Quantification of Interface Adhesion Strength of Adhesive Bonded Dissimilar Materials Using Ultrasonic Technique

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Certificate

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DEDICATION

This thesis is dedicated to our parents, teachers and colleagues for their support and encouragement.

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Abstract

Ultra-Sonic testing technique is considered a powerful tool for non-destructively assess and analyse the interface between two adhesively bonded materials. The ultrasonic waves reflect after interacting with the adhesively bonded interface. This reflection can be evaluated in order to estimate the shear strength of the adhesively bonded imperfect bond between two dissimilar materials. A correlational analysis is employed using relationship of sound waves to shearing and Regression Analysis to assess the reflected signal from the interface of two dissimilar adhesively bonded materials. In this investigation to quantify the relationship between interface adhesion strength and ultrasonic-technique, two adhesively bonded dissimilar materials were used. A block of 4340 Steel adhesively bonded with Poly-Urethane to a silica winded Composite was evaluated in this study. The reflection signal from the bonded material was analysed and compared with the reference signal acquired from the unbonded part using UT-method to obtain the Interfacial Stiffness (K_n), Reflection Co-efficient (R_L) and Return Loss (R). These three variables were then evaluated and correlated with the Shear Strength of the bonded part measured by tensile testing. Analysis of results acquired from the experiments shows that the shear-strength is cumulative linearly with the rise in Gain and Reflection Coefficient with a correlation of 98%. It validates that the shear strength can be characterized and calculated using the reflection coefficient. Moreover, the mathematical model developed discloses the feasibility that shear strength can be evaluated of two dissimilar adhesively bonded materials using non-destructive methods.

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CHAPTER 1

INTRODUCTION

1.1. Quality Control:

Quality control is one of the most importantdepartment of an Industry. The main objective of quality control is to ensure that every product they produce fulfill the specifications barrier set from company. Sometimes it become very difficult for a company to check each part because it takes much time and large resources. But on the other hand, it is very important to check and maintain quality to minimize the risk. Especially in defense industry it is very important to check the quality of each part because a minor fault can cost huge loss.

1.2. National Engineering and Scientific Commission (NESCOM):

The National Engineering and Scientific Commission (NESCOM) is an institution of government of Pakistan. This Central government controlled scientific and engineering organization is responsible for carrying out research and advancement in several fields including fluiddynamics, information technology, aerodynamics, electrical engineering, aerospace engineering, chemical engineering and mechanical engineering with main focus in the design and manufacture of communication systems and aerodynamic vehicles including missile systems and air defense systems for the Pakistan Armed Forces. The main admirativecontrol of NESCOM is under Strategic Plans Division of Pakistan's National Command Authority with its headquarter in Islamabad.

1.2.1. Problem faced in Quality control:

Worldwide many companies are manufacturing differentparts and one of the biggest problems in the industries is to maintain quality and reliability of the process of inspection of quality of manufactured parts. Similar situation is faced by National Engineering and Scientific Commission (NESCOM). During their manufacturing they are making a specific parthaving its application is in aerospace. The part is made by joining two components. One is metallic and other is made up of composite, joined with the help of resin. During the flight the part also face much thrust force and have much chances of failure. The failure is also mostly originated from the resin interphaseand they also have variation in strengths part to part although most of the conditions are kept as much constant as they can.The problem they are facing isin checking the strength of the bonded part. The conventional methods that they followed are not reliable enough and not economical as well. So, all they need is to produce a reliable and a convenient method to check the strength of the bonded part.

1.2.2. Conventional Method:

The conventional method to check the strength of such parts is to do shear test but after the shear test given sample failed and cannot be used in the application. In such situations quality assurance department do not check each part instead they randomly pick up some samples from bulk and test them. The results from these random samples also represent the un tested parts as well. Due to which the percentage of uncertainty increases, and chances of failures are also increased respectively.

In Defense industries, some of the parts and joints are very critical and their failure can cause very heavy damage. In such cases we cannot afford even minute chances of failures and uncertainty. So, they wanted to develop a process with less percentage of uncertainty.

If we wanted to decrease the percentage uncertainty, we should increase the number of test samples. By increasing test samples, we may lower the uncertainty percentage but on the other hand it is not cost effective. So, they need an alternative way to check the bond strength.

1.2.3. Solution of the Problem:

I order to solve the current situation we proposed a solution to check the bond adhesive strength with the using the Non-destructive testing technique so that we can check each part we produce without damaging them. This purposed solution counter both problems. By checking every part, we lower down the uncertainty percentage in the results and by using non-destructive testing the samples are not damaged and can be used for desired purpose.

1.3. Non-Destructive Testing:

The definition of non-destructive testing according to Wikipedia is “Nondestructive testing (NDT) is a wide group of analysis techniques used in science and technology industry to evaluate the properties of a material, component or system without causing damage”.

There are several NDT techniques which includes:

- Infrared Testing (IR)
- Ultrasonic Testing (UT)
- Film Radiography (FR)
- Liquid Penetrant Testing (PT)
- Electromagnetic Testing (ET)
- Vibration Analysis (VA)
- Magnetic Particle Testing (MPT)
- Leak Testing (LT)
- Radiographic Testing (RT)
- Straight Beam
- Visual Inspection (VI)
- Acoustic Emission Testing (AET)

Thi technique which we select for our Project is Ultrasonic testing.

1.3.1. Ultrasonic Testing:

“ In ultrasonic testing we use high frequency sound energy to measure and examine samples. This high frequency sound is also used to detect flaws, dimension measurements, characterization of materials and interfacial information etc.”

Basically,Ultrasonic testing system consist of mainly four parts,

1- Pulse maker
2- Receiver
3- Transducer
4- Display devices.

The primary purpose of pulse maker is to produce high voltage electrical pulses. These electrical pulses are received by the transducers. The transducers are in the form of crystals which can convert electrical pulses to vibrations and vibrations to electrical impulses as well. The vibrations transducer produces cause the generation of sound waves. The nature of the sound waves is dependent on the nature of electrical impulses. In this case the impulses vibrate the transducers to produce Ultrasonic sounds. The ultrasounds produced by the transducers then propagates into the materials in the form of waves. Thesewaves travel and during their propagation when find a discontinuity (like crack or interface) they act differently like reflect back, absorb or diffract. The received back signal is then transformed into electrical signal using transducer. Based on the signal we receive back we came to know the reflectorlocation, size, orientation and

other

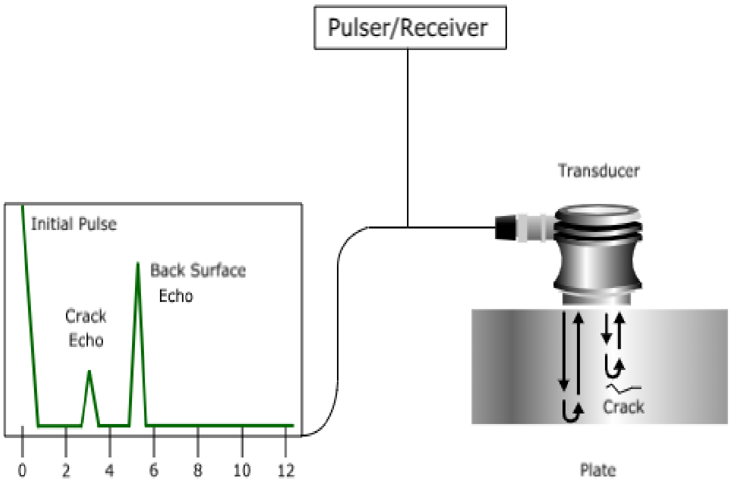

Figure 1: Schematic Diagram of working of UT Testing

features can sometimes be gained.

1.3.1.1. Wave interaction with interface:

The ultrasonic waves interact differently with different interfaces. The focus of our research project is to estimate the bond strength based onreflection of ultrasonicwaves.

In our sample we introduce the ultrasonic waves of 5 giga hertz from the metallic side of sample because the ultrasonic waves cannot propagate to enough distance. There are two interphases which are formed.

- Metal and adhesive interface

- Composite and adhesive interface

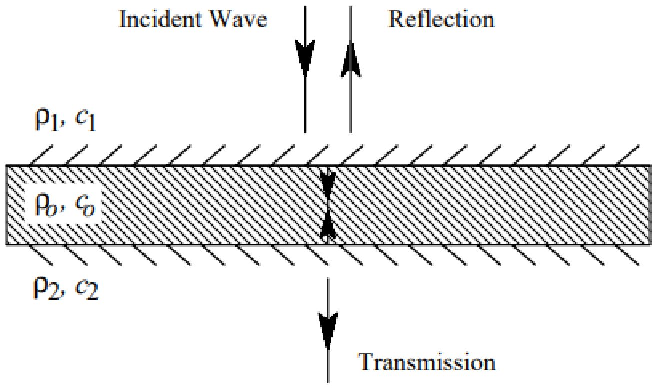

Figure 2: The schematic representation of the reflection and transmission of the ultrasonic sound waves through our sample is Shown

CHAPTER 2

LITERATURE REVIEW

This chapter will provide the review from previous researches related to the final year project. There are previous researches conducted on determining the adhesive bond strength using ultrasonic waves for different materials combination and joint standards. Other than that ultrasonic testing-NDT, phenomena of reflection, transmission and impedance in metal and composite material is discussed in this chapter.

2.1. Non-Destructive Testing:

Non-destructive testing is the group of operations used to inspect parts or assemblies for any discontinuities or irregularities without destroying the serviceability of the system. After NDT part can be used for its certain operation. NDT is usually used to ensure the quality and integrity of the material to be used in fabrication or other mechanical processes. NDT inspections determines the service life of the material. [1] A number of methods are applied to inspect the material. The commonly used techniques are magnetic testing (MT), radioactive testing (RT), ultrasonic testing (UT), electromagnetic testing (ET), liquid penetrant testing (PT) and visual testing (VT). Usually test method names depicts the equipment or medium used for testing. However, ultrasonic testing is the major development in the evolution of NDT for examining strength and toughness.

There are several NDT techniques which includes:

- Infrared Testing (IR)
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- Straight Beam
- Visual Inspection (VI)
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2.1.1. Ultrasonic Testing:

Ultrasonic testing utilizes high frequency sound waves in the range of 0.5-15 MHz, to measure the surface and sub-surface properties. It is used to inspect internal cracks, dimensional accuracy and other flaws. The basic working principle of UT machine is the quantification of transmitted and reflected sound waves in the material.

Generally, a UT system consists of a pulsar/receiver, transducer and display screen. A pulsar is an electronic device which generates high voltage electrical energy and driven by the transducer it is transmitted into the part. Transducer transforms the electrical energy into ultrasonic sound waves. These waves propagate through the material and gives a visual graph simultaneously on the display screen. When there is a crack on the wave path, a part of the transmission is damped or reflected back. Transducer converts this part of energy into an electrical signal and displays it on the screen. Knowing the speed and range of the transmitted signal, crack size and depth can be determined by analyzing the resulting graph. A coupling medium is used at the interface of the transducer and testing surface to avoid air entrapment, e.g. water, oil, glycerin and grease.[2]

2.1.2. Advantages:

Ultrasonic testing is highly sensitive to surface and sub-surface flaws relative to other methods. It can determine the depth and shape of the penetration. It requires least specimen preparation and provide results simultaneous to testing. It displays highly detailed graphs and also provide information about part's thickness. Most importantly it's user friendly. It's not hazardous to operator and the complete system is portable.

2.1.3. Limitations:

Ultrasonic testing requires direct interaction of transducer and surface. Mostly a coupling medium is required at the interface to enhance transmission of sound waves. Materials that have irregular dimensions or surface are not favorable. Especially cast iron and other coarse-grained parts show lack of sound transmission and the signal is damped. Routine calibration of machine is required, and reference part must be available for the characterization of defects. It also requires highly skilled and trained operator.

2.2. Destructive Testing:

Destructive testing involves test methods in which part is distorted to determine the mechanical properties, such as strength, toughness, ductility and hardness. Destructive is valuable when used together with non-destructive tests. NDT determines the availability of cracks, corrosion and other flaws while destructive methods examines that how much stress a material can sustain without fracture. Thus, it helps to reduce failures and quantify part's life.

2.2.1. Universal Tensile Testing Machine:

Tensile testing machines are used for universal purposes. They determine the tensile strength, yield strength, elongation and fracture toughness of the material. This machine can be configured to perform other functions such as shear, bend, tear and peel test. The major step in using this machine is to specify the dimensions, geometry and size of the sample. There are designated standards for each test to obtain best results. The machine used in this project is Shimazdu 20kN.

2.2.2. Shear Strength:

Shear strength is the ability to resist forces that slides the structure of the material against each other. It prevents the material to fail in shear. It is the load that a material can bear in a direction parallel to the material's surface without fracture. It is experienced just before material undergoes fracture.

The strain which generates as a function of shear stress τ_{xy} is a shear strain γ_{xy}. It is distortion over length however, displacement is diagonal to the surface. Hence, it's also the right-angle deformation:

$$\delta/L = \tan\gamma \approx \gamma$$

Under the function of small loads, this angular deformation is proportional to shear stress. According to Hook's law,

$$\tau_{xy} = G\,\gamma_{xy}$$

where G is called the shear modulus. [3]

2.3. Adhesive Bonded Joints:

Composite Materials of advanced technology are being used today in many applications due to their light weight and high strength. Bolted joints have been replaced by adhesive bonds corrosion and weight problems. An systematic model is required to analyze the stress distribution across the bond and also to investigate the adhesive/cohesive failure. Adhesively-bonded joints have been studied by adopting different approaches including single-lap, double-lap, scarf, and stepped-lap joints involving a continuum mechanics model in which the adherents are isotropic or anisotropic elastic, and the adhesive is modeled as elastic, elastic-plastic, or bi-elastic. [15] “Renton and Vinson used a higher order formulation that includes the adherents transverse shear and normal strains to analyze adhesive-bonded joints.” [4]Yang and Pang studied double-lap composite joints under cantilevered bending and developed a strain gap model to describe the stress-strain behavior. [5] They also derived analytical models for adhesive-bonded composite single-lap joints under cylindrical bending and tension. [6]

In 1996, Adams and Davies derived the “experiments on single-lap adhesive-bonded joints of Composite-Steel and Composite-Aluminum” based on non-linear finite element model “with different taper arrangements at the edges of joints.”[7] Later in 1997, a researcher named Tong conducted a study to analyze the “strength of adhesive-bonded double-lap composite joints.”[8]

“The finite element method has been widely used to analyze adhesive-bonded composite structures as well as adhesive-bonded repairs. Although finite element model can solve many mechanical problems with different materials and configurations, analytical solutions are still preferred to perform parametric analyses such as optimization.”[8]

An analytical model determines the stress and strain distributions of adhesive-bonded composite single-lap joints under tension. The composite adherents are assumed linear elastic while the adhesive is assumed elastic-perfectly plastic. There are three major failure modes of adhesive-bonded joints

1. Adherent failure
2. Cohesive failure
3. Adhesive failure.[9]

2.4. ASTM D 1002 – 99:

This model explains the shear strength of adhesives used for bonding a standard (ASTM- 1002) single-lap-joint specimen. This test method is primarily used for determining strength properties of adhesively bonded joints by controlling surface preparation and adhesive systems. Apparently, the shear strength of given adhesively banded single-lap joint may differ from a joint made with different adherents or by a different bonding process. Moreover, environmental changes induce internal stresses that result in varying bond strength and affect the mechanical properties of a bonded specimen such as the change of temperature and moisture causes the adhesive to shrink or swell.

The testing machine must fulfill certain requirements including the breaking load of the specimen falls between 15 and 85 units. To approach this rate of loading the machine must be set to approximately 1.27 mm/min. the jaws of the grip shall grip the outer 25 mm of each end of the test specimen firmly. The length of overlap may be varied, if necessary. However, the length of the part clamped in the jaws must not be changed.

Test specimen shall be formed of specific dimensions. The thickness of sheets as per standard is 1.62 ± 0.125 mm. Mostly the length of overlap is 1.62 mm with thickness of 12.7 ± 0.25 mm. The length of overlap joint can be calculated by the following relation;

$$\mathbf{L = F_{ry}\, t / \tau}$$

Where,

L = length of overlap (in.)

t = thickness of metal (in.)

F_{ry} = yield point of metal (psi)

τ = 150 percent of the estimated average shear strength in adhesive bond (psi)

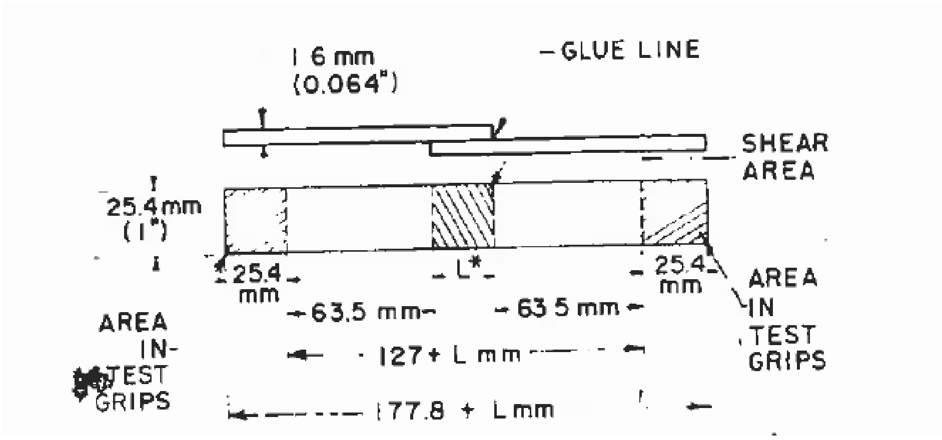


Figure 3: ASTM Standard D1002

2.4.1. Factors Affecting Joint Performance:

2.4.1.1. Adherend Thickness:

The adhesively bonded single lap joint was tested with different thickness of applied adhesive. "It showed that the calculated failure load increases as the adherend thickness increases." [4]

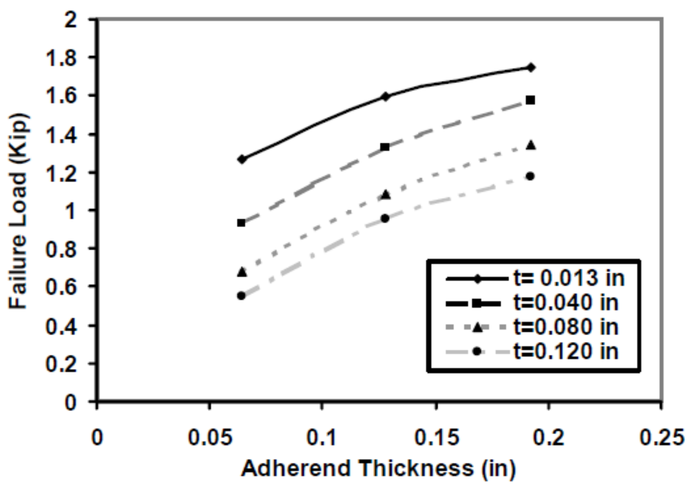


Figure 4: Adherend Thickness vs Failure Load. *[4]*

2.4.1.2. Adherend Stiffness:

"The relationship between the failure load and adherend Young's modulus was also investigated." [4] It was observed that for the same joint geometry, increasing the adherend young's modulus contribute to resistance to higher failure load.

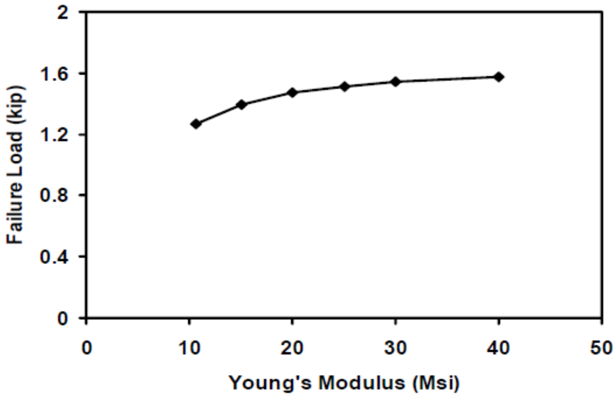


Figure 5: Young's Modulus vs Failure Load Graph. *[4]*

2.5. Non-Destructive Testing Methods for Adhesive Joints:

The use of structural adhesive is growing rapidly as unlike welding and mechanical fastening, it avoids the heat affected zones and non-uniform stress distribution. However, it depends on the properties of adhesive and cleaning of surfaces. Moreover, it is desirable to investigate the strength of adhesively bonded joint on the assembly line. It is only feasible via non-destructive testing. There are variety of non-destructive testing techniques but considering the ease of instrumentation and adequacy of automatic operations, ultrasonic and vibration methods are most suitable.

The transmission technique is effective in analyzing de-bonding, but it requires contact of probes from both sides of the joint which is not practicable in most of the cases.

Therefore, researchers tend to use pulse-echo. It is mainly dependent on stiffness of adhesively bonded joint. [10]

The Fokker bond tester usually measures the initial two frequencies of the bonded joint and compares it with the frequency of single sheet metal[11]. Another approach is the

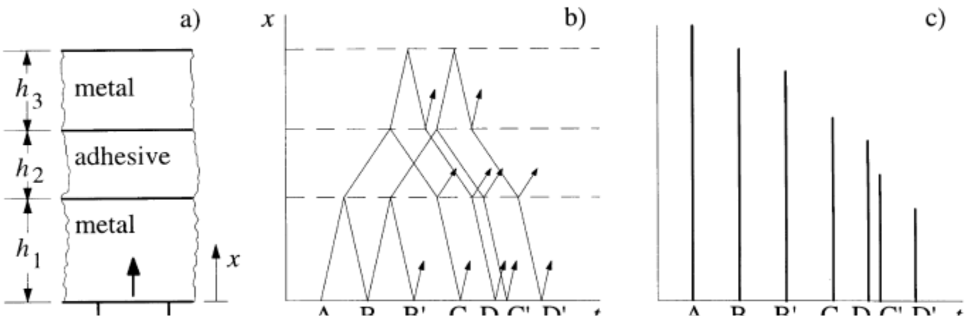


Figure 6: Progression of Sound Waves in a Material

acoustic ultrasonic technique that transmits the ultrasonic pulse via a transducer to a receiver through the joint on the same surface[12]. The spectrum of the transmitted waves is affected by the defects in the part. This phenomenon is influenced by the other factors including wave velocity, curing time of adhesive, etc.

2.5.1. The Ultrasonic Spectroscopy of Contact Interfaces

Usually the strength of engineering assemblies mainly depends on the bonding between its components. This includes welding, brazing or adhesively bonded joints. However, the efficiency of joint is also influenced by imperfections along the bond-line such as cracks, porosity, inclusions etc. These inclusions are characterized as a very thin layer interphase between the joining materials. Thus, ultrasonic testing is the most suitable method for determining the strength of an interfacial bond in terms of imperfections. Spring boundary phenomena is used to analyze the mechanical properties of the interphase. The objective is to measure the interfacial stiffness that is dependent on frequency response of the transmitted ultrasonic waves. This response is computed in terms of reflection coefficient from an interphase with spring boundary conditions. [13]

The strength of material joint can be improved by interfacial layers in solid state bonding. Thus, the transmitted ultrasonic signals are reflected from front and back of the interface either normally or obliquely, are not distinguished in the time domain and interfere. For this purpose, ultrasonic spectroscopy is utilized to characterize the two imperfect interfaces as a function of their thickness. To simplify this methodology, the factor of impedance mismatch is excluded and a homogeneous model, based on the same material substrates is considered. Aluminum layer is applied between two Aluminum plates and varying force is applied across the interface to achieve a gradient of bond imperfection. As the impedance of all the constituent materials is same so the reflection from the center layer is only a function of applied pressure and surface roughness.

When an ultrasonic wave is incident on the top of the imperfectly bonded layer between identical substrates, the theory is that the reflecting wave is separated into two interfering signals

1) Reflection from the top surface layer (first reflection signal)
2) A cumulative reflection from the bottom layer (sum of all multiple reflections)[14].

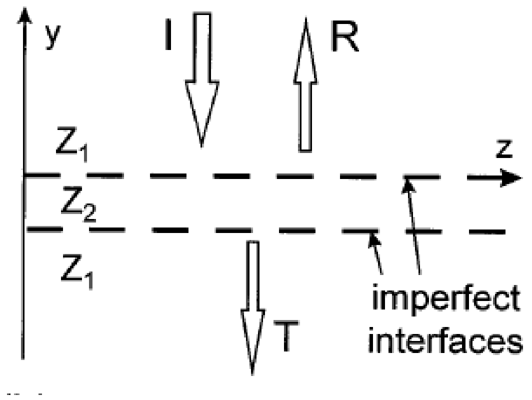


Figure 7: Layer imperfectly bonded to two solid

2.5.2. The Interface-Wave Method

It has been observed that if the shear modulus of the interface layer is smaller than that of the solid substrates then it exhibits waveguide properties. Moreover, if the interface thickness is much smaller than the transmitting wavelength, it only produces shear stresses within the film. Thus, the wave-velocity and damping of the interface can be used to determine the shear modulus of the interface. The shear slip, or failure of adhesive bond occur in two ways. The failure inside the adhesive layer is called the cohesion failure. The cohesive strength of the layer is dependent on the elastic modulus. The other is along the adhesive-substrate interface, called adhesion failure.

The adhesion failure is not defined by any physical theory. However, theoretically it is related to the cohesion failure of a weak boundary layer (WBL). WBL is a part of interface with low strength region and incase of zero thickness the whole interface region is regarded as WBL. The phenomena of dynamic shear modulus of the multilayer system based on adhesive layer and WBL helps to predict the strength of a given specimen relative to standard specimen.

A thin adhesive film between the two identical elastic substrates undergoes a transition from liquid to solid phase. However, there exist a relation between transition and adhesive-substrate bond strength. When a Rayleigh wave propagate on the adhesive interface, an alternate pattern of compression and tension generates at distance equal to half of the wavelength. Moreover, the thickness of adhesive layer is considered much smaller than the transmitted Rayleigh wavelength. [15]

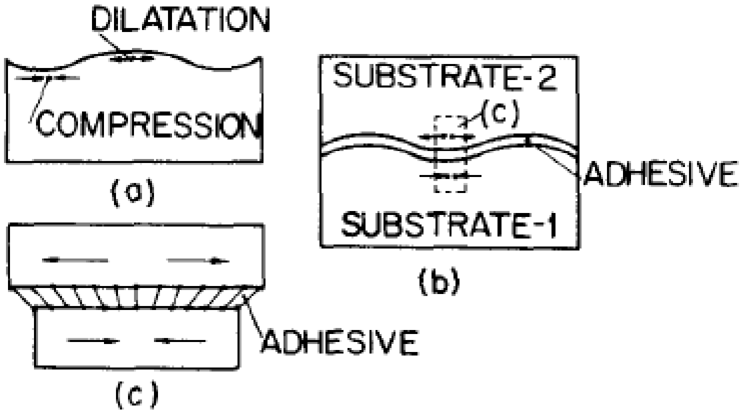


Figure 8: Thickness affects the Dilation of Sound Waves

2.6. Regression Analysis and Correlation:

"Many relationships among variables exist in the real world. One way to determine whether a relationship exists is to use the statistical techniques known as correlation and regression. The strength and direction of a linear relationship are measured by the value of the correlation coefficient. It can assume values between and including -1 and +1. The closer the value of the correlation coefficient is to -1 or +1, the stronger the linear relationship is between the variables."

Regression analysis tells us the relation between an independent and dependent variable. The regression equation contains one independent variable x and one dependent variable y' and is written as:

$$y' = a + bx$$

where a is the y' intercept and b is the slope of the regression line.

In multiple regression, there are several independent variables and one dependent variable, and the equation is

$$y' = a + b_1x_1 + b_2x_2 + \ldots\ldots b_ix_i$$

Where x_1, x_2,…..x_i are independent variables.

"As with simple regression, R^2 is the coefficient of multiple determination, and it is the amount of variation explained by the regression model. The expression $1-R^2$

represents the amount of unexplained variation, called the error or residual variation. Since R = 0.989, R^2 = 0.978 and 1 - R2 = 1 - 0.978 = 0.022. lesser the difference more the equation is feasible.”[15]

Finally, remember that a significant relationship between two variables does not necessarily mean that one variable is a direct cause of the other variable. In some cases, this is true, butother possibilities that should be considered include a complex relationship involving other (perhaps unknown) variables, a third variable interacting with both variables, or a relationship due solely to chance.

2.7. Assessment of Adhesive Bond Strength:

A detailed research has been done on the ultrasonic technique for the evaluation of dimensional defects and bond strength through the transmission of guided ultrasonic waves. [16] Detected the dry contact bonds of adhesive joints using three ultrasonic techniques. [17] Explained the dependence of normal and tangential interfacial stiffness values of the contact forces on the frequency and applied pressure. [18] Analyzed the correlation of interfacial stiffness measured ultrasonically and mechanically measured bind strength. [19] Presented a model to simulate the ultrasonic wave propagation at the adhesive interface and calculating the binding force of the joint.[20] Determined the quality of bind between an aluminum substrate and epoxy layer, using ultrasonic waves.

2.7.1. Modulation:

As the reflection coefficient is the function of frequency, thus by determining the frequency, interfacial stiffness and bond strength can be evaluated. An epoxy based adhesive bind has been made between two identical aluminum substrates. If the binding is non-uniform and the size of defects is much smaller than the transmitted ultrasonic wave then by spring boundary conditions, interaction of ultrasonic wave with the interface can be described:

$$\sigma_{yy}^{(2)} = K_n\left(u_y^{(1)} - u_y^{(2)}\right) \quad \sigma_{yz}^{(2)} = K_t\left(u_z^{(1)} - u_z^{(2)}\right),$$

$$\sigma_{yy}^{(2)} = \sigma_{yy}^{(1)} \quad \sigma_{yz}^{(2)} = \sigma_{yz}^{(1)},$$

where σ_{yy}, σ_{yz}, u_y, and u_z are normal and shear stresses and displacements on the y and z direction at the interface, subscripts 1 and 2 denote the upper and lower semi space respectively, $K_n$and $K_t$are the normal and tangential interfacial stiffness per unit area (N/m^3) respectively. [18]

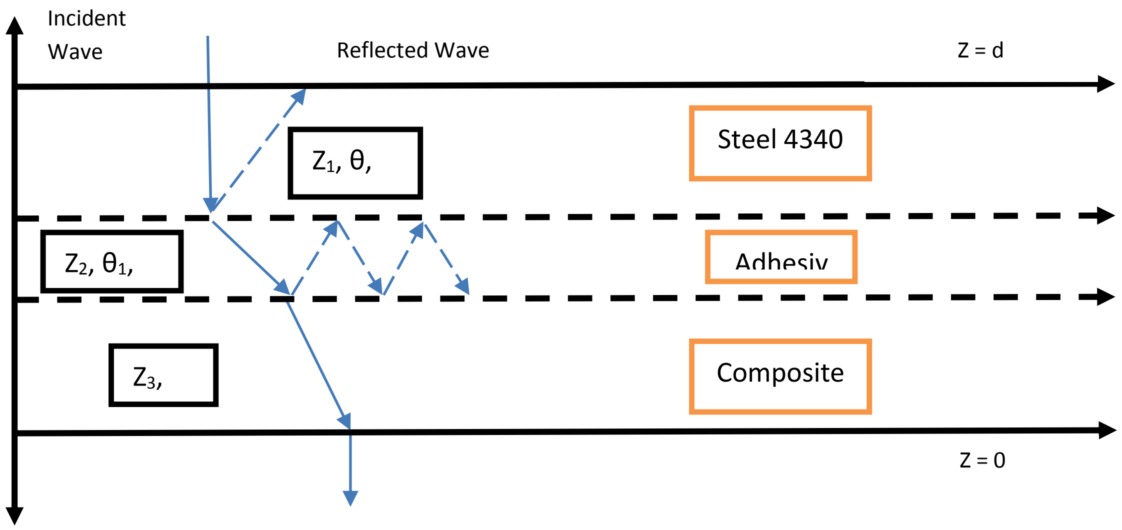


Figure 9: Imperfect interface between two adhesively imperfectly bonded solids.

The reflection coefficient R_{12} of a transmitted wave is given as:

$$R_{12} = \frac{Z_2 - Z_1 + i(\omega/K_n)Z_1Z_2}{Z_2 + Z_1 - i(\omega/K_n)Z_1Z_2},$$

However, the transmission coefficient T_{12} of the incident wave is:

$$T_{12} = \frac{2Z_2}{Z_2 + Z_1 - i(\omega/K_n)Z_1Z_2},$$

where ω is the angular frequency of the incident wave and Z is the acoustic impedance of the respective material.

Further, the reflection signal R_L is separated into two parts, a) refection from the top surface R_{12}; b) reflection from the bottom surface which is the sum of all possible reflections R_Σ.

$$R_L = R_{12} + R_\Sigma,$$

Subtitling the equations determines the reflection from the imperfectly bonded interface.

$$R_L = \frac{Z_2 - Z_1 + i(\omega/K_n)Z_1Z_2}{Z_2 + Z_1 - i(\omega/K_n)Z_1Z_2} + \frac{\frac{2Z_2}{Z_2+Z_1-i(\omega/K_n)Z_1Z_2} \times \frac{2Z_1}{Z_1+Z_2-i(\omega/K_n)Z_2Z_1} e^{2ikb}}{1 - \left(\frac{Z_2-Z_1+i(\omega/K_n)Z_1Z_2}{Z_2+Z_1-i(\omega/K_n)Z_1Z_2}\right)^2 e^{2ikb}} \times \frac{Z_1 - Z_2 + i(\omega/K_n)Z_2Z_1}{Z_1 + Z_2 - i(\omega/K_n)Z_2Z_1}.$$

2.7.2. Acoustic Impedance

Impedance evaluates the force required to introduce a certain velocity. It is the intrinsic property of the medium.

$$Z = \frac{F}{T}$$

In case of two materials in contact if $Z_1 = Z_2$ then it exhibits complete transmission and no reflection. Moreover, if $Z_1 < Z_2$ then transmission coefficient is greater than 1. This shows that the amplitude increases when a wave travels from a medium of lower impedance to a medium of higher impedance. [21]

CHAPTER 3

METHODOLOGY AND METHODS

The methodology and the methods used in this project are as follows.

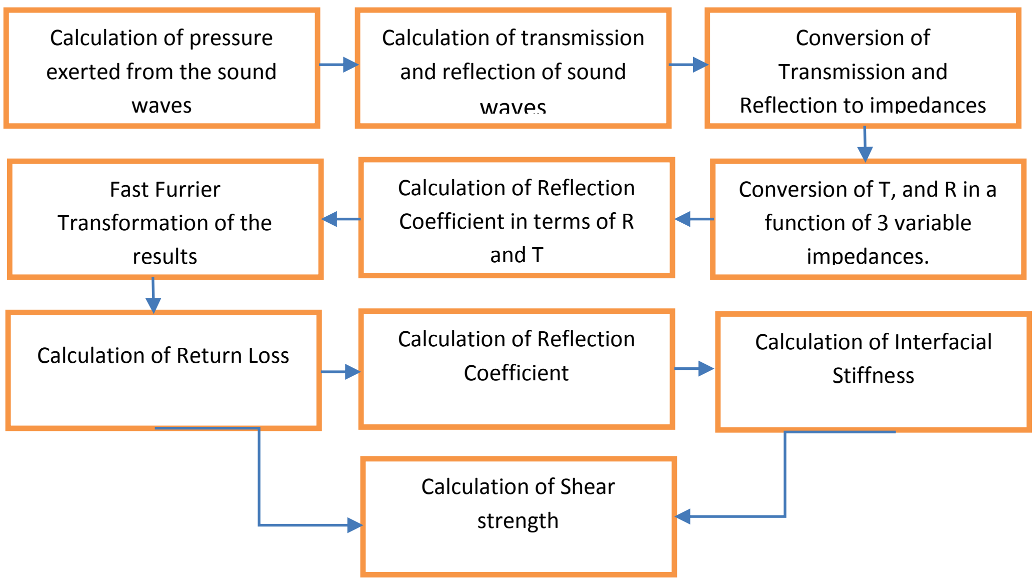
3.1. Learning of UT-NDT:

To learn UT-NDT as series of standard experiments were run of a standard Aluminum sample. To run these experiments, an apparatus was designed so that authentic results are obtained. The designed apparatus and experiments are explained in the experimental section.

3.2. Designing of the Experiments:

Experiments were designed by the mutual consideration of the industry and the availability of the apparatus in SCME. A total of 4 tests were run in SCME till 7th semester and 4 tests were run in NESCOM and the results were compiled and compared to each other. The design of experiments will contain.

I. ASTM Standard used in sample preparation for Shear Strength.
II. The frequency and type of probe used in UT-NDT.
III. The pre-credentials of Shear Strength test used in the selected ASTM standard.
IV. Medium of UT-NDT test.Type of couplant used in UT-NDT.
V. Softwares used in evaluating the results.



3.3. Designing of the Mathematical Model:

A mathematical model had to be designed to in order to quantify interfacial stiffness and shear strength results which was the aim of the project. Hence a model will be designed at the end of the project and it will be used by the industry to evaluate the shear strength of the adhesively bonded products.

The mathematical model will be designed using the following method.

3.3.1. Fast Fourier Transform of the Equation and Results:

Fast Fourier transformation was done of the equation to eliminate the complex quantities in order to get the simplified equation. This equation was used to calculate the value of Interfacial Stiffness. This interfacial stiffness was then correlated with the results of shear strength of the sample determined from the shear test on UTM machine.

3.3.2. Regression and Correlation Analysis:

Regression analysis and Correlation analysis was done for Shear Strength vs Reflection Coefficient, Strength vs Return Loss and Strength vs Interfacial Stiffness. The results obtained from this relation will tell us whether the relationship holds between the equation derived and the experimental results or not. This analysis was done on Minitab software edition 2016.

3.4. Experimental Techniques and Design of Experiments:

The experimental techniques and design of the experiments for Ultra-Sonic Testing and Shear strength test are as follows.

3.4.1. Preparation of Samples:

The samples prepared are as follows.

Table 1: Types of Sample Preparations.

Sr No	Sample No.	Conditions

1	NDT-UT-99-1	Sample prepared and cured at STP
2	NDT-UTAH-99-2	Prepared at STP and cured under Weight of 5 kg
3	NDT-UT-99-3	Prepared at STP and cured by clamping on a Vice
4	NDT-UT-99-4	Sample prepared and cured at STP

3.4.2. Experimental Techniques for Ultra-Sonic Testing:

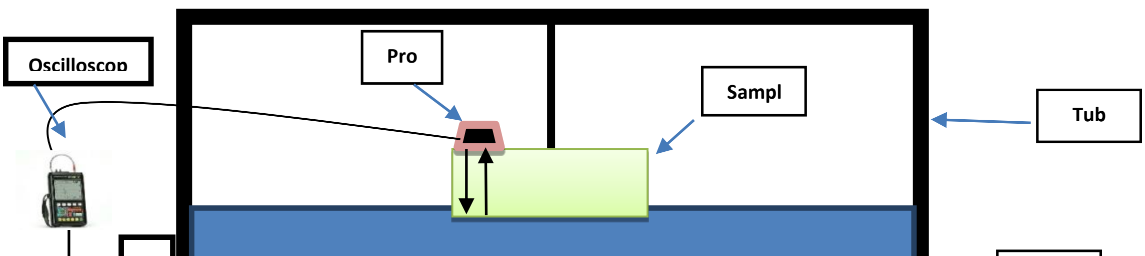
The experimental technique for Ultra-Sonic testing used was single beam transducer method. The machine used was EPOCH LT 910-258. A frequency of 5.0 MHz and an element diameter of 1 inch probe was used. The couplant used was machine oil. The machine was calibrated using a standard Al-Block provided with the machine.

Figure 10: NDT Machine used in this project

The apparatus designed for ultrasonic testing had the following credentials.

I. A metallic tub of 12 inches in length, 6 inches depth and 3 inches wide.
II. A hanger fixed with the tub to support the sample.
III. The tub can be filled with any medium in which the sample is to be placed and tested.
IV. The sample is immersed in the liquid medium to about 0.5inches.

The signal from the probe is transmitted in the sample and the reflected signal is received from the same probe. This signal is then transmitted to the oscilloscope (UT-Device) where a graph is plotted between energy and counts of reflection. This graph then can be stored in the memory and then can be analyzed using the software.



3.4.3. Experimental Techniques for Shear Testing:

In shear testing a set of ASTM standards were studied and D1002 was opted. This standard was similar to the standard being used in NESCOM for shear testing.

Both steel and composite plates were cut according to the D1002 standard, the strain rate was

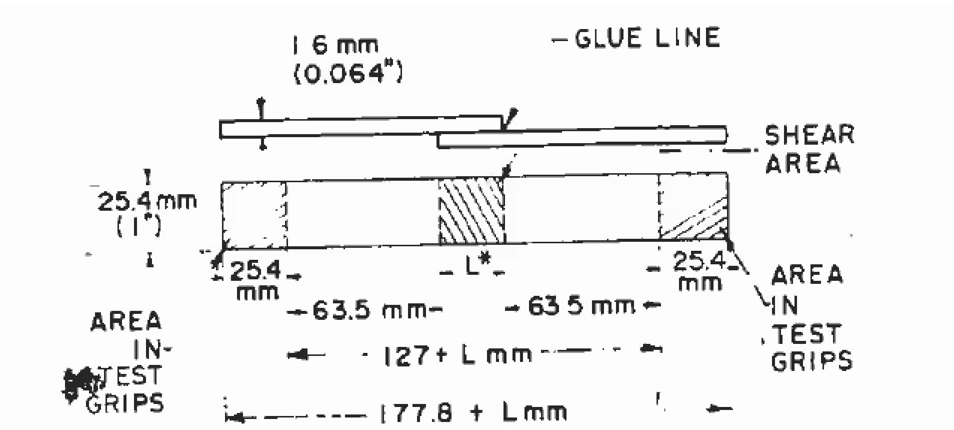


Figure 11: ASTM Standard D1002.

maintained at 1.27mm/min. The steel and composite plates were bonded by using a poly-urethene adhesive.

3.4.4. Regression and Correlation Analysis:

Regression Analysis and Correlation Analysis was done using Minitab software.

CHAPTER 4

THEORETICAL MODEL

4.1. Theoretical Model:

To modulate a formula for reflection and transmission for two dissimilar adhesively bonded materials a series of modulation steps were made.

4.1.1. Calculation of Pressure:

When sound waves enter into the material a specific pressure “P” is exerted on the interface. This pressure can be represented in terms of velocity “v”.

So,

$$P = v\omega\iota\rho$$

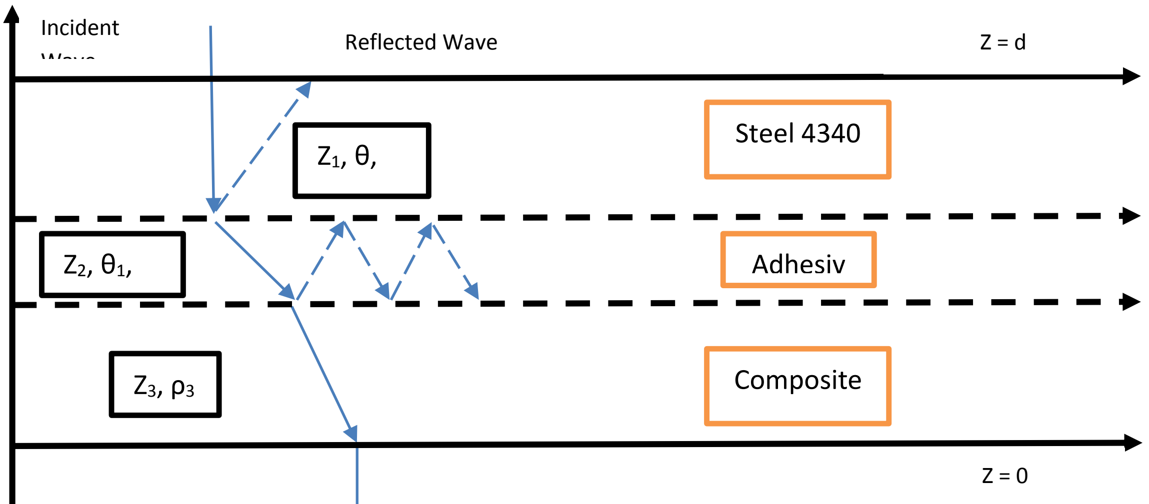
$$v = \frac{P}{\omega i\rho}$$

Where P = Pressure, v = Velocity of the wave, ω = frequency of the wave

During Ultrasonic testing, when sound wave enters and reflects to the receiver a certain time lapse occurs. This time lapse is calculated as:

$$t' = e^{-i\omega t}$$

In our case, the probe is attached directly to the surface of the sample and the time lapse occurring is in Microns. Hence, this time delay will be omitted in further calculations.



Now, let us take the incident wave pressure as P_{inc} and reflected wave as P_{ref}. The reflection coefficient will be “R”. The reflection coefficient tells us how much of a wave is reflected by an impedance discontinuity in the transmission medium.

So,

$$P_{inc} = e^{ik(xSin\theta - zCos\theta)}$$

$$P_{ref} = Re^{ik(xSin\theta + zCos\theta)}$$

where θ is the angle of incidence of the wave and “k” is wavenumber which is made by the normal to the wave front and the z-axis. The total field in the upper medium will be:

$$P_{total} = P_{inc} + P_{ref}$$

$$P_{total} = e^{ik(xSin\theta - zCos\theta)} + Re^{ik(xSin\theta + zCos\theta)}$$

$$P_{total} = e^{ikxSin\theta}\left(e^{-ikzCos\theta} + Re^{ikzCos\theta}\right)$$

Where P_{total} is the reflected wave above the medium. Now we need the value of transmitted wave. This can be taken as the negative of reflected wave value as there is no incident wave in this case.

$$P_{trans} = Te^{ik_1(xSin\theta_1 - zCos\theta_1)}$$

Where “T” is the coefficient of Transmission.

4.1.2. Calculation of Coefficient of Transmission and Reflection:

While during this project, our concern was only with the “z” direction as the angle of the probe was 0^o. There was no transmission in x or y directions. Hence, adding the values for P_{total} and P_{trans}, we will get the values for R and T.

Taking the boundary value of z=0 and P=0.

$$0 = -e^{ikxSin\theta - ikzCos\theta} - Re^{ikxSin\theta + ikzCos\theta} + Te^{ik_1xSin\theta_1 - ikzCos\theta_1}$$

$$T\cancel{e^{ikxSin\theta}} = \cancel{e^{ik_1xSin\theta_1}}(1+R)$$

Hence, we get the relation. So, reflection and transmission coefficients in single beam transducer method are independent of angle and wavenumber.

$$1 + R = T$$

4.1.3. Conversion of Coefficient of Transmission and Reflection to a Function of Impedances:

Now we have formulated the relationship between reflection and transmission coefficients, we have to convert them into a function of impedances in order to calculate the requires variables.

To do so, we know that:

$$Z = \frac{\rho c}{Cos\theta}$$

Where Z = Acoustic Impedance, c = Speed of sound in that medium, ρ = Density of the medium.

In this project: $\theta = 0^{o}$

So,

$Z_1 = \rho_1 c_1$, $Z_2 = \rho_2 c_2$, $Z_3 = \rho_3 c_3$

Using the continuity of impedances, we found that:

For reflection coefficient.

$$R_{12} = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

$$R_{23} = \frac{Z_{12} - Z_3}{Z_{12} + Z_3}$$

For transmission coefficient.

$$T_{12} = \frac{2Z_1}{Z_1 + Z_2}$$

$$T_{23} = \frac{2Z_{12}}{Z_{12} + Z_3}$$

Now, we have to calculate the values for Z_{12}.

For this, we will again use the continuity of impedances. The continuity of impedances tells us that, at boundary values, impedance is equal to P/v. we have already found the values at z = 0. Then it can be calculated at the boundry value of z = d.

So,

$$Z_{12} = \frac{[Z_1 - Z_2 Tan(kd)i]}{[Z_2 - Z_1 Tan(kd)i]} Z_2$$

4.1.4. Conversion of T, and R in a function of 3 variable Impedances:

Now, we have to convert the formulated equations of reflection and transmission equation in a function of three variables.

The formulated equations are as follows.

$$R = \frac{(Z_1 + Z_2)(Z_2 - Z_3)e^{-ikd} + (Z_1 - Z_2)(Z_2 + Z_3)e^{ikd}}{(Z_1 + Z_2)(Z_2 - Z_3)e^{-ikd} + (Z_1 - Z_2)(Z_2 + Z_3)e^{ikd}}$$

$$T = \frac{4Z_1 Z_2}{(Z_1 - Z_2)(Z_2 - Z_3)e^{ikd} + (Z_1 + Z_2)(Z_2 + Z_3)e^{-ikd}}$$

4.1.5. Calculation of R an T in terms of Interfacial Stiffness:

Using the elastic behaviour of these waves we have to modify these equations of R and T to find the interfacial strength.

Now, during propagation of sound waves in the material shearing of the material at the interface is done. Which is denoted by η.

$$\eta = \frac{1}{K_n}$$

This η is related to compression coefficient and shear strength as follows.

$$\eta = \frac{\mu}{\tau}$$

Where μ is the compression coefficient. e^{ikd} and e^{-ikd} is replaced by $iw\eta_T$.

Hence the equations for R and T becomes.

$$R = \frac{(Z_1 - Z_2 - iw\eta_T Z_1 Z_2)(Z_2 + Z_3 - iw\eta_T Z_2 Z_3) + (Z_1 - Z_3 - iw\eta_T Z_2 Z_3)(Z_1 - Z_2 - iw\eta_T Z_1 Z_2)}{(Z_1 + Z_2 - iw\eta_T Z_1 Z_2)(Z_2 + Z_3 - iw\eta_T Z_1 Z_3)}$$

Substituting the value of ηT in the equation of R

$$R = \frac{\left(Z_1 - Z_2 - i\frac{w}{K_n}Z_1Z_2\right)\left(Z_2 + Z_3 - i\frac{w}{K_n}Z_2Z_3\right) + \left(Z_1 - Z_3 - i\frac{w}{K_n}Z_2Z_3\right)\left(Z_1 - Z_2 - i\frac{w}{K_n}Z_1Z_2\right)}{\left(Z_1 + Z_2 - i\frac{w}{K_n}Z_1Z_2\right)\left(Z_2 + Z_3 - i\frac{w}{K_n}Z_1Z_3\right)}$$

The value of Transmission coefficient comes to be:

$$T = \frac{2Z_1\left(Z_2 + Z_3 - i\frac{w}{K_n}Z_2Z_3\right) + 2Z_2\left(Z_1 + Z_2 - i\frac{w}{K_n}Z_1Z_2\right)}{\left(Z_1 + Z_2 - i\frac{w}{K_n}Z_1Z_2\right)\left(Z_2 + Z_3 - i\frac{w}{K_n}Z_1Z_3\right)}$$

Now because of infinite reflections in layered media, the total reflection coefficient will be a sum of all the reflections and Reflection Coefficient.

Th sum of all internal reflection is:

$$R_e = \frac{T_{12}T_{21}e^{2ikh}}{1 - {R_{12}}^2 e^{2ikh}}R_{21} + \frac{T_{23}T_{32}e^{2ikh}}{1 - {R_{21}}^2 e^{2ikh}}R_{32}$$

The Total Reflection will be:

$$R_L = R + R_e$$

This refection coefficient can be evaluated in terms of interfacial stiffness and can be compared with shear strength.

CHAPTER 5

EXPERIMENTS AND ANALYSIS OF THE RESULTS

5.1. Observations and Calculations:

Two different tests were carried out.

1. A standard Al-sample was tested with the UT testing machine to study the UT-test methodology.
2. A sample of certain dimensions (given by the industry) was tested as per experimental method.
3. Different samples prepared under different conditions were tested with UT and shear testing.
4. Normality curve was drawn using the test results of the samples.

5.1.1. Standard Sample Testing for choosing a Standard Medium:

The experiment was done on an Aluminum sample on a temporary apparatus using a cast iron box for the liquid and plastic tubes to hang the sample. The sample was hanged in the box using the plastic pipes to a specific height such that the bottom is slightly submerged in the liquid.

The sample thickness was first measured by Vernier Calipers and it was fed to the device. Single probe method was used to execute the experiment. The velocity was set as 6002m/s. Dampness was auto set to 50ohm. The other credentials were preset.

Now the experiment was run, and the range was set so that we get the best visual and the dB value was calculated with Air as our standard environment.

The same experiment was run for different environments and the dB difference was calculated from that of Air. In this way we were able to identify the behavior of metals in UT testing and the difference if the results in different mediums.

The results for preset credentials in different mediums are as follows;

Table 2: Credentials Set for UT-NDT of Standard sample in different mediums.

Credentials	Value Set
Velocity	6002m/s
Dampness	50ohm (auto-calibrated)
Gain	30dB
Zero Offset	0
Angle of the Probe	0^o
Thickness	25.67mm
Medium	Air, Water, Brine, Oil
Rejection	0%

The Standard Al-Block had the following material properties;

Table 3: Properties of Al-Block

Material	Shear Strength	Density	Acoustic Impedance	Velocity of the wave
Al-6061/6T	310MPa	$2.7g/cm^3$	6382	17.2010^5g.m/s

Using the credentials in Air as a standard we did experiments on the same sample but in water (dense medium) to identify the trend in the dB value whether it decreases or increases. Keeping the same credentials, we got the following results.

Table 4: Results of Standard Sample Testing

Sr. No.	Test Medium	Calculated Gain (30dB)	Change in Gain

1	Air	30	0
2	Water	33.1	3.1
3	Brine Solution	33.9	3.9
4	Oil	49	19

Hence in this way we got a vivid result that in different mediums the dampness increases. This could lead us to following results:

- As the medium becomes denser the dampness increases hence we should have to carry out the whole project using the same medium/environment.
- The dampness is also telling us the strength of the bond in the sample. Hence better-quality bond influences the dampness in the UT result.
- The shear strength also depends on the quality of the bond hence the better the bond strength the better the shear strength.

Hence the medium to conduct experiments was chosen to be Air.

5.1.2. UT-Results of Samples from NESCOM:

11 samples were tested which were made in different conditions but with same type of materials. Their Ultrasonic Testing was done using the Ultrasonic Testing Machine.

The experiment was done on 4 Adhesively bonded 4340 steel and Silica Winded Reinforced Phenolic Resin Composite with Poly-Urethane adhesive on a temporary apparatus using a cast iron box for the medium and plastic tubes to hang the sample. The sample was hanged in the box using the plastic pipes to a specific height such that handling the probe during UT-Testing is easier. The sample thickness was first measured by Vernier Calipers to be 12mm and it was fed to the device. Single probe method was used to execute the experiment. The velocity was set as 5849m/s. Dampness was auto set to 50 ohm. The other credentials were preset. The range was set so that the graph’s first peak is at the 80% of the scale and the dB value was calculated with the medium as Air.

The samples were prepared as of the standard ASTM D1002. 11 samples were prepared under different conditions of load. As the strength of bond will determine the strength of the joint and hence different results can be taken.

The credentials are;

Table 5: Credentials Set for Actual Samples Testing

Credentials	Value Set
Velocity	5849m/s
Dampness	50ohm (auto-calibrated)
Gain	30dB
Zero Offset	0
Angle of the Probe	0^o
Thickness	12mm
Medium	Air
Rejection	0%

The results of NESCOM samples are as follows;

Table 6: UT Testing results of NESCOM Samples

Sr No	Sample No.	dB Absorbed
1	NDT-UT-01-1	-3 (Simple)
2	NDT-UT-01-2	-3 (Simple)
3	NDT-UT-01-3	-4 (Weight of 5 Kg)
4	NDT-UT-01-4	-4 (Weight of 5 Kg)
5	NDT-UT-01-5	-5 (Weight of 5 Kg)
6	NDT-UT-01-6	-5 (Weight of 5 Kg)
7	NDT-UT-01-7	-6 (Hold between Vice)

8	NDT-UT-01-8	-6 (Hold between Vice)
9	NDT-UT-01-9	-6 (Hold between Vice)
10	NDT-UT-01-10	-6 (Hold between Vice)
11	NDT-UT-01-11	-6 (Hold between Vice)

5.1.3. Shear Test Results of Samples from NESCOM:

In shear testing a set of ASTM standards were studied and D1002 was opted. This standard was similar to the standard being used in NESCOM for shear testing.

Both steel and composite plates were cut according to the D1002 standard, the strain rate was maintained at 1.27mm/min. The steel and composite plates were bonded by using a poly-Urethane adhesive.

The test credentials are;

Table 7: Credentials set for Shear Testing of Samples

Credentials	Set Value
Machine Type	UTM Shimazdu 20kN
Shear Test ASTM Standard	D1002
Length of the Sample	180mm (130mm + 25mm on each side)
Width of the Sample	25.4mm
Thickness of the Sample	6mm each plate
Strain Rate of the Sample	1.27mm/min

The Test Results are shown in Table 8.

Table 8: Shear Testing results of NESCOM samples.

Sr No	Sample No.	Shear Strength (MPa)
1	NDT-UT-777-01-1	7.1

2	NDT-UT-777-01-2	8.2
3	NDT-UT-777-01-3	9.4
4	NDT-UT-777-01-4	9.35
5	NDT-UT-777-01-5	10.9
6	NDT-UT-777-01-6	10.9
7	NDT-UT-777-01-7	12.2
8	NDT-UT-777-01-8	11.6
9	NDT-UT-777-01-9	12.5
10	NDT-UT-777-01-10	11.5
11	NDT-UT-777-01-11	11.5

5.2. Analysis of the Results:

The analysis was done using different methods which included.

- Calculation of Reflection Coefficient from the Mathematical Model using experimental results.
- Correlational analysis of Reflection Coefficient and Gain values with shear strength.
- Regression analysis to validate the correlation analysis

The calculations done from us are as follows:

Table 9: Compiled results of all the samples

Sample	dB	Shear Strength (MPa)	Return Loss	R_L

1	-3	7.1	-1.5	1.5
2	-3	8.2	-1.5	1.5
3	-4	9.4	-2	2
4	-4	9.35	-2	2
5	-5	10.9	-2.5	2.5
6	-5	10.9	-2.5	2.5
7	-6	12.2	-3	3
8	-6	11.6	-3	3
9	-6	12.5	-3	3
10	-6	11.5	-3	3
11	-6	11.5	-3	3

R_L = -Return Loss

Return Loss = 10 log $\frac{P_i}{P_r}$

P = AI

P_i = Transmission Power **A = Area of the Probe** **R_L = Reflection Coefficient**

P_r = Reflection Power **I_i = Intensity of Transmitted wave**

I_r = Intensity of Reflected wave

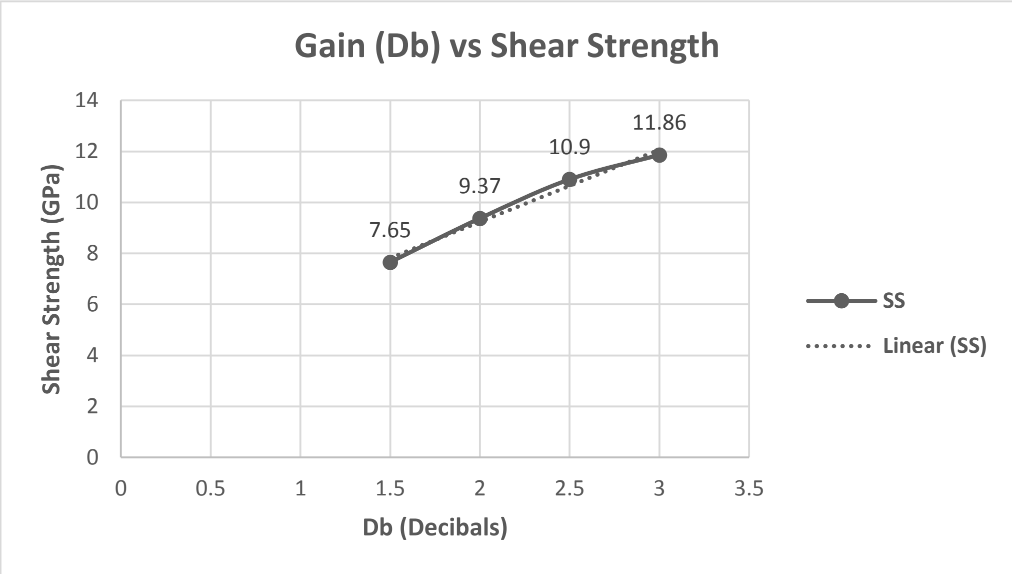


Figure 12: Graph between Gain and Shear Strength. Gain on x-axis and Shear Strength on y-axis.

After the calculations a Normality curve test was run between dB and Shear Strength and Shear Strength and R_L. This test will test us whether the relationship between shear strength and Ultrasonic Testing results exists or not. Minitab was used to run this test.

5.3. Analysis of Gain and Shear Strength:

5.3.1. Correlations: Gain (dB), Shear Strength (MPa):

Pearson correlation of dB and Shear Strength (MPa) = 0.969

P-Value = 0.000

5.3.2. Regression Analysis: Gain (dB) versus Shear Strength (Mpa):

The regression equation is

dB = - 2.27 + 0.685 Shear Strength (Mpa)

S = 0.318857   R-Square = 97.9%   R-Square (adj) = 97.2%

We can see that in the normality curve most of the results are in the region between -1 and 1 and the correlation is 96.9% for shear strength and reflection coefficient.

5.4. Analysis of Reflection Coefficient and Shear Strength:

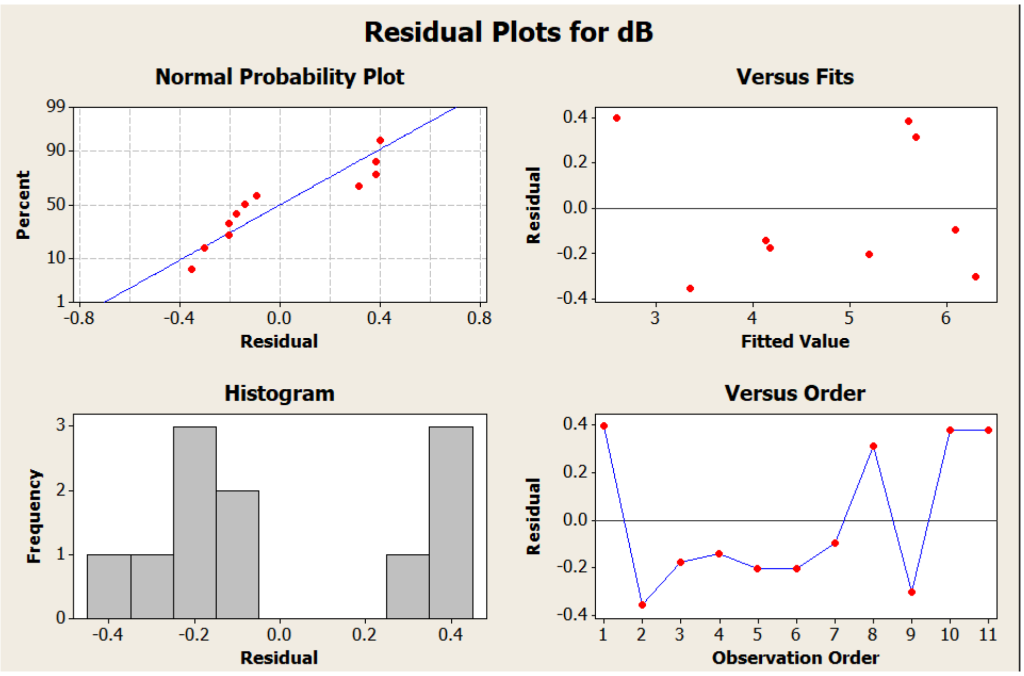


Figure 13: Regression plots of Gain vs Strength

5.4.1. Correlations: Shear Strength (MPa), RL:

Pearson correlation of Shear Strength (MPa) and RL = 0.982

P-Value = 0.000

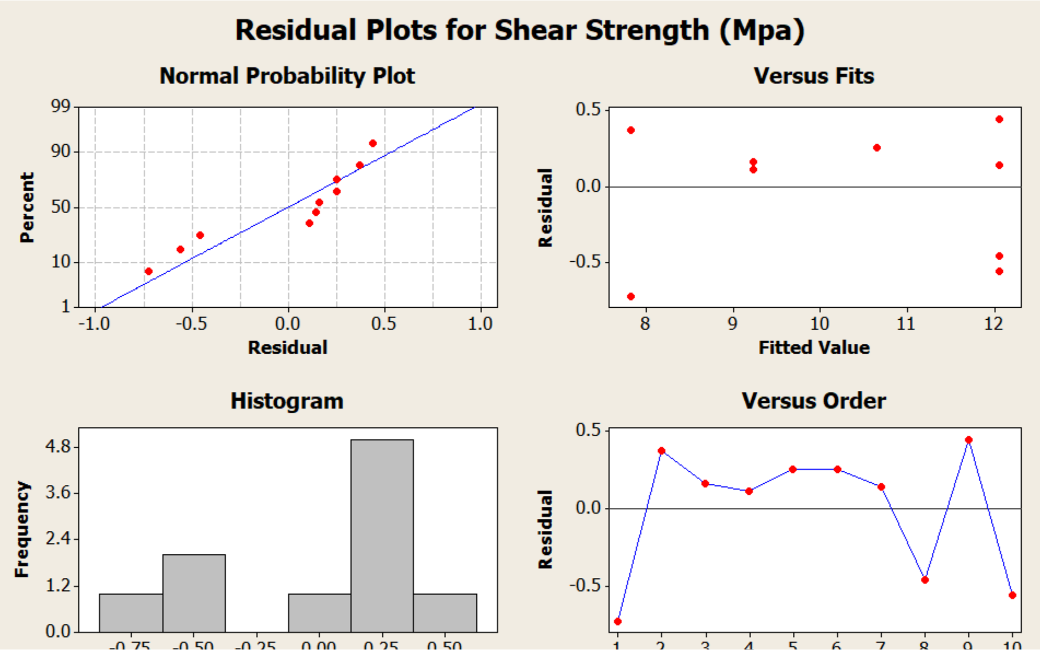


Figure 14: Regression Plots of Reflection Coefficient with Shear Strength

5.4.2. Regression Analysis: Shear Strength (MPa) versus RL:

The regression equation is

Shear Strength (MPa) = 3.60 + 2.82 RL

S = 0.443115 R-Square = 98.5% R-Square (adj) = 98.8%

Now, when correlation between R_L and Shear Strength was analysed it came to be 98.2%. Hence, we can see that relating shear strength and reflection coefficient is more feasible than relating shear strength and gain.

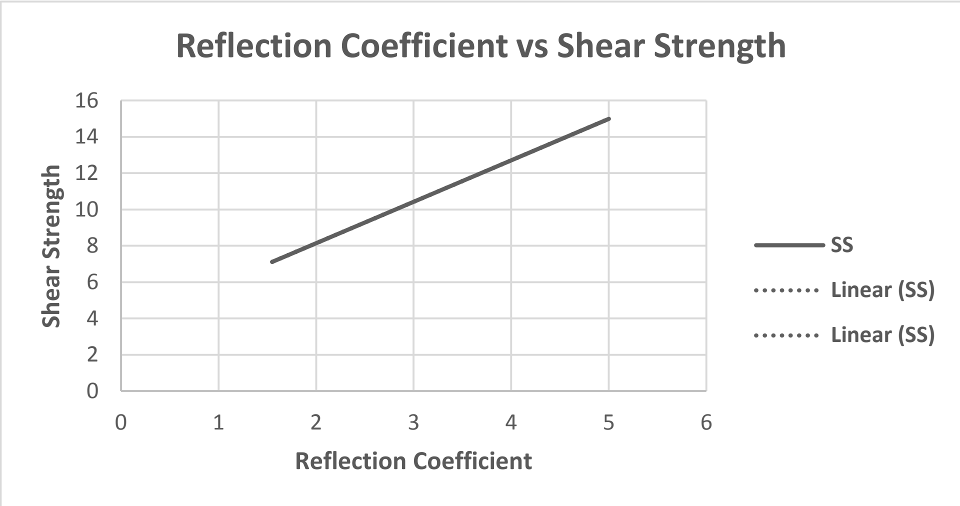


Figure 15: Grpah between Shear Strength and Reflection Coefficient. RL on x-axis and SS on y-axis

5.5. Resultant Equation for Shear Strength and Reflection Coefficient:

After the testing of each sample at NESCOM as well as in SCME, we found that in order to quantify Shear Strength using UT-NDT we have to find a relationship between shear strength and a specific UT variable.

We found out that shear strength can be related with both change in dB as well as reflection coefficient. It means that shear strength can be explained both in terms of dB and RL. But during correlation analysis, R_L was related 98% while dB was 96.9%. Hence, we can use these results to obtain a possible equation or relation between shear strength and Reflection coefficient.

$$\textit{Shear Strength} = 2.8R_L + \alpha$$

Shear Strength = MPa **R_L = Reflection coefficient**

α = Strength Constant (different for different Materials 3.53 in this industrial particular case)

CHAPTER 6

CONCLUSION

The main aim of this research was to develop a reliable method to check the strength of adhesively bonded joint precisely with the help of ultrasonic testing technique. After learning the ultrasonic technique in the initial phase, a series of samples were tested based on the phenomena of absorption and reflection of ultrasonic waves from the interface. The shear test of these samples was also done and the test results determined their actual bond strength. Theses experimental values were compared with the values of bond strength and bond stiffness obtained on the basis of ultrasonic wave intensity (dB) transmitted through the adherend interface.

In the second part of the project we developed a mathematical model to quantify interfacial stiffness and shear strength results that was the main aim of the project. After several steps discussed above and using reference research material, we succeeded in deriving a mathematical modulation that determines the adherend bond strength based on several variables.

In the third part of the project we started working on the statistical analysis to validate the derived modulation. For this purpose we used two type of analysis techniques. First method was correlation analysis. The range of results obtained after this analysis lies between +1 and -1. +1 indicates the strongest positive correlation possible, and -1 indicates the strongest negative correlation possible. The value we obtained using the data of Gain (dB), Shear Strength (MPa) is 0.969 and correlation analysis of shear strength (MPa) versus reflection, gives a value of 0.982. The second method is regression analysis. Regression analysis is a set of statistical processes for estimating the relationships among variables. After this analysis, we succeeded in deriving a relation statically as follows;

Gain (dB) versus Shear Strength (MPa)

dB = - 2.27 + 0.685 Shear Strength (MPa)

Regression Analysis of Shear Strength (MPa) versus RL

Shear Strength (MPa) = 3.60 + 2.82 RL

In the last part we derived the final equation based on highest value of wave reflection during correlation analysis. The final relation can be applied practically and can be used for real time testing in industry.

Moreover, this relation is not limited to any specific material. It can be employed for any material by just changing the variables accordingly.

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