pull-out tension.
5) 2 specimens of 12 mm plate thickness with OL of 15t; cured at 45°C temperature and tested under pull-out tension.
6) 2 specimens of 12 mm plate thickness with OL of 20t; cured at 45°C temperature and tested under pull-out tension.

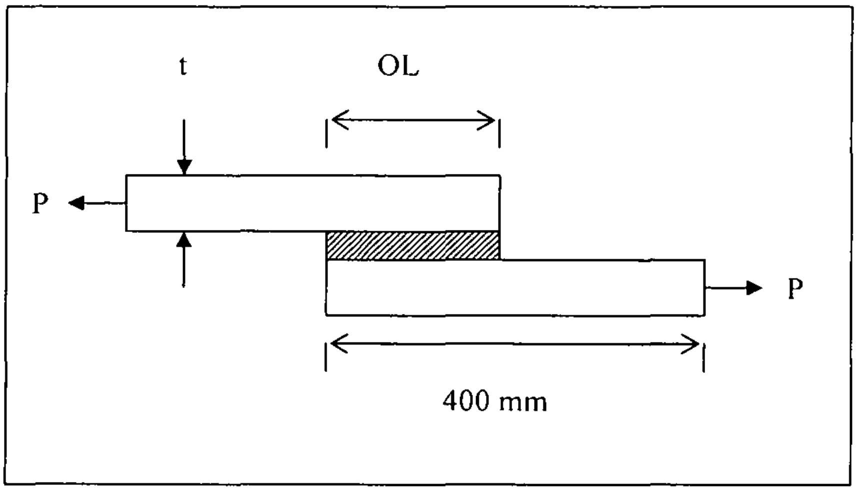


Figure 3.4: Single-lap joint post-cured at 75°C

1) 2 specimens of 10 mm plate thickness with OL of 10t; cured at 75°C temperature and tested under pull-out tension.
2) 2 specimens of 10 mm plate thickness with OL of 15t; cured at 75°C temperature and tested under pull-out tension.
3) 2 specimens of 10 mm plate thickness with OL of 20t; cured at 75°C temperature and tested under pull-out tension.
4) 2 specimens of 12 mm plate thickness with OL of 10t; cured at 75°C temperature and tested under pull-out tension.
5) 2 specimens of 12 mm plate thickness with OL of 15t; cured at 75°C temperature and tested under pull-out tension.
6) 2 specimens of 12 mm plate thickness with OL of 20t; cured at 75°C temperature and tested under pull-out tension.

3.3.2 Single-strap joint

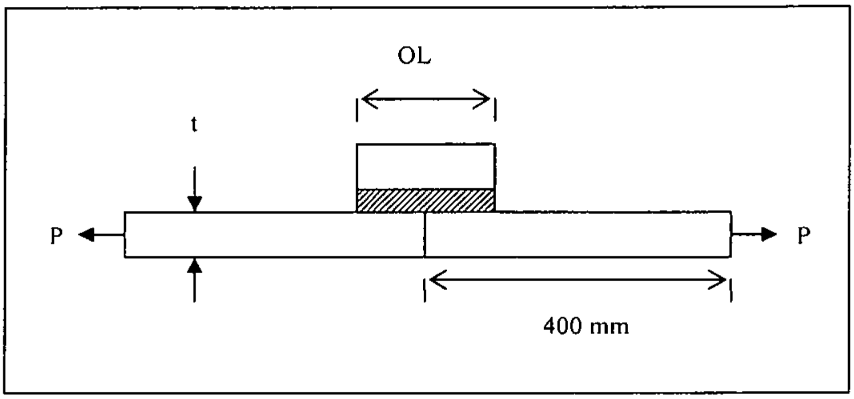


Figure 3.5: Single-strap joint cured at ambient temperature

1) 2 specimens of 10 mm plate thickness with OL of 10t; cured at ambient temperature and tested under pull-out tension.
2) 2 specimens of 10 mm plate thickness with OL of 15t; cured at ambient temperature and tested under pull-out tension.
3) 2 specimens of 12 mm plate thickness with OL of 10t; cured at ambient temperature and tested under pull-out tension.
4) 2 specimens of 12 mm plate thickness with OL of 15t; cured at ambient temperature and tested under pull-out tension.

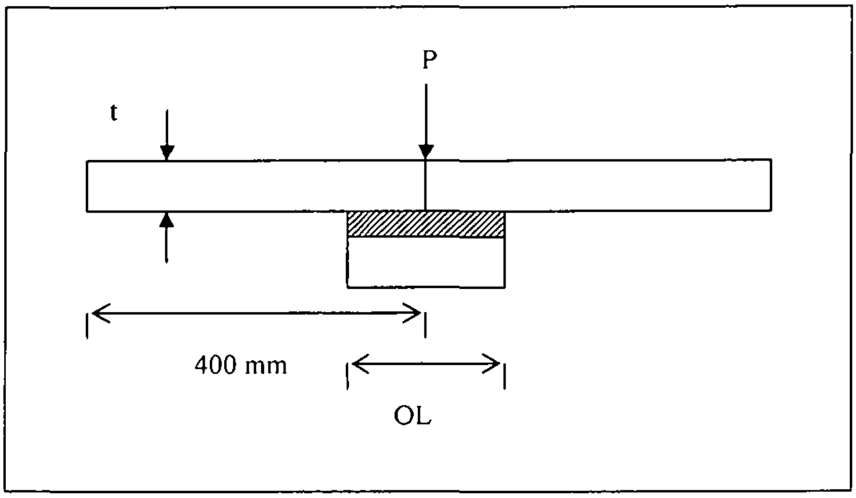


Figure 3.6: Single-strap joint cured at ambient temperature

1) 2 specimens of 10 mm plate thickness with OL of 15t; cured at ambient temperature and tested under static flexure.
2) 2 specimens of 12 mm plate thickness with OL of 15t; cured at ambient temperature and tested under static flexure.

3.3.3 Double-strap joint

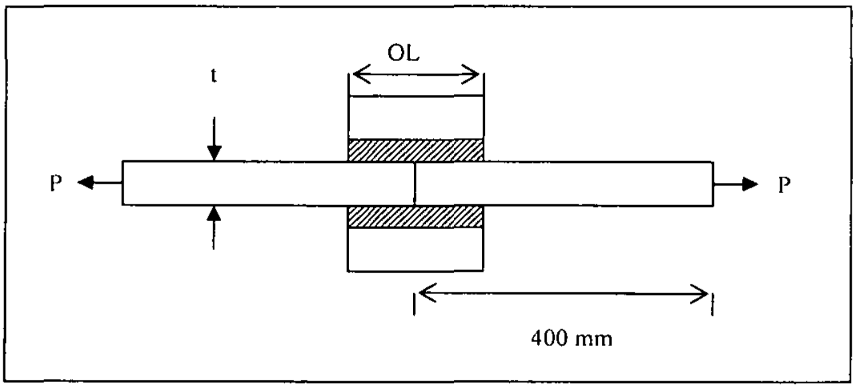


Figure 3.7: Double-strap joint cured at ambient temperature

1) 2 specimens of 10 mm plate thickness with OL of 10t; cured at ambient temperature and tested under pull-out tension.
2) 2 specimens of 10 mm plate thickness with OL of 15t; cured at ambient temperature and tested under pull-out tension.
3) 2 specimens of 12 mm plate thickness with OL of 10t; cured at ambient temperature and tested under pull-out tension.
4) 2 specimens of 12 mm plate thickness with OL of 15t; cured at ambient temperature and tested under pull-out tension.

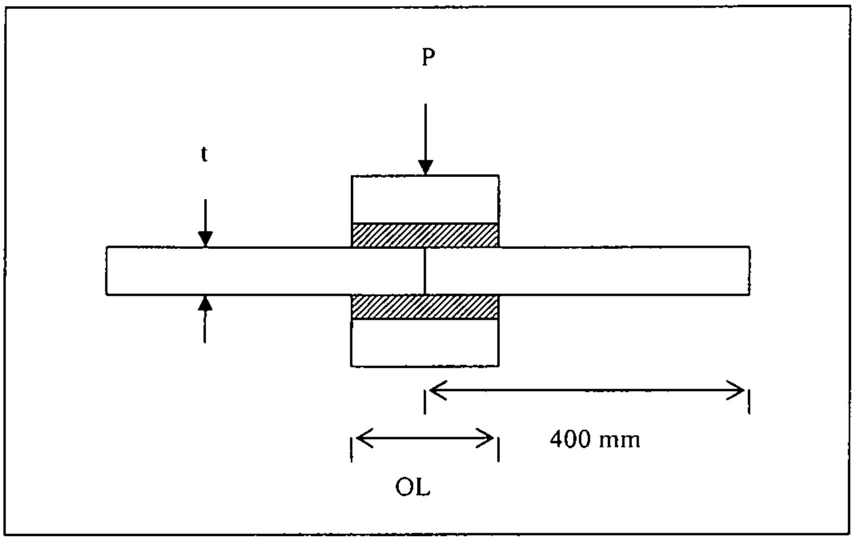


Figure 3.8: Double-strap joint cured at ambient temperature

1) 2 specimens of 10 mm plate thickness with OL of 15t; cured at ambient temperature and tested under static flexure.
2) 2 specimens of 12 mm plate thickness with OL of 15t; cured at ambient temperature and tested under static flexure.

3.4 Mechanical Testing

A series of mechanical tests were performed in order to characterize the behavior of the adhesive jointed specimens. Pull-out tensile and static flexural modes of loading were employed to evaluate the strengths of the jointed specimens.

Joint strength is not the only parameter for testing. Testing is also used to evaluate the appropriateness of the joint geometry, the joint preparation technique, the adhesive application and coverage of surfaces to be bonded, and the effectiveness of the setting or the curing cycle. Adhesive joints in general can be tested for tensile, shear, peel, cleavage, impact and flexural strength, fatigue strength and life, environment durability, and special properties (Messler, 2004).

Pull-out tensile testing was carried out using the Universal Testing Machine (UTM) until fracture occurred. The displacements of bonded joint and the corresponding loads were recorded in the built in software. Static flexural testing was also carried out until the fracture or debonding occurred.

CHAPTER 4: RESULTS AND DISCUSSION

In the following sections experimental results of different tests on epoxy connections are presented and a detailed discussion is made and elaborated on the effects of various parameters on the performance of different types of epoxy joints.

4.1 Performance of Adhesive Joints when subjected to Pull-out Tension

4.1.1 Effects of overlapping length and curing temperature

The overlapping length was chosen on trial as a function of adherend thickness, which was 10, 15 and 20 times the thickness. Similarly, effects of curing temperature on joint performance was investigated by curing specimens in ambient, 45°C, or 75°C respectively. For this test the joint type was lap-joint or known as single-lap joint. The summary of results is tabulated in Table 4.1.

Table 4.1: Results (overlapping length and curing temperature)

Plate Thickness ,t (mm)	Joint Design	Overlapping Length (mm)	Curing Temperature °C	Failure Load (kN)	Maximum Displacement (mm)
10 mm	Lap-joint	100, 10t	Ambient	38.32	0.59
			45	79.52	0.37
			75	68.98	0.66
		150, 15t	Ambient	62.02	0.88
			45	83.29	0.70
			75	53.65	0.31
		200, 20t	Ambient	80.27	0.50
			45	76.44	0.57
			75	58.12	0.52
12 mm	Lap-joint	120, 10t	Ambient	76.37	0.56
			45	99.78	0.92
			75	71.27	0.79
		180, 15t	Ambient	53.44	0.98
			45	114.96	0.81
			75	60.90	0.77
		240, 20t	Ambient	53.29	0.30
			45	94.31	0.72
			75	72.88	0.27

Figure 4.1 and Figure 4.2 show the Load-Displacement curve of 10mm and 12mm thick plates respectively, for both cases plates were cured at 45°C. The Load-Displacement curves for other specimens are included in Appendix B: Load-Displacement Curves for Other Specimens.

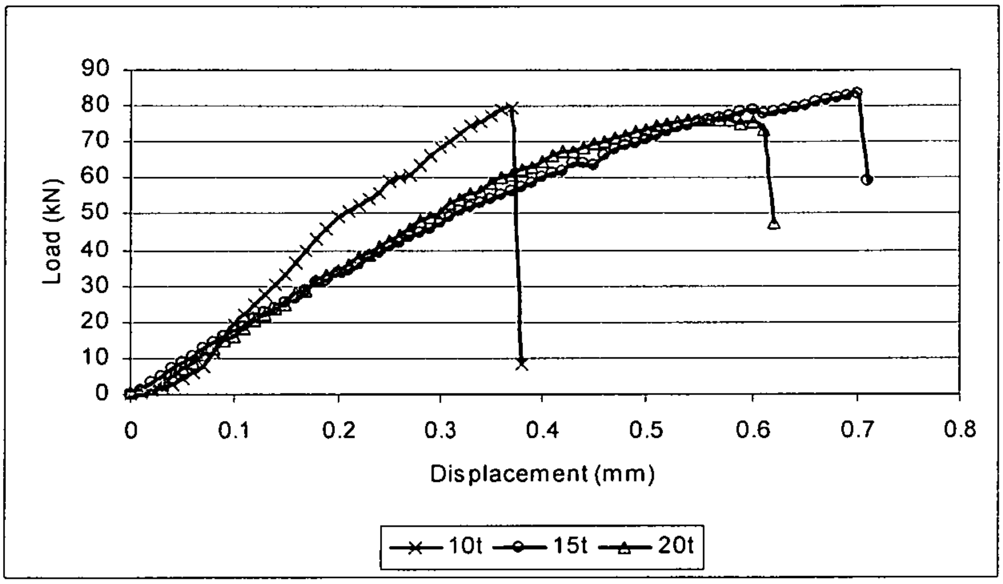


Figure 4.1: Load-displacement curves for 10mm specimens cured at 45°C temperature

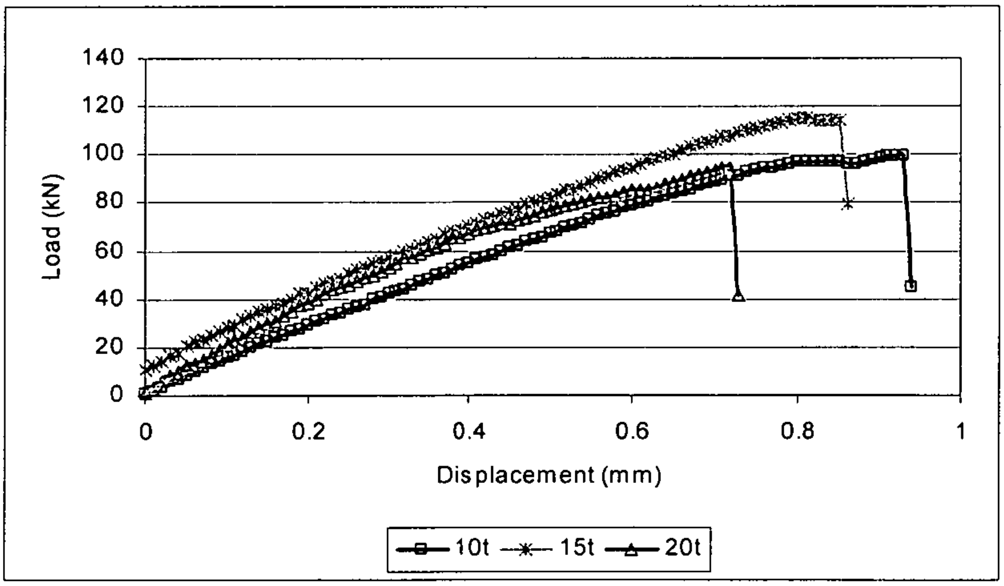


Figure-4.2: Load-displacement curves for 12mm specimens cured at 45°C temperature

Since at the start of loading the specimens, there was observed almost a linear increment of load with respect to the displacement, while reached at ultimate load there was a sudden drop in load without further slip (the line is vertical). At failure there was observed debonding between two plates and there was no signs of shearing of epoxy layer, which indicate that the failure is purely a debonding failure, that caused as a result of slip between the surface of harden epoxy layer and the steel adherend. The similar load-displacement behavior was observed in all of the specimens. From Figure 4.1 it is observed that joints with overlapping length (OL) of 15t and 20t experienced 50 to 70% more slip than the 10t OL, however, 10t OL joint has shown more stiffness than the other two joints because the load-displacement curve is steeper than the other two curves. Where as for 12mm thick plates as shown in Figure 4.2 all three curves are almost similar, therefore all three joints have shown similar stiffness.

Based on the load-displacement curves, there was no indication of plastic yielding of the adhesive in shear or in other word brittle failure occurred. Generally, for single-lap joint with thin metal substrates, the combined differential straining of the substrates and the rotation of the overlap area, caused by out-of-plane loading, tend to generate excessive stresses at the ends of the overlap in the substrates and in the adhesive layer as shown in Figure 4.3. This eventually leads to the initiation of fracture in the adhesive and subsequent crack propagation along the adhesive bondline (Fessel et al, 2007). However, thicker adherend which is more rigid, the distortion is not a much as thin adherend. In general, the stiffer the adherend as in this case; metal adherend, with respect to the adhesive, the more uniform the stress distribution in the joint and the higher the bond strength (Petrie, 1999). Brittle failure was observed although the adhesive and the adherend were not yielding. This might be due to the improper and inadequate surface preparation. It is believed that failure at low load indicates that the weak boundary layer was still present on the adherend surfaces.

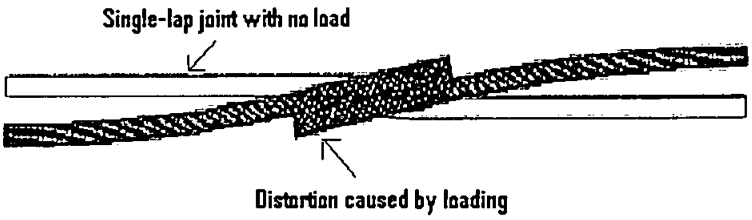


Figure 4.3: Distortion in single-lap joint with thin adherend

Based on Adams & Comyn (2000), by defining the applied force as P, the overlap length l, and width b, and it is assumed that the shear stress was uniform throughout the adhesive, the shear stress in the joint can be determined using equation (1). The model of lap-joint is also assumed to have a rigid adherend and the adhesives may deform only in shear.

$$\tau = P / bl \qquad (1)$$

Furthermore, the relative slip which is the ratio of displacement to the overlapping length in terms of percentage can be determined using equation (2). These two equations resemble the stress and strain in the joint.

Relative Slip = (Displacement / Overlapping length) x 100% (2)

The results of shear stress and relative slip for all specimens are illustrated in Table 4.2, Table 4.3 and Table 4.4.

Table 4.2: Shear stress and relative slip for specimens cured at ambient temperature

Thickness, (mm)	Overlapping Length (mm)	Shear Stress (kPa)	Relative Slip (%)
10	100	3832	0.59
	150	4135	0.59
	200	4014	0.25
12	120	6364	0.47
	180	2969	0.54
	240	2220	0.13

Table 4.3: Shear stress and relative slip for specimens cured at 45°C temperature

Thickness, (mm)	Overlapping Length (mm)	Shear Stress (kPa)	Relative Slip (%)
10	100	7952	0.37
	150	5553	0.47
	200	3822	0.29
12	120	8315	0.77
	180	6387	0.45
	240	3930	0.30

Table 4.4: Shear stress and relative slip for specimens cured at 75°C temperature

Thickness, (mm)	Overlapping Length (mm)	Shear Stress (kPa)	Relative Slip (%)
10	100	6898	0.66
	150	3577	0.21
	200	2906	0.26
12	120	5939	0.66
	180	3383	0.43
	240	3037	0.11

Figure 4.4 and Figure 4.5 further illustrate the effect of overlapping length and curing temperature on the shear strength of the joint. As observed, 100 mm and 120 mm overlapping length or 10 times the adherend thickness show the highest shear strength in the joints. It is obvious that most of the stress is concentrated at the ends of the overlap (where the failure in the bond always begins); with most of the rest of the lap carrying a comparatively low stress (Messler, 2004).

The reason of higher shear capacity and in some cases higher stiffness of joints with an overlapping length of 10t would be that for longer epoxy layer the axial stiffness AE/L to be lower, therefore 10t or in some cases 15t joints have shown higher stiffness and shear capacity. Since the pull-out forces transferred to the epoxy layer tend to induce axial tensile stresses (see Appendix C: Shearing of Epoxy Layer), and due to lower stiffness of longer overlapping length it lost its stiffness and hence has lower shear capacity. An example of a steel bar which has length L and subjected to force P that caused it to elongate shall be used to further understand this effect. See Appendix D: Deformation of a Steel Bar.

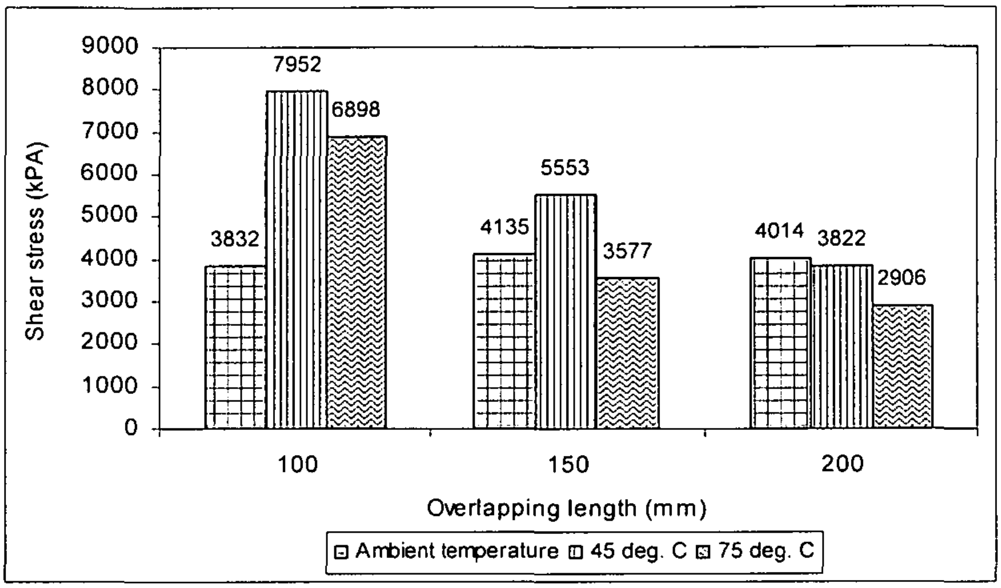


Figure 4.4: Shear stress for 10mm specimens

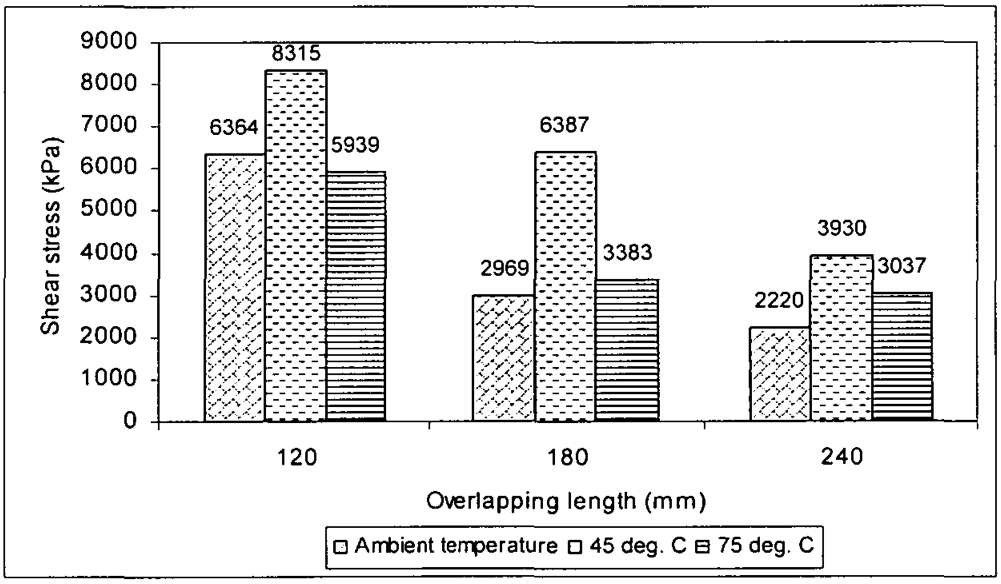


Figure 4.5: Shear stress for 12mm specimens

For a longer overlap joint, the majority of the load applied is carried by the plastic adhesive zones developed at the ends of the bonded overlap and separated by a lightly loaded elastic region. Therefore, the actual stress in a lap joint for a given applied load decreases with the increase in the length of the overlap (Tong & Soutis, 2003 and Alexander, 1995).

It is observed that the shear stress increases with increase in curing temperature to 45°C that showed the highest shear stress with most of the specimens. This indicates that the epoxy is fully cured and thus enhanced the strength of the joint. It is also proves the expectancy of service temperature of Sikadur®-30, at 50°C. However, further increase in curing temperature, for example in this case 75°C decreases the shear stress in the joint although the joints still perform satisfactorily. A rise in temperature has two primary effects on adhesives. First, their shear and tensile strength properties reduce, slowly at first and then dramatically in the region of their T_g, remaining very low up to the point at which the material begin to char. Second, over the same temperature range their natural tendency to creep increases rapidly in similar fashion (Shenoi et al, 1993).

In short, as shown in Figure 4.4 and Figure 4.5, it was found that the maximum shear stress for the 10mm plate thickness which is 7.952 MPa occurs at 45°C curing temperature for the overlapping length of 10t. The maximum slip also occurs at the overlapping length of 10t but at 75°C curing temperature with a value of 0.66 %. Similarly, the maximum shear stress for the 12mm plate thickness occurs at 45°C curing temperature for the overlapping length of 10t at a value of 8.315 MPa. The maximum slip in contrast, occurs at 45°C and at the overlapping length of 10t with a value of 0.77 %.

Figure 4.6 shows the effect of adherend thickness on the maximum shear stress. It is observed that the shear stress increases with increase in adherend thickness. According to Messler, it is best to keep the adhesive thickness thin, presuming that there is good adhesion between the adhesive and the adherends in which the adherends should be stiffer and stronger than the adhesive. The reason is that the adherends actually act to reinforce the adhesive causing it to act stiffer and stronger. Therefore, by increasing the adherend thickness and apply the same thickness of adhesive to all specimens, the joint would become stiffer and stronger. However in this research project, overlapping length utilized was actually the function of adherend thickness. Thus, in order to verify and validate the above statement, the modification should be done using the same overlapping length for different adherend thickness, in this case 10 mm and 12 mm thick plates.

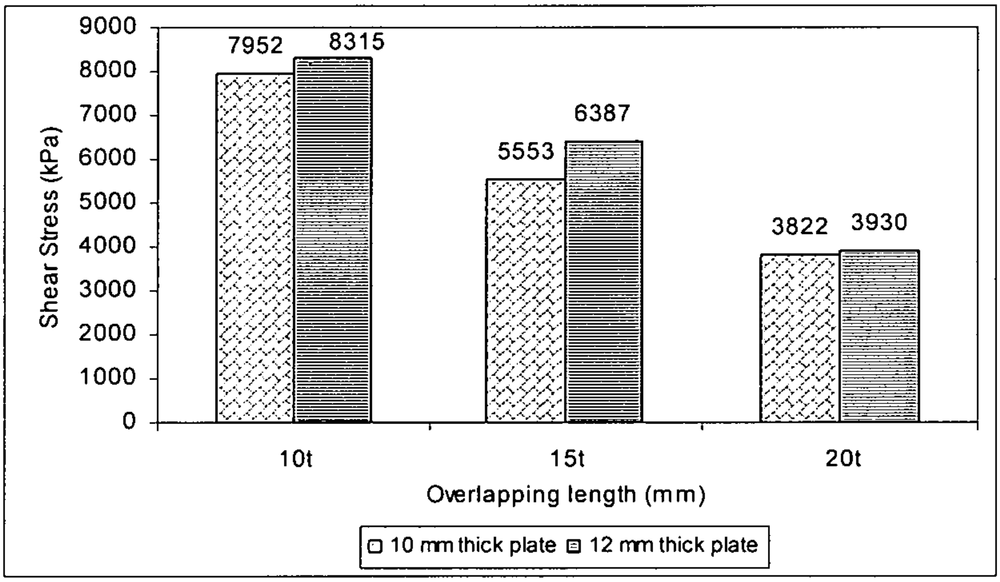


Figure-4.6: Effect of adherend thickness on maximum shear stress

4.1.2 Effects of joint configuration and type

The specimens were designed based on the optimum overlapping length obtained from the investigation of the effects of overlapping length and the curing temperature which is 10 times the plate thickness. The overlapping length of 15 times the plate thickness was also used as a comparison. All specimens were cured at ambient temperature. Three joint configurations were used; single-lap joint, single-strap joint and double-strap joint. The specimens were tested for pull-out tension capacity as tabulated in Table 4.5.

Table 4.5: Results (joint configuration and type)

Plate Thickness, t (mm)	Joint Design	Overlapping Length (mm)	Curing Temperature °C	Failure Load (kN)	Maximum Displacement (mm)
10 mm	Lap-joint	100, 10t	Ambient	38.32	0.59
	Single-strap			61.46	0.44
	Double-strap			152.42	0.73
	Lap-joint	150, 15t	Ambient	62.02	0.88
	Single-strap			43.24	0.26
	Double-strap			198.59	1.06
12 mm	Lap-joint	120, 10t	Ambient	76.37	0.56
	Single-strap			42.54	0.24
	Double-strap			183.39	0.99
	Lap-joint	180, 15t	Ambient	53.44	0.98
	Single-strap			47.15	0.24
	Double-strap			111.92	0.48

The similar trends as discussed in section 4.1 are observed in this case as shown in Figure 4.7 to Figure 4.10. At first, there was observed almost a linear increment in load with respect to displacement until the joint reached at its ultimate strength. In all graphs, it can be seen that the double-strap butt joint has the highest stiffness compared to other types of joint because the load-displacement curve is steeper than the other two curves.

The shear stress and relative slip are also calculated using the same equations; Equation (1) and Equation (2) as in Section 4.1. The results of shear stress and relative slip for all specimens are illustrated in Table 4.6 and Table 4.7. It was observed that the sudden drop in load with respect to the displacement as in the case of Section 4.1.1 did not occur in this study on joint configuration. This is due to the abrupt failure in which the strap plates were totally debonded from the specimens.

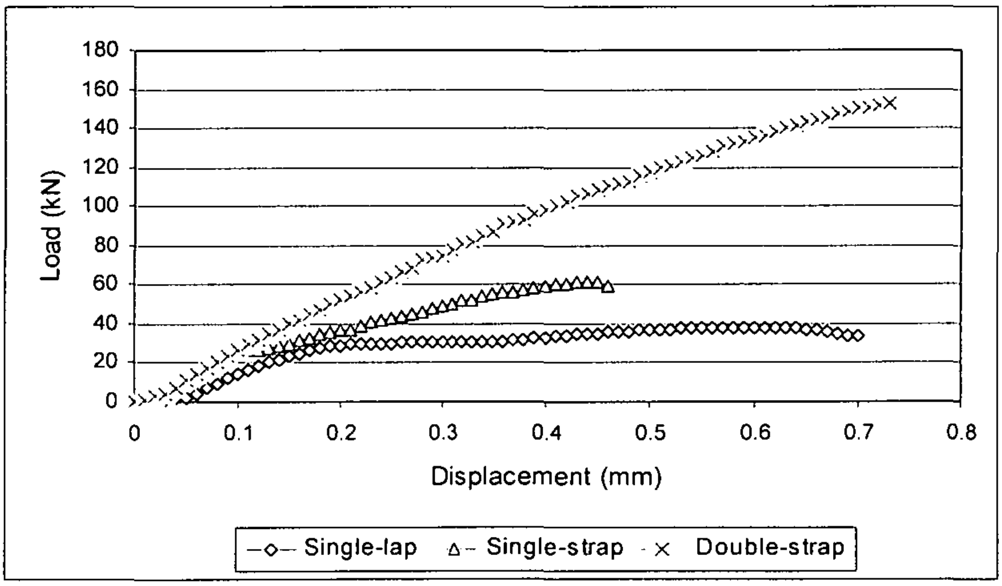


Figure 4.7: Load-displacement curves for 10mm specimens with 10t (100mm) overlap length

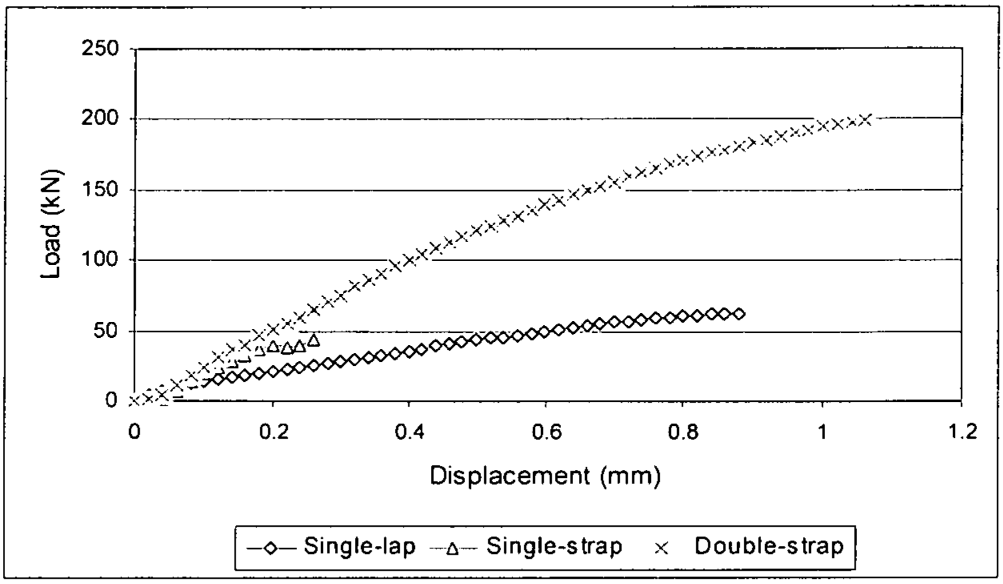


Figure 4.8: Load-displacement curves for 10mm specimens with 15t (150mm) overlap length

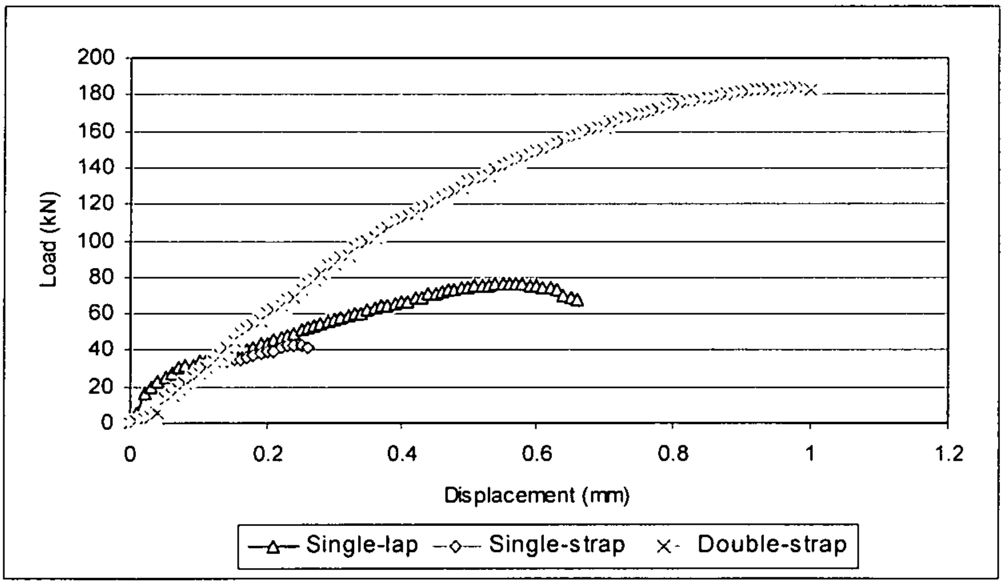


Figure 4.9: Load-displacement curves for 12mm specimens with 10t (120mm) overlap length

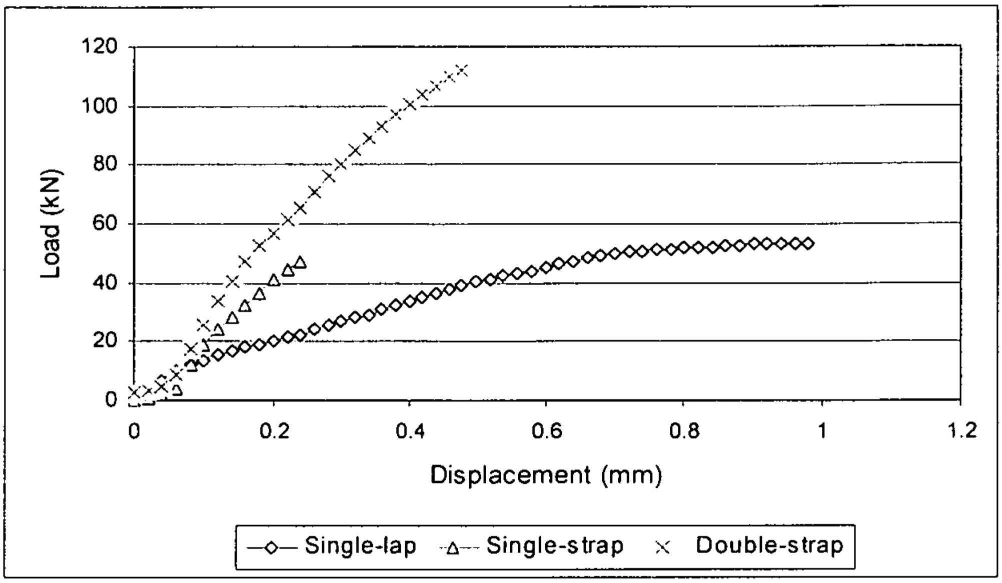


Figure 4.10: Load-displacement curves for 12mm specimens with 15t (180mm) overlap length

Table 4.6: Shear stress and relative slip for 10mm specimens

Thickness, (mm)	Joint Design	Overlapping Length (mm)	Shear Stress (kPa)	Relative Slip (%)
10	Lap-joint	100	3832	0.59
	Single-strap		6146	0.44
	Double-strap		7621	0.73
	Lap-joint	150	4134.7	0.59
	Single-strap		2882.7	0.17
	Double-strap		6619.7	0.71

Table 4.7: Shear stress and relative slip for 12mm specimens

Thickness, (mm)	Joint Design	Overlapping Length (mm)	Shear Stress (kPa)	Relative Slip (%)
12	Lap-joint	120	6364.2	0.47
	Single-strap		3545	0.20
	Double-strap		7641.3	0.83
	Lap-joint	180	2968.9	0.54
	Single-strap		2619.4	0.13
	Double-strap		3108.9	0.27

Figure 4.11 and Figure 4.12 show the comparison of shear stress for different joint configuration. It is observed that the overlapping length of 10t has the highest shear strength which was given by the double-strap joint. However, for the 10 mm plates, the overlapping length of 15t also showed the remarkable strength and in contrast, for 12 mm plates, the overlapping length of 15t showed the lowest strength compared to all specimens. Since the results are not constant, as for now it can be said that the effective overlapping length is around 10t to 15t. However, the effects of overlapping length should be further investigated using a constant overlapping length for all specimens regardless of the plate thickness, t.

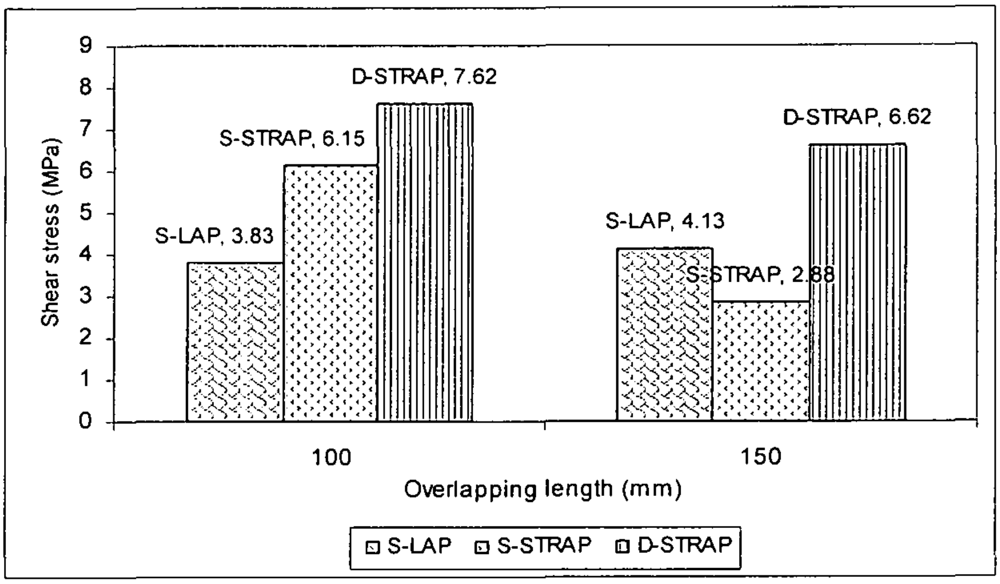


Figure 4.11: Shear stress of 10 mm specimens for various joint designs

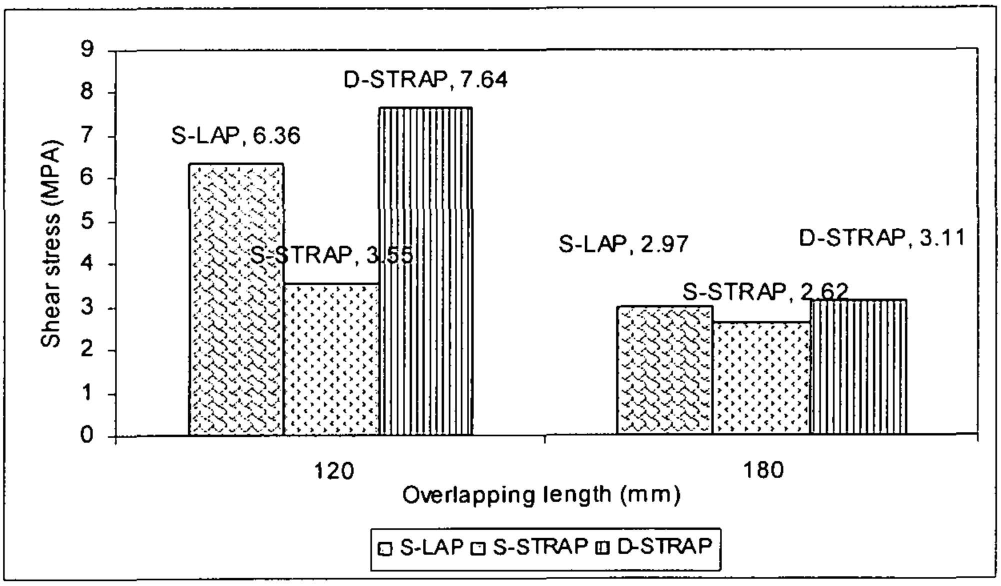


Figure 4.12: Shear stress of 12 mm specimens for various joint designs

To further discuss the effects of joint design, it is better to understand the configuration of joint itself and the location of applied load as shown in the following Figure 4.13.

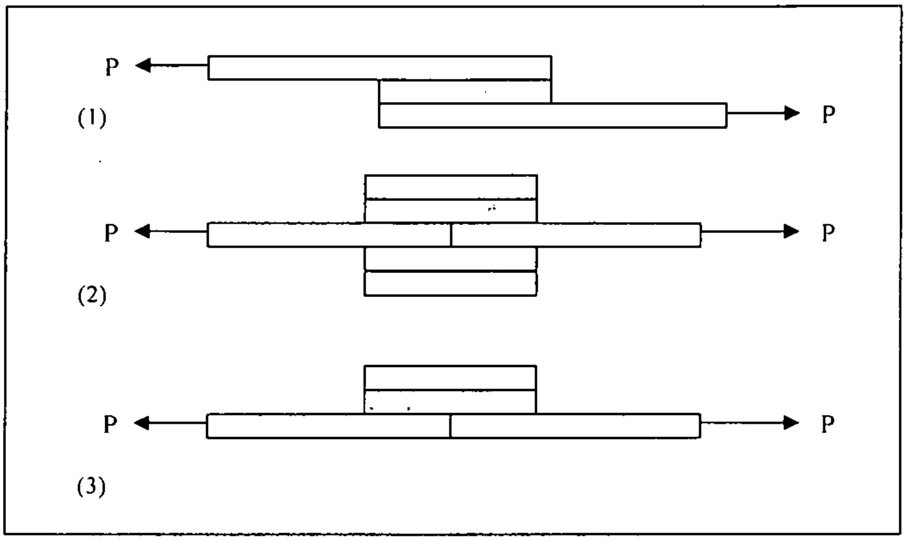


Figure 4.13: Joint design and applied load

The nature of joint design influenced the ultimate strength of the joint. Joint design No (1) which was lap-joint, the load that was transferred induced shear force in epoxy layer. Due to the thickness of the epoxy layer, load was also transferred as the axial force in the joint. The bending effect due to loading eccentricity can be neglected because the thickness of adhesive layer used was only 5mm compared to the adherend thickness. As for the joint design No (2) and No (3) which were double-strap butt joint and single-strap butt joint respectively, the load was transferred as axial force which induced slip off at the interface between the epoxy layer and the adherend. However, joint design No (3) showed the lowest strength because both ends of overlap experienced the slip off while for the joint design No (2) the slip off was significantly minimized by having epoxy layer at both sides of the joint. In general failure was started at the interface between the epoxy layer and the adherend.

4.1.3 Mode of failure when subjected to pull-out tension

Through visual observation, the type of failure that occurred during the experiment was mixed failure (combination of adhesive and cohesive failure) and debonding failure as shown in Figure 4.14 and Figure 4.15. It can be seen clearly in the picture, a thin oxide layer was detached from the surface of steel plate.. This is probably due to the presence of weak boundary layer on the surface of the adherends although the very first layer of the steel surface was removed using mechanical abrasion. The ideal type of failure is the cohesive failure (failure within the adhesive itself) because the maximum strength of the materials comprising the joint has been reached thus there would be no doubt of improper preparation of the joint before bonding or other improper bonding procedures (Messler, 2004).

However, the mode of failure should not be the sole criterion for judging whether a particular adhesive-bonded joint was successful. Some combination of adhesive and adherends may fail adhesively but exhibit greater strength than a similar joint bonded with a weaker adhesive that fails cohesively. In practice, it is the ultimate strength of a joint, regardless of what process is used to make it, that is usually the more important measure of success than the mode of failure (Messler, 2004).

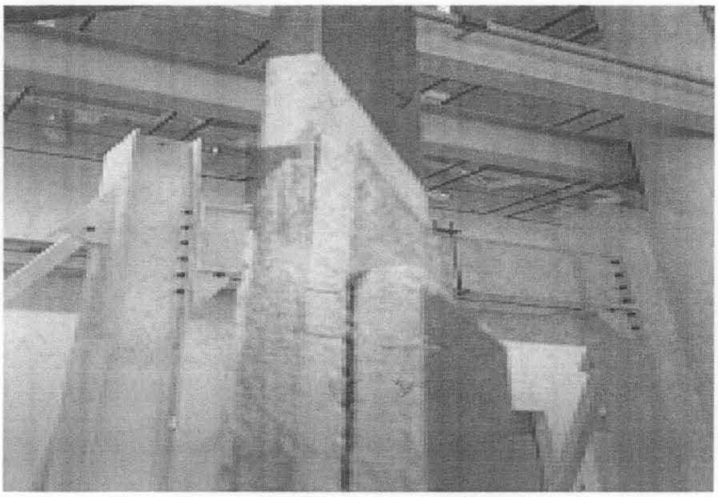


Figure 4.14: Interfacial failure

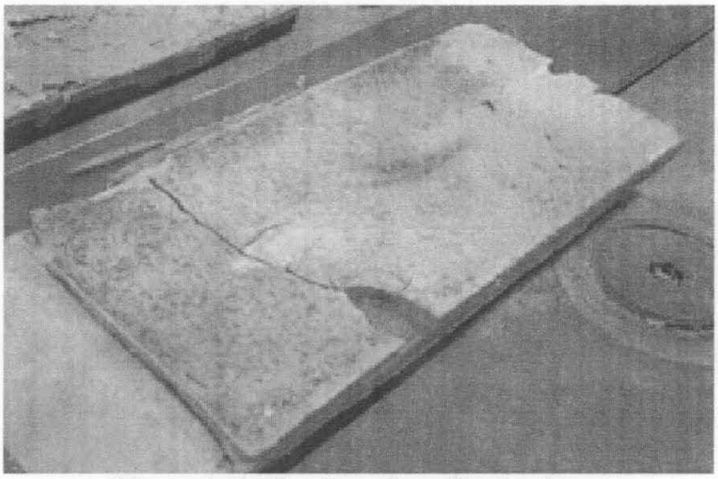


Figure 4.15: Crack on the adhesive layer

The failure might be also due to the uneven application of the epoxy as honeycombs were detected in some of the specimens as shown in Figure 4.16. Failure of the joint could also occur due to misalignment of the substrates. There could also possible that the adhesive was contaminated during the process. Premature failure could also develop in the bonding due to adverse stresses, for example peeling, rate of application of stresses, fatigue, temperature, humidity and solvents (Messler, 2004 and James, 1995).

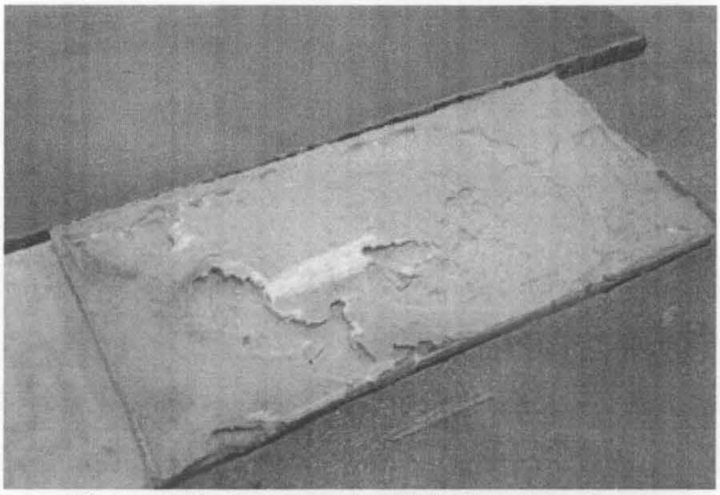


Figure 4.16: Honeycomb within the epoxy layer

There were several errors detected during and before the experiment was commenced. Error was common during surface preparation due to lack of facilities. Working the best that could be done was just by mechanically abrading the surface and polishing the steel plates using grinding plate and wire brush before directly applying the epoxy adhesive to avoid corrosion of the steel adherends. However, it has been noted that surface preparation is the key to bond durability.

Another error that could be observed was the orientation of the steel plate configuration. The plates were not aligned properly, or out-of-plane, than as straight as it was supposed to be. Some of the plates upon arrival were not exactly flat and hence when overlap it might induce stresses during curing. All of these factors influenced the results in achieving the maximum strength of the epoxy joints. The orientation of the steel plates should be in-plane alignment for testing in shear to obtain the maximum shear stress.

4.2 Performance of Adhesive Joints when subjected to Bending

4.2.1 Effects of joint configuration

The effects of joint configuration on flexural capacity were also investigated using single-strap joint and double-strap joint subjected to three-point loading. The arrangement of joint design is shown in Figure 4.17. The summary of results is tabulated in Table 4.8.

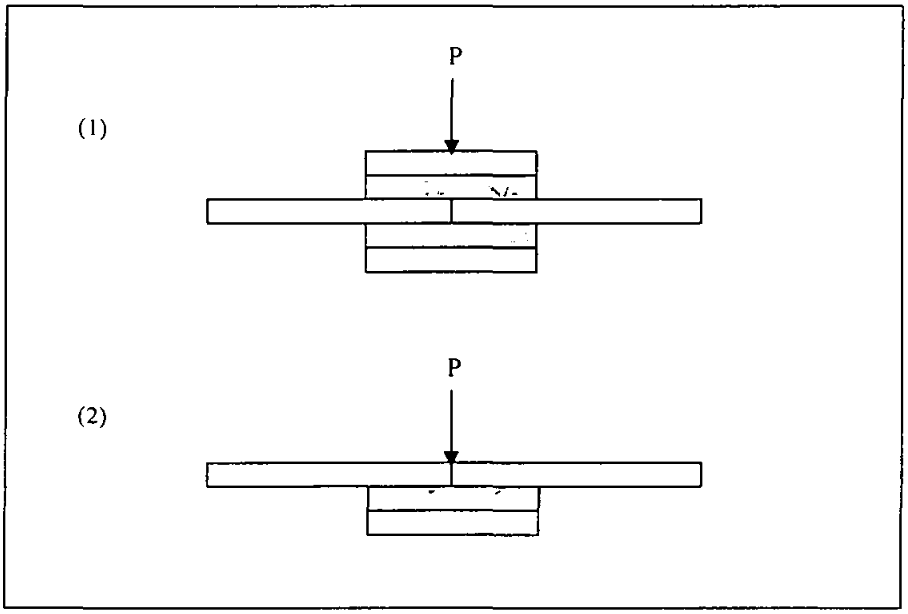


Figure 4.17: Arrangement of joint design and applied load subjected three-point loading

Table 4.8: Results of three-point flexural testing

Thickness (mm)	Joint Configuration	Failure Load (kN)	Maximum Displacement (mm)
10 mm	Single-strap	1.26	4.12
	Double-strap	7.00	33.01
12 mm	Single-strap	1.85	2.42
	Double-strap	10.98	14.03

The comparison between experimental failure load and theoretical failure load is shown in Table 4.9. Sample calculation is included in Appendix E: Theoretical Failure Load in Flexural Testing.

Table 4.9: Experimental and theoretical failure load

Thickness (mm)	Joint Configuration	Experimental Failure Load (kN)	Theoretical Failure Load (kN)	Joint Efficiency (%)
10 mm	Single-strap	1.26	14.2	8.87
	Double-strap	7.00	32.65	21.44
12 mm	Single-strap	1.85	19.5	9.49
	Double-strap	10.98	44.05	24.93

In flexural testing, double-strap joint showed the highest failure load for both 10mm and 12mm thick specimens as illustrated in Figure 4.18. Table 4.9 shows the comparison between the experimental and theoretical failure load of the specimens subjected to bending. It is evident that the double-strap joint showed a remarkable structural performance compared to the single-strap joint. By having two straps and two layers of adhesive on top and bottom, the cleavage stress developed at the edges of overlap was minimized. On the other hand, by having only one strap as in the case of single-strap joint, the cleavage stress developed is significant hence the joint failed at low load. The joint efficiency was calculated with the assumption that there is a perfect interfacial bond between the adhesive and the adherend. However, the actual loading capacity was influenced by the cleavage stress at the edges of the overlap and also the presence of weak oxide layer on the adherends.

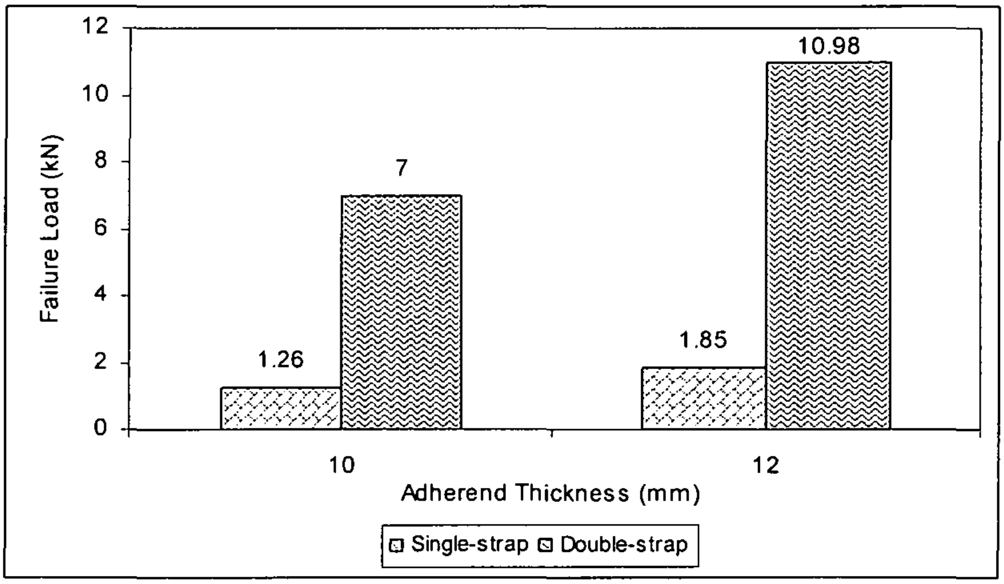


Figure 4.18: Failure load in flexural testing

4.2.2 Mode of failure when subjected to bending

In flexural or bending test, most of the joints failed due to the debonding or peeling-off. It was observed that the failure started at the interface between the adherend and the epoxy layer. Most of the double-strap joints were very strong. It was observed that the adherends have yielded after the flexural testing as depicted in Figure 4.19. Some of adhesive layer were also tear off from the adherend and hence revealed its surface. A thin oxide layer was attached to the adhesive hence indicates that the weak boundary layer was not totally removed or the adherend surfaces were contaminated prior to the adhesive application (Figure 4.20).

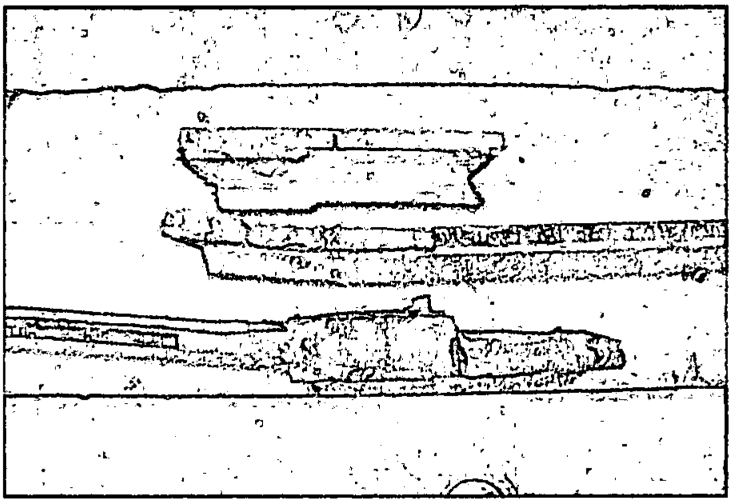


Figure 4.19: Permanent bending of adherend

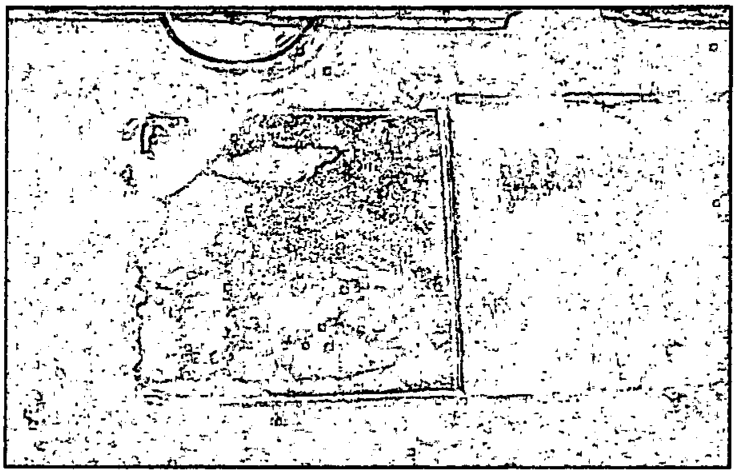


Figure 4.20: Oxide layer

4.3 Summary of Results and Discussion

In this study adhesive joints using Sikadur®-30 with a constant thickness of epoxy layer were studied. Specimens cured in 45°C showed higher capacity. An overlapping length between 10-15t was found as the optimum length whereas double-strap joint was found stronger than the continuous steel plate of the same length. It was concluded that failure occurred cohesively within the oxide layer if oxides were present on the substrate surface prior to the adhesive application.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From the test results and discussion following conclusion have been made:

a. The stiffness and load carrying capacity of adhesive joints subjected to pull-out tension increases with decrease in overlapping length that is 10 to 15 times the adherend thickness. It is because of the reason that the stiffness is inversely proportional to the length of the epoxy layer. However, this phenomenon will be valid to the minimum overlapping length that is required for load resistance. It is also the function of the thickness of the epoxy layer

b. Curing at a temperature of 45°C showed the highest shear strength of the joints in most of the specimens, hence may be termed as the optimum curing temperature. It is due to the fact that the amount of heat evolved at 45°C resulted in speeding up the setting time of the joint material and caused to gain early strength. However curing higher temperature as in this study at 75°C reduced the shear capacity, because at higher curing temperature creep in epoxy layer would have become very significant.

c. During pull-out tension, most of the failures were caused by bond-slip failure between the epoxy layer and the steel plates. There were few failures caused by epoxy layer failure, it was happened when there were some honey-combing within the epoxy layer.

d. Double-strap joint has shown very high bending capacity when subjected to mid point bending load compared to single-strap joint with the efficiency of 12 to 15% more than the single-strap joint. It is believed that by having two straps and two layers of adhesive on top and bottom of the joint as in the case of double-strap joint minimize the effect of cleavage stress.

e. In case of bending test, most of the joints failed due to debonding or peeling-off due to the presence of weak oxide layer on the adherend surfaces prior to bonding process.

f. It can be summarized that double-strap joint has shown much higher capacity under all loading conditions such as pull-out tension and bending.

g. It can be concluded that the failure occurred cohesively within the oxide layer if oxides were present on the substrate surface prior to the adhesive application.

5.2 Recommendation

The growing understanding of adhesives as a joint material is significant. The study has proven to be a step closer for the adhesive bonding to be an established steel connection that would help give an alternative to those traditional connections of bolting, welding and riveting. It is recommended to carry out the comprehensive experimental analysis and numerical simulation of adhesive joint in steel construction using the full scale structural section such as beam, channel, truss and frame. It is also recommended to simulate the environmental exposure on those structures. The comprehensive experimental analysis shall include these criteria such as the effects of various types of adhesive, adherend thickness and also adhesive or bondline thickness.

REFERENCES

Adams, R.D. (2000) *Adhesive Bonding: Science, Technology and Applications*, Woodhead Publishing Limited, CRC Press LLC.

Adams, R.D. Comyn, J. (2000). Joining using adhesives. *Assembly Automation. 20*(2), pp. 109-117

Adams, R.A. and Wake W.C. (1984). *Structural adhesive joints in engineering*. London: Elsevier Applied Science.

Aga, Z.A. and Woldesenbet, E. (2006). Bond thickness effect on impact response and damage of adhesively-bonded graphite/epoxy composites. *Journal of Adhesion Science Technology, 21*(1), pp. 21-34.

Alexander, B. (1995). *Design of Mechanical Joints*, Marcel Dekker Inc.

Cantrill, J., Kapadia, A., and Pugh, D., (2004). Lessons learnt from designing and producing adhesively bonded structures in a shipyard. *Proceedings of the Mechanical Engineers, Part M,* accepted for publication.

Chastain, C.E. (1974). Designing adhesive joints, *Appliance Engineer. 8*(4). pp.22-25

Clarke, J.L., (1996). Structural design of polymer composites. *Eurocomp Design Code and Handbook,* E&FN Spon.

Colombi, P. and Poggi, C. (2006). Strengthening of tensile steel members and bolted joints using adhesively bonded CFRP plates. *Construction and Building Materials, 20* (2006), pp.22-23

Crocombe, A.D. (1989). *International Journal of Adhesion & Adhesives, 9*(145)

Deb, A. Malvade, I. Biswas, P. Schroeder, J. (2007). An experimental and analytical study of the mechanical behavior of adhesively bonded joints for variable extension rates and temperatures. *International Journal of Adhesion and Adhesive, 28* (2007), pp. 1-15

Dixon, D.G. (1995). Adhesive bonding for high temperature applications. *Proceedings of the Fourth International Conference on Structural Adhesives in Engineering.* (pp. 257-260). London: The Inst Materials.

Fessel. G, Broughton, J.G, Fellows N.A, Durodola J.F, and Hutchinson A.R. (2007). Evaluation of different lap-shear joint geometries for automotive applications. *International Journal of Adhesion and Adhesives, 27*(7), pp. 574-583.

Fisher, L.W., (2005) *Selection of engineering materials and adhesives*, USA: Taylor & Francis Group.

Gaston, T. (2003). *Building a better adhesive bond.* Retrieved November 21, 2006, from http://machinedesign.com/ContentItem/62546/Buildingabetteradhesivebond.aspx

Gaul, R. and Apton, N., (1959). Epoxy adhesives in concrete, *Civil Engineering New York, 20* (11), pp 50-52

Harper, C.A, and Petrie, E.M. (2003). *Plastic Materials and Process: a concise encyclopedia.* John Wiley and Sons

Hart-Smith, L.J. (1973). NASA Contract Report, NASA CR-112235.

Hashim, S.A. (1999). Adhesive bonding of thick steel adherends for marine structures, *Marine Structures 12* (1999), pp. 405-423.

Hayward, A. Weare, F. and Oakhill, A. (2002) *Steel Detailer's Manual*, Blackwell Publishing. Retreived April, 3 2008 from http://books.google.com

Hollaway, L.C. (2005). Advances in an adhesive joining of dissimilar materials with special reference to steel and frp composites. *Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005),* 11-21. Retrieved December 20, 2007, from http://www.iifc-hq.org/BBFS-Papers/K2_0002.pdf

Hollaway, L.C., and Leeming M.B. (1999). *Strengthening of reinforced concrete structures: Using externally-bonded FRP composites in structural and civil engineering*, Cambridge: Woodhead Publishing Ltd.

Ishii, K. Imanaka, M. Nakayama, H. and Kodama, H. (1999). Evaluation of the fatigue strength of adhesively bonded CFRP/metal single and single-step double-lap joints, *Composites Science and Technology, 59* (1999), pp. 1675-1683

James, F. (1995). Bonding suggestions for the piezoelectric motor systems, University of Missouri-Rolla, US.

Jeandrau, J. (1989). New concepts for designing structural adhesively bonded joints. *Prooceedings of the Second International Conference on Structural Adhesives in Engineering* (pp. 149-156). Bristol: Butterworth

Kecsmar, J. (2003). Structural design of aluminum ship structures. *MPhil thesis*, University of Southampton.

Kinloch, A.J. (1987). *Adhesion and adhesives.* London: Chapman & Hall.

Lee, H, and Neville, K. (1967) *Handbook of epoxy resins,* New York: McGraw-Hill.

Lees, W.A. (1989). *Adhesives and the Engineer,* London: Mechanical Engineering Publications Limited.

Lian, M.K. (1998). Study of Durability of Epoxy Bonded Joints in Aqueous Environments. (MSc. Dissertation, Virginia Polytechnic Institute and State University).

Liu, D. Raju, B.B. and Dang, X , (2000). *International Journal of Impact Engineering, 24.* pp 733-746.

MacGinley, T.J. (1997) *Steel Structures: Practical Design Studies*, Taylor & Francis.

Mays, G.C. & Hutchinson, A.R. *Adhesive in Civil Engineering*, New York: Cambridge University Press

Mazumdar, S.K. (2002) *Composites Manufacturing: Materials, Product, and Process Engineering*, CRC Press LLC. Retrieved March, 24 2008 from http://books.google.com

Messler, R.W. Jr. (2004). *Joining of Materials and Structures, From Pragmatic Process to Enabling Technology*, Oxford: Elsevier Butterworth-Heinemann

Millard, E.C. (1984). Use of structural adhesives in aircraft turbine engine nacelles. *Proceedings of the International Conference on Adhesion.* (pp. 341-346). Nottingham: PRI

Moavenzadeh, F. (1990) *Concise Encyclopedia of Building & Construction Materials*, Cambridge: MIT Press.

Pasternak, H. Schwarzlos, A. and Schimmack, N. (2004). The application of adhesive to connect steel members. *Journal of Constructional Steel Research* 60 (2004).

Pereira, A.B. de Morais, A.B. (2003). Strength of adhesively bonded stainless steel joints, *International Journal of Adhesion and Adhesive 23* (2003), pp. 315-322

Perry, H.A., (1958) How to calculate stresses in adhesive joints, *Product Engineering,* July, pp. 64-67

Petrie, E. M. (1999) *Handbook of Adhesives and Sealants*, Mc Graw-Hill Handbooks. Retrieved March, 24 2008 from http://books.google.com

Petronio, M. (1977) *Handbook of Adhesives*, 2nd edition, (Ed. Skeist, I), New York: Van Nostrand Reinhold Co.

Pocius, A.V. (2002). *Adhesion and Adhesive Technology – An Introduction*, 2nd edition, Hanser Gardner Publications.

Savage, G. (2005). Failure prevention in bonded joints on primary load bearing structures. *Engineering Failure Analysis 14* (2007), pp. 321-348

Schneberger, G.L., (1983). *Adhesives in manufacturing*, New York: Marcel Dekker, Inc

Shenoi, R.A Wellicome, J.F and Western European Graduate Education Marine Technology. (1993). *Composite Materials in Maritime Structure*. New York: Cambridge University Press.

Shields, J., (1985). *Adhesives Handbook,* 3rd edn, London: Newnes-Butterworth.

Srivastava, V.K. (2003). Characterization of adhesive bonded lap joints of C/C-SiC composites and Ti-6Al-4V alloy under varying conditions. *International Journal of Adhesion & Adhesives, 23* (2003), pp. 59-67.

Sika, (2007). Sikadur 30 Technical Datasheet. Retrieved July 28, 2007, from http://www.sika.com.my/my-con-pds-sikadur_30.pdf

Täljsten, B. (2005). The importance of bonding – A historic overview and future possibilities. *Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005),* 1-10. Retrieved December 20, 2007, from http://www.iifc-hq.org/BBFS-Papers/K1_0004.pdf

Tong, L. and Soutis (eds). (2003). C. *Recent Advances in Structural Joint and Repairs for Composite Material*, Netherlands: Kluwer Academic Publisher.

Tremper, B. (1960) Repair of damaged concrete with epoxy resins. *Journal of the A.C.I.*, *57,* pp 173-182

Wakeman, C.M., Stover, H.E., and Blye, E.N., (1962). Glue for concrete repair. *ASTM, Bulletin, 2*(2), pp 93-97

Appendix A: Experimental Work Procedures

Figure A-1: Surface preparation

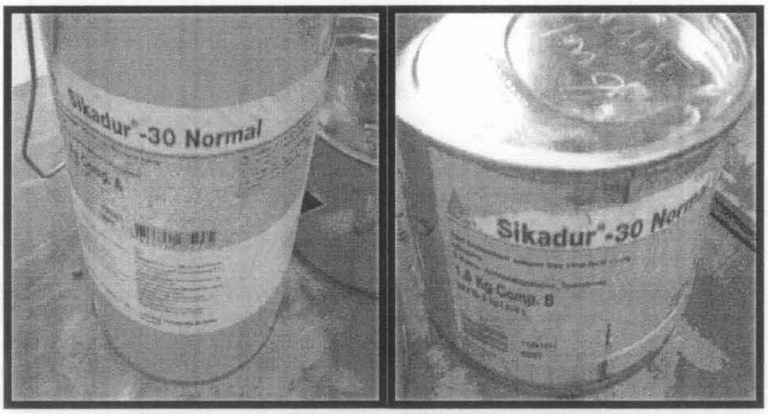


Figure A-2: Sikadur-30 epoxy adhesive

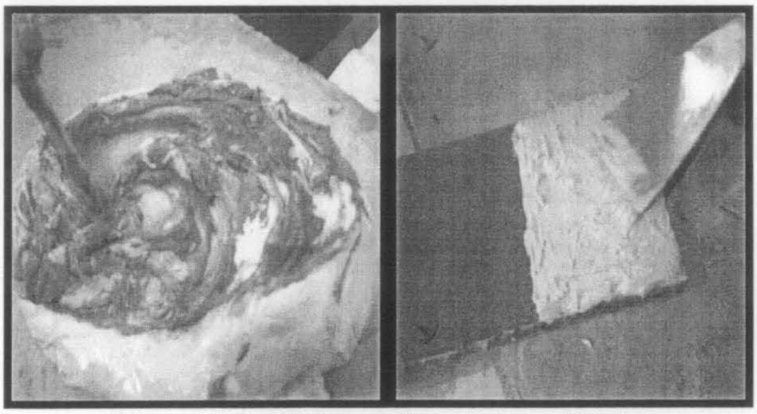


Figure A-3: Mixing and applying adhesive

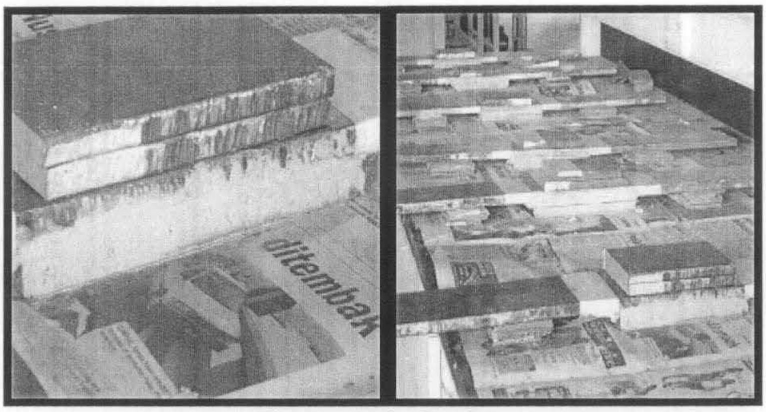


Figure A-4: Curing

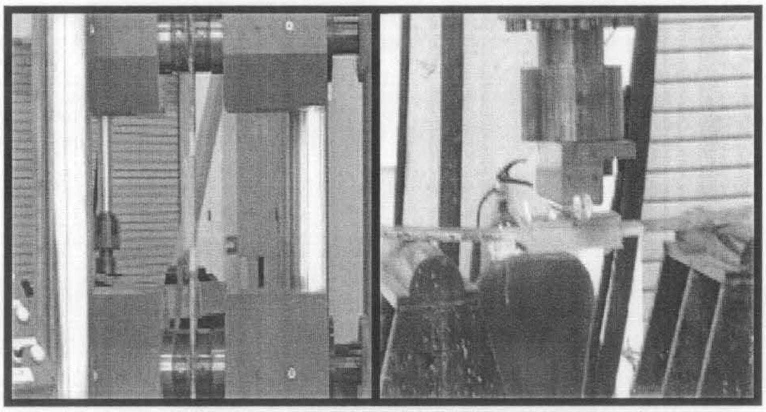


Figure A-5: Mechanical testing

Appendix B: Load-Displacement Curves for Other Specimens

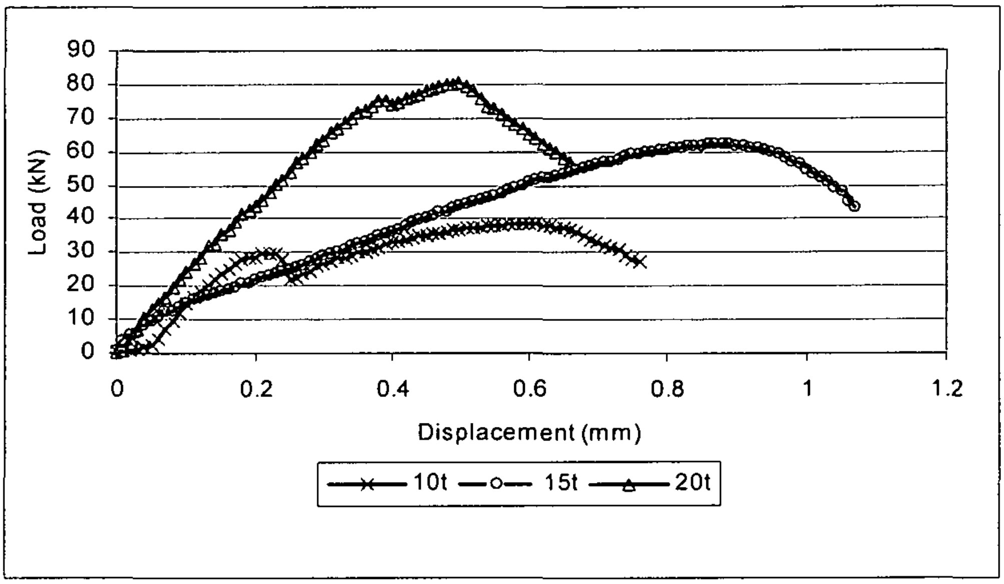


Figure B-1: Load-displacement curves for 10mm specimens at ambient temperature

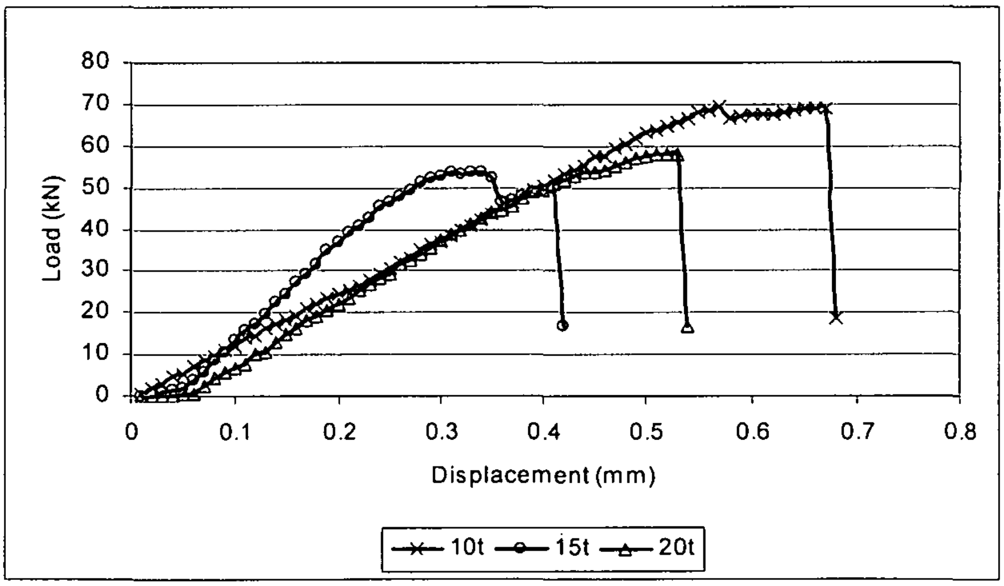


Figure B-2: Load-displacement curves for 10mm specimens at 75°C temperature

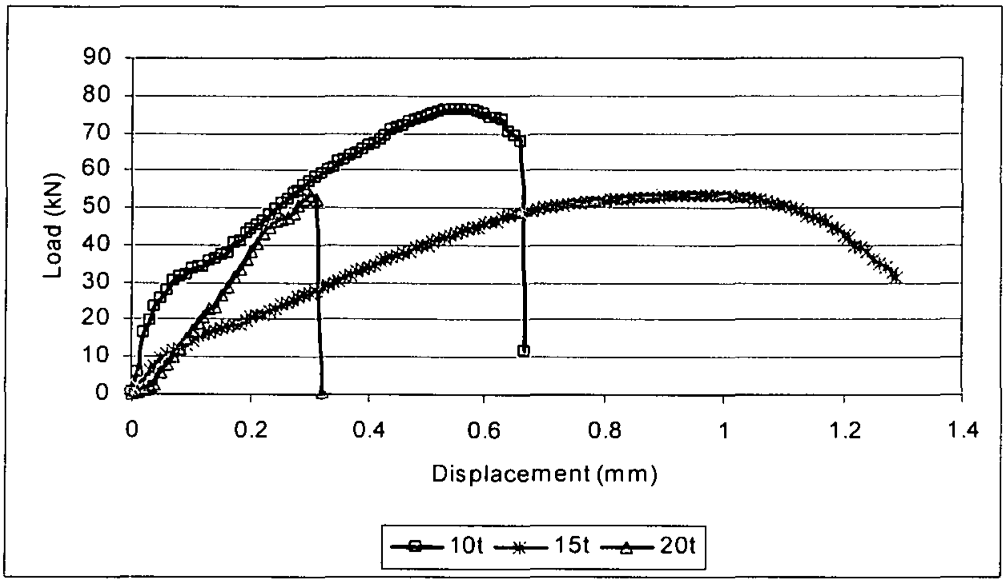


Figure B-3: Load-displacement curves for 12mm specimens at ambient temperature

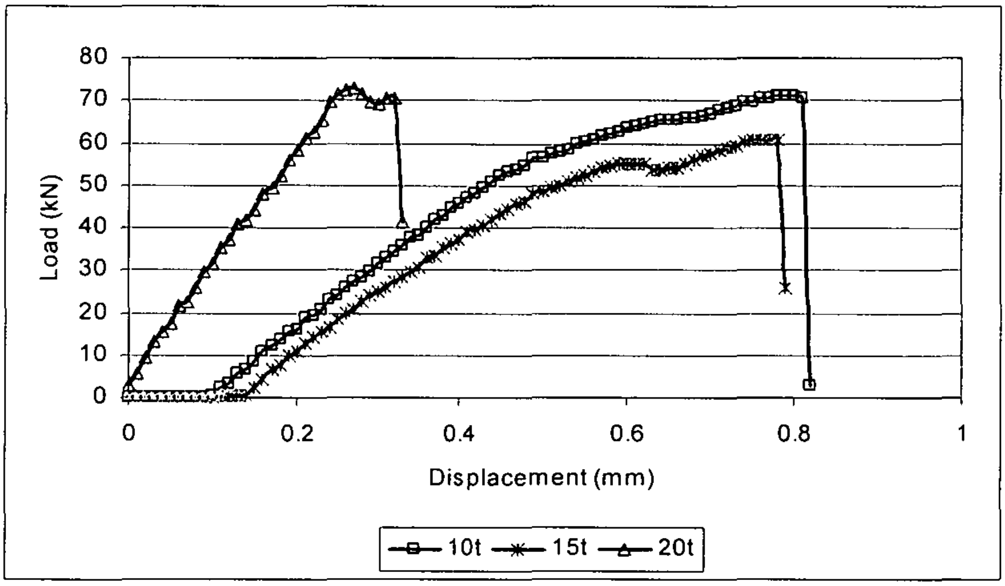


Figure B-4: Load-displacement curves for 12mm specimens at 75°C temperature

Appendix C: Shearing of Epoxy Layer

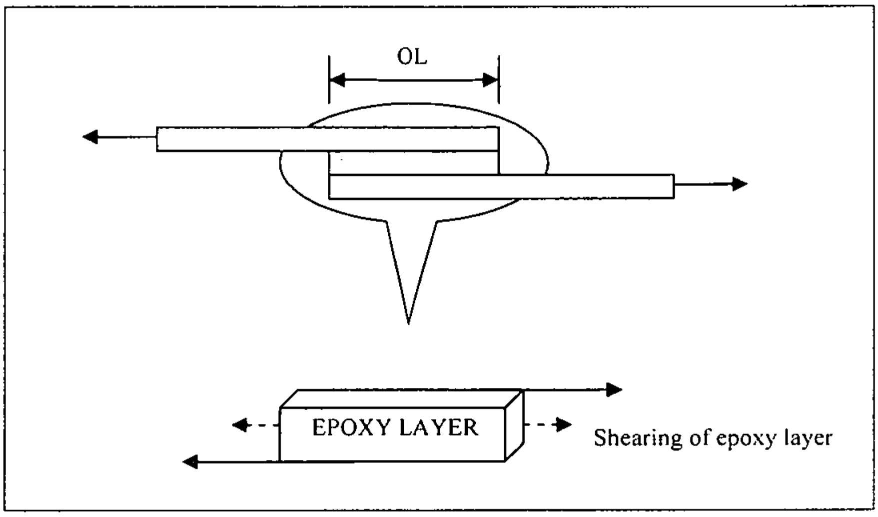


Figure C-1: Shearing of epoxy layer

Appendix D: Deformation of Steel Bar

$$\text{Stress, } \sigma = P / A \qquad \text{Strain, } \varepsilon = \Delta L / L$$

$$\text{Elasticity, } E = \sigma / \varepsilon$$

$$(P / A) / (\Delta L / L) = E$$

$$PL / A\,\Delta L = E$$

$$\text{or } P = (AE / L)\,(\Delta L)$$

$\Delta L = 1$, therefore $P = AE / L = k$ = stiffness (force required to produce unit deformation)

$$k \propto 1 / L$$

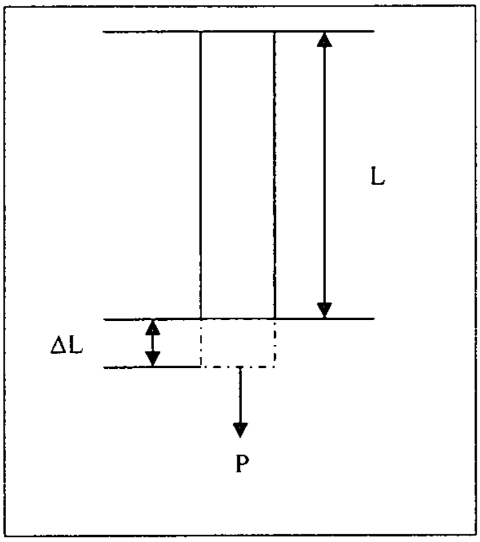


Figure D-1: Deformation of a steel bar

Appendix E: Theoretical Failure Load for Flexural Testing

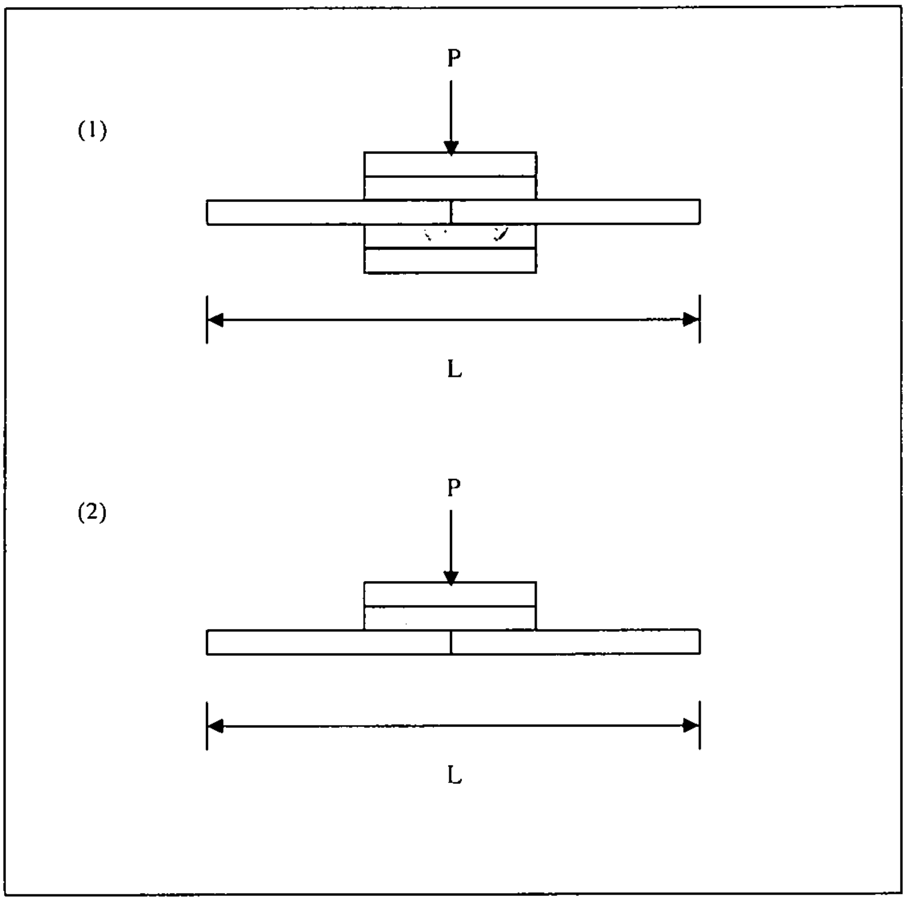
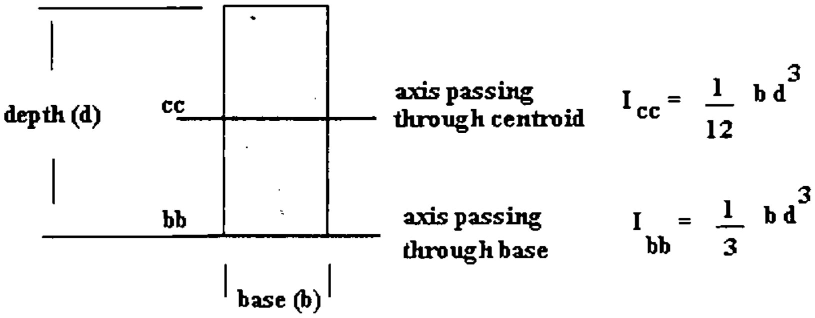


Figure E-1: Specimens subjected to bending

Assumption(s):

1) Moment of inertia, I was calculated based on Parallel Axis Theorem,



Moments of inertia about different axis may calculated using the **Parallel Axis Theorem**, which may be written: $\mathbf{I_{xx} = I_{cc} + Ad_{c\text{-}x}^2}$ This says that the moment of inertia about any axis ($\mathbf{I_{xx}}$) parallel to an axis through the centroid of the object is equal to the moment of inertia about the axis passing through the centroid ($\mathbf{I_{cc}}$) plus the product of the area of the object and the distance between the two parallel axis ($\mathbf{Ad_{c\text{-}x}^2}$).

2) Perfect interfacial bond between adhesive and adherend

1. Single-strap joint for 10mm thick plate:

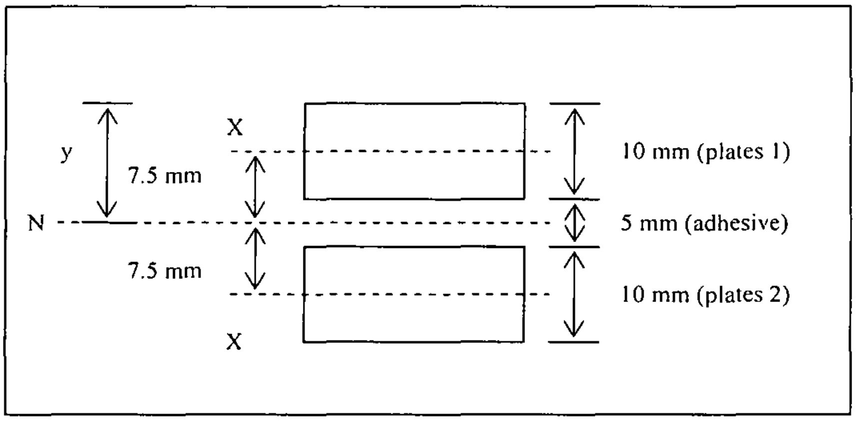


Figure E-2: Single-strap joint for 10 mm thick plate

a) Calculation of moment of inertia, $\mathbf{I_{total}}$,

Plate 1 (A) or Plate 2 (B)

Width, b = 100 mm

Depth, d = 10 mm

$I_A = b\ d^3 / 12$

$= (100)\ (10)^3 / 12$

$= 8333.33\ mm^4$

$\mathbf{I_A = I_B}$

$\mathbf{Ad_{N\text{-}X}^2} = (b\ d)\ (d_{N\text{-}X})^2$

$= (100 * 10)\ (7.5)^2$

$= 56250\ mm^4$

$\mathbf{I_{total} = I_A + Ad_{N\text{-}X}^2 + Ad_{N\text{-}X}^2 + I_B}$

$= 8333.33 + 56250 + 56250 + 8333.33$

$= 129166.66\ mm^4$

b) Calculation for theoretical load, P

p_y = 275 N/mm^2
y = 12.5 mm
S = I_{total} / y = 10333.33 mm^3
M_c = p_y S = 2841665.75 Nmm
@ 2.84 kNm
M = PL / 4
P = 4M / L
L = 0.8 m
M @ M_c = 2.84 kNm
Thus,
P = 14.2 kN #

2. Single-strap joint for 12mm thick plate:

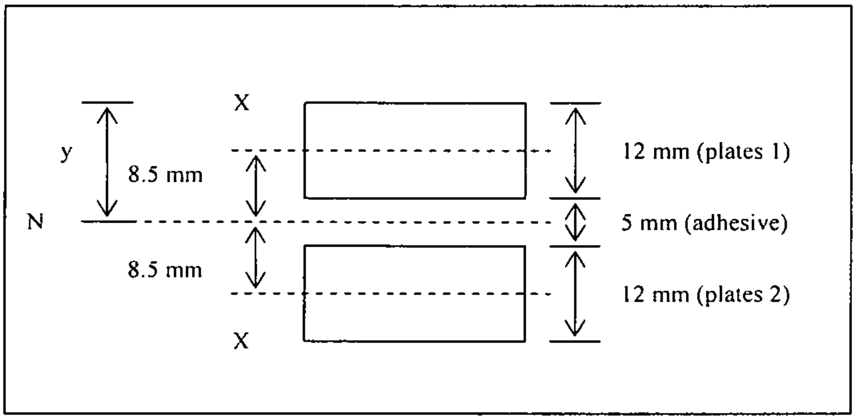


Figure E-3: Single-strap joint for 12 mm thick plate

a) Calculation of moment of inertia, $\mathbf{I_{total}}$,

Plate 1 (A) or Plate 2 (B)

Width, b = 100 mm

Depth, d = 12 mm

$\mathbf{I_A} = b\,d^3 / 12$

$= (100)\,(12)^3 / 12$

$= 14400\ \text{mm}^4$

$\mathbf{I_A = I_B}$

$\mathbf{Ad_{N\text{-}X}^2} = (b\ d)\ (d_{N\text{-}X})^2$

$= (100 * 12)\ (8.5)^2$

$= 86700\ \text{mm}^4$

$\mathbf{I_{total}} = \mathbf{I_A + Ad_{N\text{-}X}^2 + Ad_{N\text{-}X}^2 + I_B}$

$= 14400 + 86700 + 86700 + 14400$

$= 202200\ \text{mm}^4$

b) Calculation for theoretical load, P

p_y = 275 N/mm^2

y = 14.5 mm

S = I_{total} / y = 13944.83 mm^3

M_c = p_y S = 3834828.25 Nmm

@ 3.83 kNm

M = PL / 4

P = 4M / L

L = 0.8 m

M @ M_c = 3.83 kNm

Thus,

P = 19.5 kN #

3. Double-strap joint for 10mm thick plate:

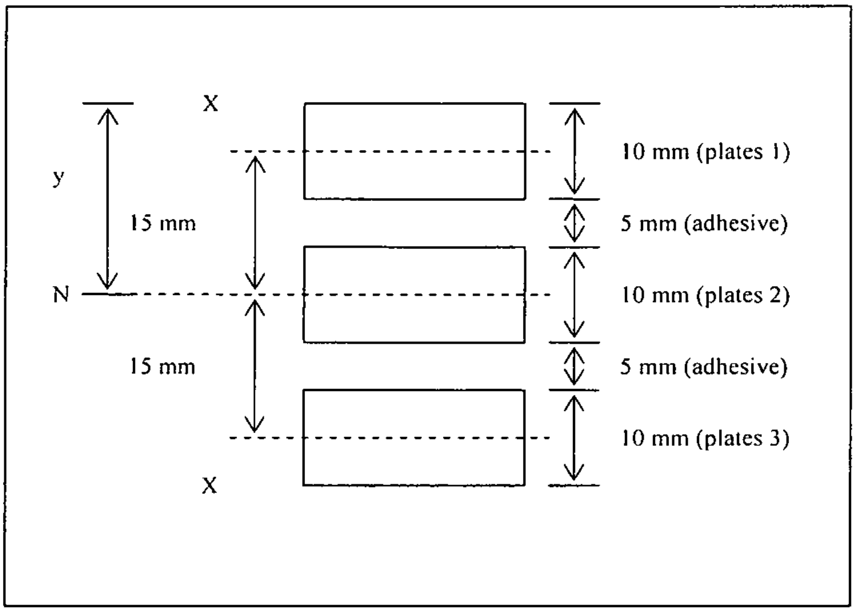


Figure E-4: Double-strap joint for 10 mm thick plate

a) Calculation of moment of inertia, $\mathbf{I_{total}}$,

Plate 1 (A) or Plate 2 (B) or Plate 3 (C)

Width, b = 100 mm

Depth, d = 10 mm

$\mathbf{I_A} = b\, d^3 / 12$

$= (100)\,(10)^3 / 12$

$= 8333.33 \text{ mm}^4$

$\mathbf{I_A = I_B = I_C}$

$\mathbf{Ad_{N\text{-}X}^2} = (b\ d)\,(d_{N\text{-}X})^2$

$= (100 * 10)\,(15)^2$

$= 225000 \text{ mm}^4$

$\mathbf{I_{total} = I_A + Ad_{N\text{-}X}^2 + I_C + Ad_{N\text{-}X}^2 + I_B}$

$= 8333.33 + 225000 + 8333.33 + 225000 + 8333.33$

$= 474999.99\ \text{mm}^4$

b) Calculation for theoretical load, P

p_y = 275 N/mm^2

y = 20 mm

S = I_{total} / y = 23750 mm^3

M_c = p_y S = 6531250 Nmm

@ 6.53 kNm

M = PL / 4

P = 4M / L

L = 0.8 m

M @ M_c = 6.53 kNm

Thus,

P = 32.65 kN #

4. Double-strap joint for 12mm thick plate:

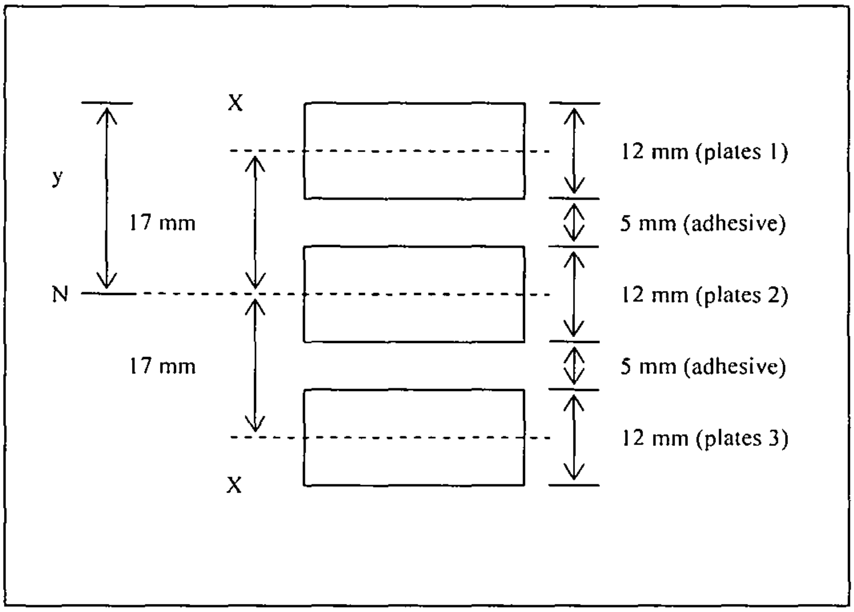


Figure E-5: Double-strap joint for 12 mm thick plate

a) Calculation of moment of inertia, I_{total},

Plate 1 (A) or Plate 2 (B) or Plate 3 (C)

Width, b = 100 mm

Depth, d = 12 mm

$\mathbf{I_A} = b\, d^3 / 12$

$= (100)\,(12)^3 / 12$

$= 14400 \text{ mm}^4$

$\mathbf{I_A = I_B = I_C}$

$\mathbf{Ad_{N\text{-}X}}^2 = (b\ d)\ (d_{N\text{-}X})^2$

$= (100 * 12)\,(17)^2$

$= 346800 \text{ mm}^4$

$\mathbf{I_{total} = I_A + Ad_{N\text{-}X}^2 + I_C + Ad_{N\text{-}X}^2 + I_B}$

$= 14400 + 346800 + 14400 + 346800 + 14400$

$= 736800 \text{ mm}^4$

b) Calculation for theoretical load, P

p_y = 275 N/mm^2

y = 23 mm

S = I_{total} / y = 32034.78 mm^3

M_c = p_y S = 8809564.5 Nmm

@ 8.81 kNm

M = PL / 4

P = 4M / L

L = 0.8 m

M @ M_c = 8.81 kNm

Thus,

P = 44.05 kN #