Experimental Modal Analysis of Double Lap Adhesive Joint for Aluminum Plates

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Abstract—There are many joints used in Automobiles, Aerospace, Marine structures etc. such as lap joint, double-strap joint, rivet joints and adhesive joints etc. The failures in adhesively bonded joints are mainly of two types, adhesive and cohesive; occurring mainly due to interfacial (adhesive) cracking, also called de-bonding, at geometric boundaries due to stress concentrations, or resulting from faulty joining in fabrication. In this work vibration analysis or modal analysis of adhesively bonded double lap joint is done by means of finite element Modeling and comparison is done by means of experimental analysis. Experimental modal analysis also known as modal analysis or Model testing deals with determination of natural frequencies, damping ratio and Mode Shapes through vibration testing. Rubber is used as visco-elastic material. The modal can also be used to predict system modal damping values by properly choosing material damping values of the beam and the adhesive. By changing Overlap Ratio and Surface Roughness different natural frequencies are obtained. Experimental analysis is done by preparing double lap joint with aluminum material. Araldite (Epoxy adhesive) is used as an adhesive. Analysis is done by using FFT analyzer. The effect of Surface Roughness and Overlap Ratio on natural frequency is also carried out. The braking strength of adhesive joint is found out by using universal testing machine and it is compared with riveted joint.

Index Terms— *Adhesive, Visco-elastic material, Passive damping, Composites.*

I. Introduction

In recent years, adhesives have been widely used to bond dissimilar material members particularly in aircraft and automobile structures. In many applications adhesively bonded joints are more suitable than traditional joining techniques such as mechanical fastening, especially for components made from composite or polymeric materials, because they can provide uniform distribution of load, resulting in better damage tolerance and excellent fatigue life. Because of the involvements of many geometric, material and fabrication variables, and complex failure modes and mechanics present in the joints, a deep understanding of the failure behavior of adhesively bonded joints, particularly under combined loading conditions, is needed in order to fully achieve the benefits of adhesive bonding. There are several typical failure modes associated with adherence and adhesive in adhesively bonded composite repairs including substrate yielding, patch fiber breaking in tension, fiber failing in compression, adhesive shearing, substrate-adhesive peeling, patch-adhesive peeling, patch inter-laminar peeling, and patch inter-laminar shearing. Since substrate yield is not a catastrophic failure mode, an optimal design will focus on other failure modes associated with the patch and adhesive.[1].

The failures in adhesively bonded joints are mainly of two types, adhesive and cohesive; occurring mainly due to interfacial (adhesive) cracking, also called de-bonding, at geometric boundaries due to stress concentrations, or resulting from faulty joining in fabrication. Well-bonded joints should fail within the adhesive (cohesive) or within the adherends (inter-laminar failure) when broken apart. Failure at the adherend-adhesive interface (interfacial failure) generally indicates that the bond was not performed properly. Adhesive bonding usually requires curing of adhesive at temperature higher than applied condition. Joints and fasteners often have a significant effect on the dynamical behavior of assembled mechanical structures and the analytical prediction of structural responses therefore depends upon the accuracy of joint modeling. Detailed constitutive models that fully describe the behavior of frictional interfaces are often unduly complicated; in which case simpler phenomenological models having parameters identified from vibration tests may be preferable. Unfortunately the direct measurement of forces transmitted between two contacting surfaces and their relative displacements are not possible in practice and it is therefore necessary to rely on measurements remote from joints. In this paper, the parameters of an assumed nonlinear joint model are identified by force-state mapping from time-domain acceleration records in response to single-frequency excitation close to the first natural frequency. The problem of lack of accessibility for measurement at the joint is overcome by casting the governing equation of the system in modal coordinates so that modal parameters are identified to represent the nonlinear behavior of the joint. A particular result from the experimental program is the identification of viscous damping coefficients dependent upon displacement amplitude. The significance of this result is that the complex phenomenon of energy dissipation in lap joints can be represented by a simple analytical model capable of producing accurate results.[2].

Various types of double-lap specimens with different overlap lengths and adhesive thicknesses were used in the experimental program to investigate the effect of bonding dimensions on fatigue strength. Experimental results indicate that under the fixed average shear stress condition, the larger adhesive thickness detrimentally affects fatigue strength. Similarly, the fatigue resistance decreases as the overlap increases except for the specimens with an adhesive thickness of 0.5 mm. The finite element method was adopted herein to obtain the local stress states at the interface between the adhesive and the adhered. Three selected parameters based on the simulated interfacial stresses were considered to correlate with the fatigue life data of all specimens with various adhesive dimensions. These parameters are maximum interfacial peeling stress, maximum interfacial shear stress and a linear combination of interfacial peeling stress and shear stress. These three interfacial parameters yield much better correlation results than the bulk average stress parameter. The evaluation results demonstrate that peeling stress and the linear combination of interfacial peeling stress and shear stress provide better correlation results than the interfacial shear parameters, revealing that the interfacial peeling Stress is the main driving force of the fatigue failure of the single-lap joints.[1].

II. LITERATURE REVIEW

Before starting with actual working, it's always helpful to study literature and work already carried out in similar field. This study helps to decide the project outline and flow. Some research papers, articles are available in which similar type of issues, case studies have discussed. In this chapter, summary of such papers and literature published by various researchers is described.

Vibration Analysis of Adhesively Bonded Lap Joint:

Prof.R.A.Deshmukh, Prof.S.A.Sonawane[1] In many structures such as those for flight and space vehicles etc. adhesively bonded structures have often been used recently, because of great advances in adhesive bonding techniques. Many aerospace structures such as truss system of space telescope and space station are constructed using predominantly composites beams, plates and bonded joints. These structures should possess sufficient inherent damping capacity to keep vibration and acoustics response caused by external disturbances within acceptable limits. The current trend is to use viscoelastic material in the joints for passive vibration control in the structures subjected to dynamic loading. There are many joints used in aerospace structures such as lap joint, double-strap joint etc. In this work Vibration analysis of adhesively bonded lap joint is done by means of ANSYS software and comparison is done by means of experimental analysis. Rubber is used as viscoelastic material. By changing the thickness of rubber and overlap ratio different natural frequencies are obtained. Experimental analysis is done by preparing lap joint with aluminum and rubber material. Locktite is used as an adhesive. Analysis is done by using FFT analyzer. Damping ratio is also calculated for different joints. The effect of thickness of rubber and overlap ratio on natural frequency is also carried out.

Modal Analysis of Adhesively Bonded Joints

Y. B. Patil, R. B. Barjibhe,[2] It is important to study the modal analysis (natural frequency and mode shape) of the single lap adhesive joint to understand the dynamic nature of the systems, and also in design and control. In this work modal analysis of bonded beams with a single lap epoxy adhesive joint of plates are investigated. The three specimen are used which consist of Al-Al plates, Cu-Cu plates and Ms-Ms plates. ANSYS 11.0 finite element software is use for modal analysis of single lap adhesive joint. The results show that the natural frequencies are directly proportional to the Young's modulus and Density ratio.

Stress Analysis of Adhesively Bonded Double- Lap Joints

Solyman Sharifi, and Naghdali Choupani[3], Adhesively bonded joints are preferred over the conventional methods of joining such as riveting, welding, boltingand soldering. Some of the main advantages of adhesive jointscompared to conventional joints are the ability to join dissimilar materials and damage-sensitive materials, better stress distribution, weight reduction, fabrication of complicated shapes, excellent thermal and insulation properties, vibration response and enhanced damping control, smoother aerodynamic surfaces and an improvement in corrosion and fatigue resistance. This paper presents the behavior of adhesively bonded joints subjected to combined thermal loadings, using the numerical methods. The joint configuration considers aluminum as central adherend with six different outer adherends including aluminum, steel, titanium, boronepoxy, unidirectional graphite-epoxy and cross-ply graphite-epoxy and epoxy-based adhesives. Free expansion of the joint in x direction was permitted and stresses in adhesive layer and interfaces calculated for different adherends.

Adhesively Bonded Joints in Composite Materials

MD Banea and LFMda Silva[5] A review of the investigations that have been made on adhesively bonded joints of fibre-reinforced plastic (FRP) composite structures (single skin and sandwich construction) is presented. The effects of surface preparation, joint configuration, adhesive properties, and environmental factors on the joint behaviour are described briefly for adhesively bonded FRP composite structures. The analytical and numerical methods of stress analysis required before failure prediction are discussed. The numerical approaches cover both linear and non-linear models. Several methods that have been used to predict failure in bonded joints are described. There is no general agreement about the method that should be used to predict failure since the failure strength and modes are different according to the various bonding methods and parameters, but progressive damage models are quite promising since important aspects of the joint behaviour can be modelled by using this approach. However, a lack of reliable failure criteria still exists, limiting in this way a more widespread application of adhesively bonded joints in principal load-bearing structural applications. An accurate strength prediction of the adhesively bonded joints is essential to decrease the amount of expensive testing at the design stage.

M. Luci, A. Stoi, J. Kopa[6] Single lap adhesively bonded joints were investigated in this paper as a frequently applied adhesive joint design in engineering practice. Experimental tests and numerical modeling of single lap adhesive bonded joints were performed. During the investigation the overlap length has been changed in the range from 15 to 60 mm. The experimental specimens have been made of aluminum Al99.5 as adherend material. Dimensions of prepared adherend plates were *a´ b´ s* = 30 ´ 90 ´ 1,95 mm. All bonded joints have been realized using an engineering two-component epoxy adhesive. Such prepared joints have been stretched up to the break in the jaws of the tensile testing machine. The analysis is focused on determination of an optimum overlap length. The true diagram of stresses of adherend (metals) and adhesive has been considered and comparison of data (applied force vs. end

displacement) obtained with numerical analysis and experimental investigation. Both results correlate well.
Effect of Adhesive Thickness, Adhesive Type[15]

SolymanShariei and NaghdaliChoupani [23] have presented the adhesively bonded joints are preferred over the conventional methods of joining such as riveting, welding, bolting and soldering. Some of the main advantages of adhesive joints compared to conventional joints are the ability to join dissimilar materials and damage-sensitive materials, better stress distribution, weight reduction, fabrication of complicated shapes, excellent thermal and insulation properties, vibration response and enhanced damping control, smoother aerodynamic surfaces and an improvement in corrosion and fatigue resistance. This paper presents the behavior of adhesively bonded joints subjected to combined thermal loadings, using the numerical methods. The joint configuration considers aluminum as central adherend with six different outer adherends including aluminum, steel, titanium, boronepoxy, unidirectional graphite-epoxy and cross-ply graphite-epoxy and epoxy-based adhesives. Free expansion of the joint in x direction was permitted and stresses in adhesive layer and interfaces calculated for different adherends.

III. History of Adhesive Joint

Man has used adhesives or glues since the dawn of history. The ancient Egyptians attached veneers to furniture with glue. These early glues were all natural substances. Nowadays synthetic resins and polymers are in used. The earliest use of adhesives was discovered in 2001 in Italy. It is discovered that glue was used to join two stones with each other which are from the Middle Pleistocene era (circa 200,000 years ago). This is thought to be the oldest discovered application of adhesive joints. Use of plant and animal based glue was common in next generations. These adhesives were simple one component adhesive. Plant based adhesives are sticky enough, but brittle and less resistive to environmental conditions. The first use of compound adhesives was discovered in Sibudu, South Africa. A 70,000 year old stone segment joint was found out in which the adhesive used was composed of a combination of plant gum and red ochre (natural iron oxide). Adding ochre to plant gum produces a stronger produce and protects the gum from disintegrating under wet conditions. The ability to produce stronger adhesives allowed middle Stone Age humans attach stone segments to stick in greater variations and led to the development of new tools. Then slowly adhesive joining technology starts developing. The Greeks and Romans made great contributions to the development of adhesives.[4]

The development of modern adhesives began in 1690 with the founding of the first commercial glue plant in Holland. In 1920s, 1930s, and 1940s development of adhesives became more fast and production of new plastics and resins ware taken place due to the World Wars. These advances greatly improved the development of adhesives by allowing the use of newly developed materials that produced variety of properties. Aerospace industries first used the adhesive joints on larger scale due to the fact that they are light in weight and then many researchers' starts working in this field. With changing needs and developing technology, development of new synthetic adhesives continues to the present. However, due to their low cost, natural adhesives are still more commonly used.[4]

IV. Types and Advantages of Adhesive Bonding

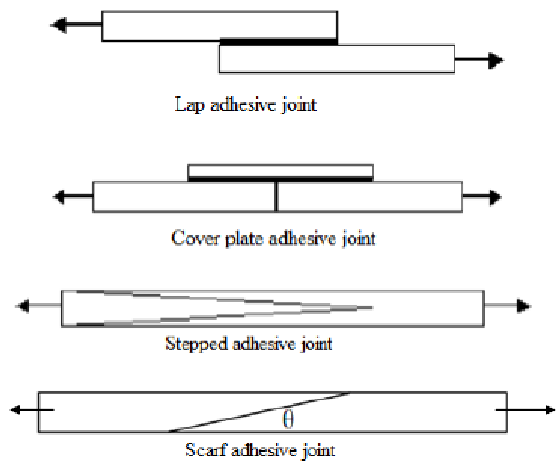


Fig. 01 Types of adhesive joints

-Continuous bond: On loading, there is more uniform distribution of stresses over the bonded area. The local concentrations of stresses present in spot welded or mechanically fastened joints are avoided. Bonded structures can consequently offer a longer life under load.

-Less weight: Low weight of joint in comparison with other types of joint is one of the great advantages of adhesive joint. Adhesive joint gives high strength to weight ratio.

V. Types of Adhesives

Types of adhesives available have huge variety. These are classified as:

A. Natural adhesives:

These are the earliest adhesives used by human being. As name suggest these adhesives are obtained from natural resources. Easy availability and low cost are the main advantages while low strength and moisture resistance are the main disadvantages of these adhesives.

e. g. animal glue.

B. Elastomer Adhesives:

This is the mixture of natural and synthetic rubber. They possess good tensile strength and moisture resistance, but shear strength is very low.

e. g. natural rubber.

C. Modern Adhesives:

Modern adhesives are classified either by the way they are used or by their chemical type. Some of the main types of modern adhesives are as follows.

VI. Modes of Loading Adhesive Joints and Failure

It is very important to understand types of loading stresses involved in adhesively bonded joints. Strength of adhesive joints mainly depends on two major parameters i. e. material involved in the adhesive joint and types of loading stresses involved within the joint. The basic types of stresses involved in the adhesive joints are tension, compression, shear, cleavage and peel stresses as shown in Fig.02

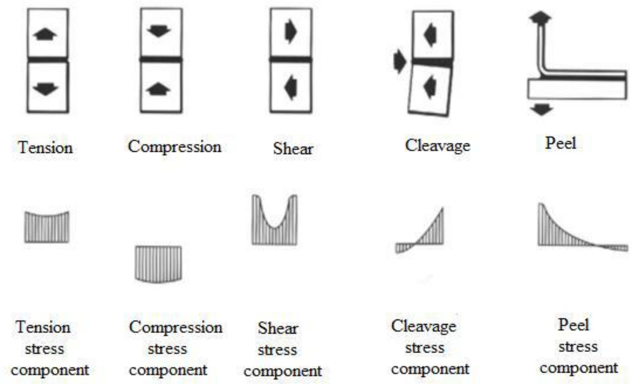


Fig.02 Types of loading stresses in adhesive joint

When failure of adhesive joint happens by failure of adhesive itself is called as cohesive failure. It is shown in fig. 1.3. Since failure is taking place within the adhesive layer, bond strength is greater than adhesive strength. Hence the joint which fails by cohesive failure is generally higher than those fails by adhesive failure.03

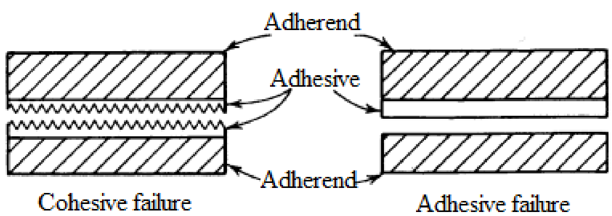


Fig.03 Basic modes of failure in adhesive joint

VII. Objective and Problem Definition

A. Objective:

The main objective of this study is to understand and analyze the Double lap adhesive joint. To study the Vibration analysis and modal analysis of Double lap adhesive joint. Also to find out the effect of Overlap ratios, Surface roughness, plate width and Rubber thickness on the natural frequency of joint.

B. Problem Definition:

Adhesive joints are still not used effectively even though adhesive bonding technology has several advantages over conventional joint processes. Because of the involvement of geometrical and fabrication variables in the configuration of double lap adhesive joint a deep understanding of these variables is required. In every adhesive joint load is transmitted from one adherend to another adherend through adhesive layer. So problem can be defined as experimental Vibrational study of double lap adhesive joint on FFT analyzer. The goal of this thesis is to provide a better understanding of the mechanics within the joint, so future designers can apply these concept to optimize future composite joints, and thereby minimize the amount of experimental testing required.

VIII. Experimental Modal Analysis

A. The Basic Idea:

Experimental modal analysis, also known as modal analysis or model testing deals with determination of natural frequencies, damping ratio and mode shapes through vibration testing. The two basic ideas are involved

1) When a structure, machine or any system is excited its response exhibits a sharp peak at resonance when the forcing frequency is equal to its natural frequency when damping is not large.

2) The phase of the response changes by 180 degrees as the forcing frequency crosses the natural frequency of the structure or machine and the phase will be 90 degrees at resonance.

B. The Necessary Equipment:

For measurement of vibration following hardware requires:

1. An exciter or source of vibration to apply a known input force to the structure or machine.
2. A transducer to convert the physical motion of the structure or machine into an electrical signal.
3. A signal conditioning amplifier to make the transducer characteristics compatible with the input electronics of the digital acquisition system.
4. An analyses to perform the task of signal processing and model analysis using suitable software
5. The Impact Hammer:

Specifications of Accelerometer used:

Type Larson and Davis	Make
Housing material	Titanium

Height: 23.60 mm

Weight: 27 gram

Mounting Threads Female

Electrical connector Type Co-axial

Electrical connector location Side

Sensitivity: 103 mV/g

Max. Acceleration: 50g

C. Preparation Of Lap Joint:

The preparation of lap joint Specimen is the first step in the modal testing .The material used for primary beams is Aluminum. As a first step aluminium beam are cut into pieces 115 mm long 30 and 40mm wide and 5 mm thickness for the primary beam, the aluminum beams are then surface finished with the help of abrasive paper.

The damping material used for modal testing of joint is natural Rubber the damping material is a standard viscoelastic material 1mm thickness In order to get a perfect bond between damping material and beam, a very thin layer of adhesive araldite s applied. The viscoelastic layer is then correctly bonded in the overlap region the beam. The resulting joint specimen is the cured at room temperature for more than 24 hours.

D. Procedure To Carry Out Experimental Modal Analysis Using FFT:

The basic experimental modal setup is shown in fig 5.1. The frequency response function (FRP) in terms of reacceptance ratio of displacement to forces was measured using the experimental setup. The double lap joint was fixed to the rigid fixture and tested at cantilever boundary condition.

An impact with a force transducer is used as an excitation source (channel 1) and an accelerometer is used as the output (channel 2).The point of impact and position of the accelerometer are chosen such a way that the natural frequencies of the system can be easily determined by locating peaks of transfer function.
Test would be conducted as follows:
1. Mount an accelerometer on the joint and connect it to channel 2 of the analyzer.
2. Connect an instrumented force hammer to channel 1.
3. Impact the joint with few blows. These blows will be needed to setup the analyzer for the test. This is often the most tedious part of the test.
4. Set the analyzers trigger level (channel 1). Set the input attenuation of channel 1 and channel 2 to avoid overload.
5. Choose a time window which shows preparing down of time domain output of system.
6. Average several blows.
7. View transfer function magnitude and phase.
8. View the coherence display. A value near 1.0 indicates a good test.
9. The FRF data then transferred to modal analysis software to estimate modal parameters (Natural frequencies and damping ratios)
10. Use single degree of freedom form curve fitting routine over each modal peak to obtain modal parameters for that mode.

This procedure is repeated for the remaining joints. Fig.04 shows the experimental set up.

Fig.04 Experimental set up

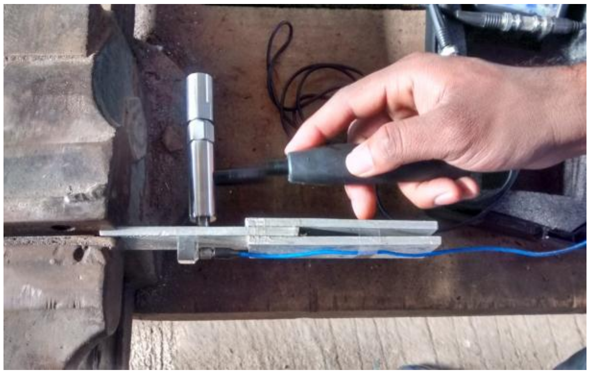


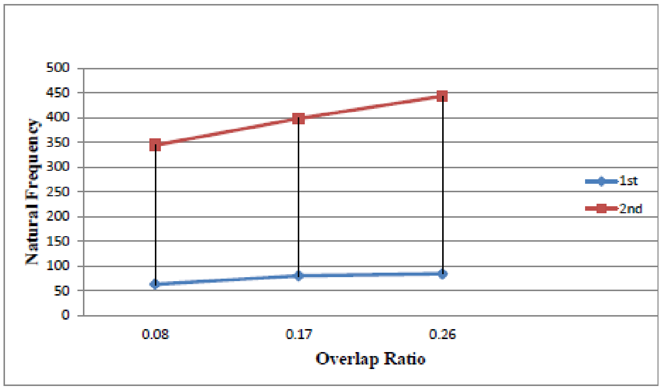
Fig.05 Photograph showing Experimental procedure

Experimental Analysis:

A. For 30mm plate:

Table 01 Effect of overlap ratio on natural frequency:

Overlap	Natural Frequency (Hz)		Breaking Strength (Mpa)
	1	2	
0.08	63	344	2.254
0.17	80	398	
0.26	84	443	



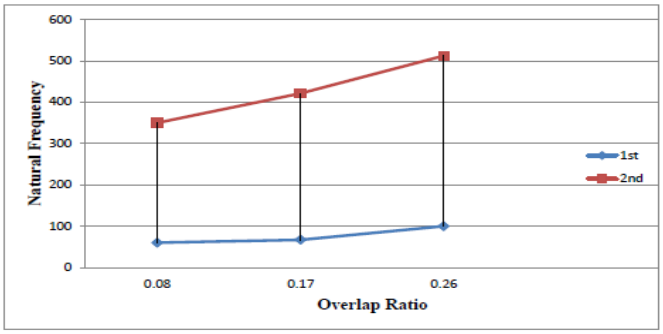
Graph 01: Graph of Overlap Ratio Vs Natural Frequency for Zero Surface Roughness

Table 01 and Graph 01 show the effect of Overlap ratio on natural frequency for 30mm plate width, with the increase in overlap ratio natural frequency increases. With FFT analyzer only two natural frequencies are obtained for adhesive joint.

B. For 30mm plate with 1 mm rubber thickness:

Table 02 Overlap ratios and their Natural Frequency for 1mm Rubber thickness

Overlap Ratio	Rubber Thickness (mm)	Natural Frequency (Hz)		
		1	2	3
0.08	1	60	350	---
0.17	1	67	421	---
0.26	1	79	512	---



Graph 02: Graph of Overlap Ratio Vs Natural Frequency for 1mm Rubber Thickness

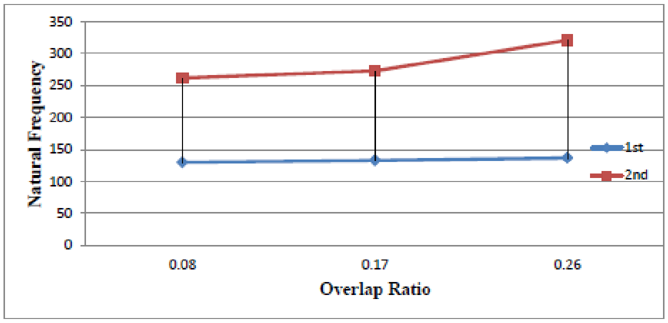
Table 02 and Graph 02 shows the effect of the Overlap ratio of the natural frequency of 30mm plate width, with the increase in the overlap ratio natural frequency increases, but due to the addition of 1mm rubber thickness natural frequencies are reduced by some Hertz . It may be because vibration damping due to rubber.

Experimental Analysis For Rivetted Joint:

C: For 30mm plate:

Table 03 Overlap ratio Vs Natural Frequency for 30mm Plate Width:

Design of Experiment (30 mm width plate)				
Sr. No.	Overlap Ratio	Natural frequency(Hz)		**Breaking Strength (Mpa)**
		1	2	
1	0.08	130	262	1.699
2	0.17	133	273	
3	0.26	137	321	



Graph 03: Graph of Overlap Ratios Vs Natural Frequency for 30mm Plate Width

Table 03 and Graph 03 show the effect of overlap ratio on natural frequency for 30mm plate width with riveted joints, it is clearly observed that with the increase in overlap ratio natural frequency increases. With FFT analyzer only two natural frequencies are obtained for riveted joint also. The large amount of difference is obtained in natural frequencies for adhesive and riveted joint for first and second mode shapes.

IX. Finite element analysis

Element Used: For Finite Element Analysis of adhesively bonded Double lap joint Solid 92 element is used. The analysis of the joint is done by using Cantilever boundary condition.

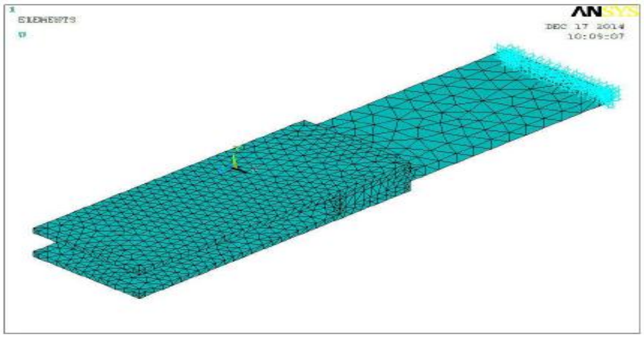


Fig 06 Meshing of Double Lap joint

Table 04 ANSYS Result In Tabular Form:

Design of Experiment (30 mm width Plate)					
Sr. No.	Overlap Ratio	Rubber Thickness	Natural Frequency(Hz)		
			1	2	3
1	0.08	0	65.52	362.94	382.14
4	0.17	0	72.29	419.07	441.83
7	0.26	0	80.32	461.97	549.43
Sr. No.	Overlap Ratio	Rubber Thickness	Natural Frequency(Hz)		
			1	2	3
10	0.08	1mm	62.59	361.54	480.44
11	0.17	1mm	68.68	441.16	523.82
12	0.26	1mm	75.72	548.80	573.24

Finite Element Analysis For Adhesive Joint:

For 30mm Width Plate:

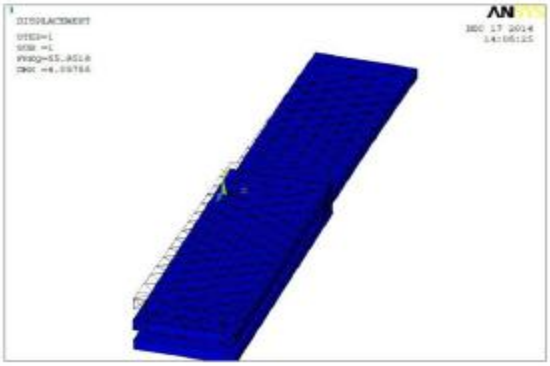


Fig.07 1st Mode Shape for 0.08 Overlap Ratio

Fig.08 2nd Mode Shape for 0.08 Overlap Ratio

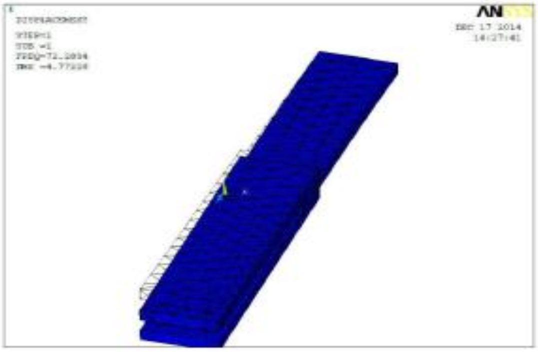


Fig.09 1st Mode Shape for 0.17 Overlap Ratio

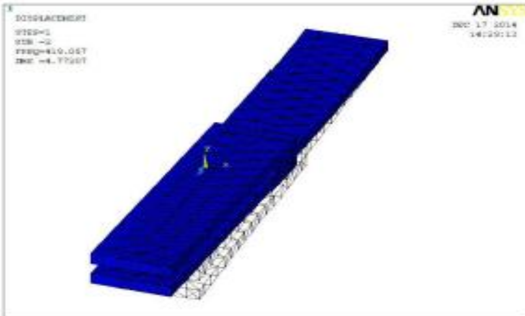


Fig.10 2nd Mode Shape for 0.17 Overlap Ratio

From the above figure it is observed that the in the Second mode shape for 0.17 overlap ratio and 30mm width plate the Frequency of vibration for adhesively bonded joint is 419.05Hz

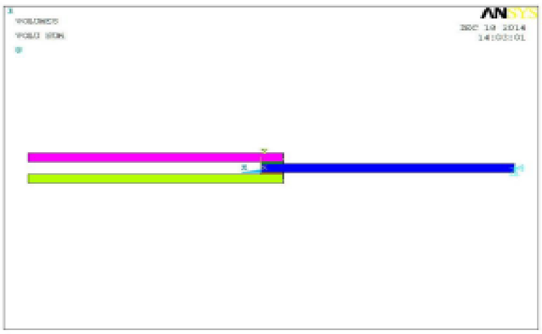


Fig.11 30mm width plate with 1mm rubber thickness

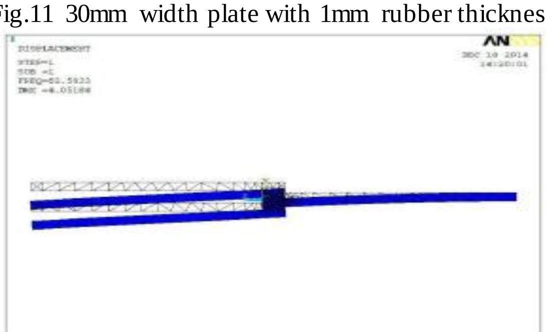


Fig.12 Basic Model of Double Lap adhesive joint with 1mm Rubber Thickness

From the above figure it is observed that the in the First mode shape for 0.08 overlap ratio and 1mm rubber thickness for 30mm width plate the Frequency of vibration for adhesively bonded joint is 62.59 Hz.

Finite Element Analysis For Rivetted Joint:
For 30mm Width Plate:

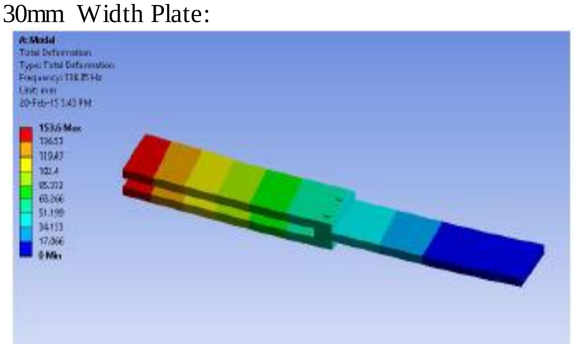


Fig.13 1st Mode Shape for 0.08 Overlap Ratio

From the above figure it is observed that the in the first mode shape for 0.08 overlap ratio for 30mm width plate the Frequency of vibration for riveted joint is 136.05 Hz

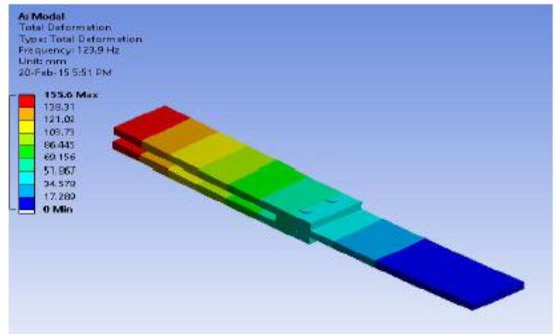


Fig.14 1st Mode Shape for 0.17 Overlap Ratio

From the above figure it is observed that the in the first mode shape for 0.17 overlap ratio for 30mm width plate the Frequency of vibration for riveted joint is 123.09 Hz

X. Conclusion

In this dissertation work vibration analysis of adhesively bonded double lap joint is done by using FEA and experimental methods. By observing the results obtained in both methods it concludes that:

It is used to predict the natural frequencies and mode shapes of bonded lap joint system. The modal can also be used to predict system modal damping values by properly choosing material damping values of the beam and the adhesive. The results obtained from Finite element modeling and experimentation has found good agreement. the variation in results can be observed from Minimum 2% to maximum 11%.

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