Vibration Analysis of Adhesively Bonded Single Lap Joint

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Abstract- In automotive industry & aerospace application, joining the components by using adhesives is an attractive method compared to other joining processes. Significant advantages of structural adhesive bonding are like improved strength, stiffness, reduced corrosion elimination of spot weld metal finishing application, reduction in overall manufacturing cost etc. Also joining of dissimilar materials is also important advantage.

The objective of current dissertation work is to analyze the vibration characteristics of adhesively bonded single lap joint with different overlap ratios. Investigation of natural frequencies of flexural vibrations of a system consisting of a pair of parallel & identical elastic cantilevers bonded by viscoelastic material along a part of their sides adjacent to their free ends.

In the proposed work adhesively bonded lap joints will be prepared by using aluminum plates. Two aluminum plates, first having dimensions 140 mm length, 25.4 mm width & 3 mm thickness & second 140 mm length, 25.4 mm width & 3 mm thickness are joined together in the single lap configuration with a mixture of araldite resin & hardener. Analysis will be done experimentally with the help of FFT analyzer & fixture. Natural frequencies will be detected by hitting the lap joint system with impact hammer, the response at a point of a lap joint will be measured by using an accelerometer FFT analyzer analyzed the output of accelerometer.

FEM software package is used for vibration analysis of adhesively bonded lap joint with different overlap ratios for determining different parameters like Natural frequency, Mode shapes.

Thus experimental & software results obtained will be compared & results will be concluded.

1 INTRODUCTION

In automotive industry & aerospace application, joining the components by using adhesives is an attractive method compared to other joining processes. Significant advantages of structural adhesive bonding are like improved strength, stiffness, improved noise vibration & harshness (NVH) & aerodynamics, reduced corrosion, elimination of spot weld metal finishing application, reduction in overall manufacturing cost, increased design freedom etc. Also joining of dissimilar materials is also important advantage. Generally an adhesively bonded structure consists of three components of three different mechanical properties, namely two adherents & adhesive layer. Here we have to study the response of single lap joint subjected to a load. Single lap joint is formed by joining two Aluminum adherents by viscoelastic adhesive layer for particular lap area. The bond strength & adhesive mechanical properties could be severely affected by improper surface preparation, curing procedure, entrapped void or porosity in the bond area. In the entire procedure four specimens are prepared with the variation parameter of overlap length. First specimen having overlap length of 10 mm & other four are 20 mm, 30 mm & 40 mm & 50 mm. Natural frequency change are studied with respect to change in overlap length.

2. PROBLEM DEFINITION & METHODOLOGY

2.1. Problem Statement

Vibration analysis of adhesively bonded single lap joint by FEM & experimental method.

Vibration analysis includes determination of vibration parameters i.e. natural frequency & mode shapes at various points of lap joint.

2.2. Methodology

In the current work adhesively bonded lap joints are prepared by using aluminum plates. Two aluminum plates of given dimensions are joined by using a mixture of araldite resin & hardener.

First FEM analysis is carried out by using ABAQUS 6.1 package. Results obtained from FEM will be compared with experimental analysis & conclusions will be carried out. After FEM analysis experimental analysis will be carried out by using different instruments as FFT analyzer, accelerometer, impact hammer etc. Natural frequencies with different mode no. & different overlap ratios will be found out.

3. ADHESIVE JOINT PROPERTIES

Generally epoxy adhesives are more preferable & most versatile of the structural adhesives. Although generally characterized as being strong but brittle, they can be formulated to be more flexible without loss of tensile strength. Epoxy adhesives are able to bond a variety of effectively & can be formulated to cure at either room temperature or elevated temperatures, under dry or wet condition. Epoxy resins are a group of thermosetting materials that posses the epoxy or oxirane group & are convertible into three dimensional structures by a variety of curing reactions. The epoxy resins formed from bisphenol A & epichlorohydrin constitute the predominant type of resinous intermediates.

Epoxy adhesives consist of an epoxy resin plus hardener. They allow great versatility in formulation since there are many resins & many different hardeners. Epoxy adhesives can be used to join most materials. These materials have good strength, do not produce volatiles during curing, & have low shrinkage. Epoxy adhesives are available in one part, two part & film form & form extremely strong durable bonds with most materials in well designed joints. Epoxy adhesive are perhaps the most versatile of the structural adhesives. Epoxy adhesives may not be as inexpensive as other adhesive but they are quiet competitive on a cost performance basis.

While capable of effectively bonding nonstructural substrates, epoxy adhesive also show excellent performance in structural bonding applications demonstrating good adhesion & mechanical properties in metal to metal bonding applications.

3.1. Advantages

Many advantages of adhesives includes,

❖Dissimilar materials can be joined.
❖The bond is continuous.
❖Stronger & stiffer structures.
❖On loading there is a more uniform stress distribution.
❖Local stress concentrations are avoided.
❖Porous materials can be bonded.
❖Adhesives prevent cathodic corrosion.
❖Adhesives seal & join in one process.
❖No finishing costs.
❖Good fatigue resistance.
❖Vibration damping.
❖Reduced weight.
❖Large areas can be bonded.
❖Small areas can be bonded accurately.
❖Fast or slow curing systems available.
❖Easy to combine with other fastening methods.
❖Easily automated / mechanized.

3.2. Limitations

Following are some limitations,

❖Need to prepare the surface.
❖Environmental resistance depends on the integrity of the adhesive.
❖Need to ensure wetting.
❖Increasing the service temperature decreases the bond strength.
❖Bonded structures are usually not easily dismantled for in service repair.

3.3. Physical Properties

Following table shows a typical data for two component adhesives. These consist of a general purpose adhesive, a fast setting adhesive & a high performance adhesive.

Table1:Physical properties of two components epoxy paste.

Property	General Purpose	Fast Setting	High Performance
Color when mixed	Cream	Gray	Gray
Viscosity			
Resin	50	260	91
Hardener	35	160	103
Mixed	45	250	54
Sp. Gravity			
Resin	1.17	1.48	1.16
Hardener	0.92	1.44	0.97

Although epoxy adhesives are typically brittle, they can be modified, as shown by the elongation of the high performance adhesive. The table also shows that their gel time & cure schedule can be manipulated for fast or slow cures.

3.4. Mechanical Properties:

As with the physical properties, a wide range of mechanical performance properties as available from epoxy adhesives. Table 2 shows typical mechanical properties of the same adhesives. As table shows these three epoxy adhesives demonstrate good lap shear strength to aluminum as well as to their substrates. Also evidences in the good resistance to environmental exposure of epoxy adhesives.

Table 2: Mechanical properties of two components epoxy paste..

Property	General Purpose	Fast Setting	High Perfo.
Al. Lap shear strength, MPa			
At -60^{0}C	20	10	29
At 25^{0}C	18	20	31
At 82^{0}C	< 2	< 8	18

4. FINITE ELEMENT ANALYSIS:

4.1. Finite Element Method

The finite element has become a powerful tool for the numerical solution of a wide range of engineering problems. Application range from deformation & stress analysis of automobile, aircraft, building & bridge structures to field analysis of heat flux, fluid flow, magnetic flux & other flow problems. With the advance in computer technology & CAD systems, complex problems can be modeled with relative ease. In this method of analysis a complex region defining a continuum is discretized in to simple geometric shapes called finite elements. The material properties & governing relations are considered over these elements & expressed in terms of unknown values at element corners. An assembly process, duly considering the loading & constraints, results in a set of equations gives us the approximate behavior of the continuum in deformation & stress conditions.

4.2. Solving a Problem By FEA

Solving a practical problem by FEA involves learning about the program, preparing a mathematical model, discitizing it, doing the calculations & checking the results. Most often, more than one cycle through these steps is required. Time spent by the computer is very small fraction of time compared to time spent by the analyst. But the analyst must have an understanding of what the computer is doing.

1) *Problem Classification:* The analyst must understand the nature of the problem. Without this step a proper model can not be devised. At present, software does not automatically decide that non-linear analysis is to be undertaken if stresses are high enough to produce yielding & buckling is to be considered if thin sections carry compressive load. Although the trend is for software to be given more decision making capability.

2) *Mathematical Model:* Before undertaking FE descritization & a numerical solution, we devise a model problem for analysis. This step involves deciding what features are important to the purpose at hand, so that unnecessary details can be omitted & deciding what theory or mathematical formulation describes behavior. Thus we may ignore geometric irregularities, regard some loads as concentrated & say that some supports are fixed. Materials may be idealized as linear & isotropic. The simplified problem with the analysis theory to be applied in solving it constitutes the mathematical model.

4.3. Finite Element Analysis for Current Work

For the investigation of natural frequency & mode shape in the single lap joint, finite element is applied using ABAQUS 6.4 package. 8 node 6 face Hex element C3D8I is chosen as an element for aluminum, adherend & for adhesive layer.

1) *Modeling:* Modeling of single lap joint was done with the help of CATIA software. The two areas for the adherend & volume for an adhesive layer thickness were modeled according to the overlap length & thickness of adhesive. For the comparison of experimental result with the FEA result, five different models were created where the length of overlap increased. Adherend & adhesive were created in different groups, as it was easier to assign the material properties & boundary conditions.

2) *Meshing:* It is important to have fine mesh at the overlap region but at the same time, total number of elements must be controlled in order to save the computational time as well to minimize the errors.

Upper adherend, lower adherend, adhesive layer were meshed independently in separate groups. Both the upper & lower adherends were meshed with same number of elements.

3) *Contact Modeling:* Contact modeling was the most crucial step while modeling the adhesive bonded lap joint. Two contact elements were used in the analysis, one for bottom surface of upper adherend & top surface of adhesive layer, & other for bottom surface of adhesive layer & top surface of adherend.

4) Boundary Conditions: The single lap joint specimen was held between the fixture as shown in figure. One end of the specimen was clamped while other end was free so as to form cantilever condition. The length of the specimen other than clamped was free to deform. therefore the nodes in the clamped region were constrained in X, Y, Z direction for translational as well as rotational motion.

4.4. Material Properties

1) Adherend Material: The criteria for selecting the adherent materials were that they had to be readily available & commonly used in practical applications. Therefore aluminum was selected as the adherend since it is readily available & has properties similar to more specialized alloys used in lightweight structure. The properties of aluminum material are provided by the manufacturer.

2) Adhesive Material: To achieve good bond, the next step is selection of good adhesive but it involves many factors like properties of adhesive, joint design, environment etc. Many companies have produced chart which help in the selection process.

Epoxy adhesive was used to bond the adherends, the properties of the adherends were taken from the website.

Table 3: Material properties of the adherend & adhesive material

Material	Young's Modulus (E) (GPa)	Poisson's Ratio (μ)	Density (ρ) (Kg/m^3)
Aluminum	64.0	0.33	2700
Adhesive	3.0	0.31	1500

4.5. FEM Results

Figure shows the two beams joined by adhesive layer. The upper & lower beams are made up of aluminum & adhesive layer is of epoxy adhesive. Dimensions of the joints used in the analysis are as follows.

4.5.1. FEM Analysis for Specimen 1

Overall Length of the bonded joint for specimen 1, L_1 = 270 mm
Overlap Length for specimen 1, l_1 = 10 mm.
Clamping length, l' = 35 mm.
Length of upper plate, Lu = 140 mm
Length of lower plate, L_l = 140 mm
Width of plate, W = 25.4 mm.
Thickness of plate, t = 3 mm
Boundary condition : One end is fixed & other end is free.

Table 4: Natural Frequencies & Displacements for Specimen 1.

Mode	Natural Freq. (Hz)	Displacement (mm)
1	32.537	0.889
2	202.04	0.814
3	265.99	0.044
4	569.64	0.815
5	627.76	0.778
6	1114.5	0.803
7	1525.8	0.0972
8	1822.6	0.809
9	1872.5	0.778
10	2767.2	0.803

Table 5: Natural Frequencies & Displacements for Specimen 2.

Mode	Natural Freq. (Hz)	Displacement (mm)
1	35.024	0.889
2	219.51	0.82
3	286.36	0.0485
4	613.61	0.815
5	654.03	0.778
6	1228.6	0.802
7	1655.7	0.0639
8	1942.6	0.778
9	1961.9	0.81
10	3078.3	0.803

Table 6: Natural Frequencies & Displacements for Specimen 3.

Mode	Natural Freq. (Hz)	Displacement (mm)
1	37.808	0.889
2	242.42	0.889
3	307.65	0.893
4	662.52	0.895
5	680.33	0.918
6	1384.6	0.891
7	1774.2	0.91
8	2027.7	0.903
9	2123.1	0.91
10	3498.5	0.896

Table 7: Natural Frequencies & Displacements for Specimen 4.

Mode	Natural Freq. (Hz)	Displacement (mm)
1	40.931	0.889
2	272.01	0.889
3	331.15	0.893
4	709.36	0.919
5	717.88	0.895
6	1587.4	0.892
7	1911.6	0.911
8	2137.3	0.902
9	2325.7	0.907
10	3896.4	0.897

Table 8: Natural Frequencies & Displacements for Specimen 5.

Mode	Natural Freq. (Hz)	Displacement (mm)
1	44.462	0.889
2	310.46	0.89
3	357.35	0.893
4	742.35	0.919
5	782.84	0.895
6	1845.2	0.892
7	2076	0.912
8	2280.1	0.901
9	2600.6	0.904
10	4270.5	0.896

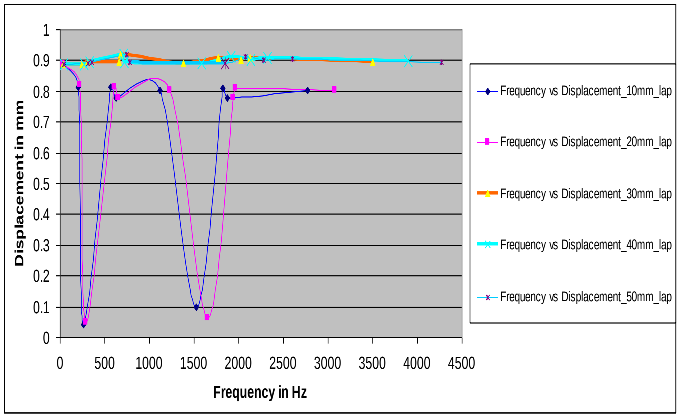

Fig. 1 Comparison of Natural Frequency Vs. Displacement for all specimens.

5. EXPERIMENTAL ANALYSIS

Experimental modal analysis of a system, deals with determination of natural frequencies & mode shapes through the vibration testing. In the case of vibration, the analysis includes the study of acceleration, velocity & displacement responses of the system. Two basic ideas involved in modal analysis are,

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

* The phase of the response changes by 180^0 as the forcing frequency crosses the natural frequency of the structure or machine & the phase will be 90 at response.

5.1. Experimental Analysis for Current Work

1) Specimen Preparation: The specimen preparation involved following stages,
i) Material selection & ii) Pretreatment of adhesive joint & Assembly of adhesive joint.

2) Actual Experimentation: For actual experimentation i.e. measurement of vibration following instruments are required.

i) Exciter: The exciter may be an electromagnetic shaker or an input hammer. The electromagnetic shaker can provide large input forces so that the response can be measured easily. Also the output of the shaker can be controlled easily, if it is of electromagnetic type. The excitation signal is usually of a swept sinusoidal or a random type signal. In the swept sinusoidal input a harmonic force of magnitude F is applied at a number of discrete frequency, the structure or machine is made to reach a steady state before the magnitude & phase of the response are measured.

ii) Impact Hammer: The impact hammer is a hammer with a built-in force transducer in its head. The impact hammer can be used to hit or impact the structure or machine being tested to a wide range of frequencies without causing the problem of mass loading. The impact hammer is simple, portable, inexpensive & much faster to use.

iii) Transducer: The piezoelectric transducers are most popular. A piezoelectric transducer can be designed to produce signal proportional to either force or acceleration. In an accelerometer the piezoelectric material acts as a stiff spring that causes the transducer to have a resonant or natural frequency.

iv) Signal Conditioner: The output impedance of the transducer is not suitable for direct input in to the signal analysis equipment. Signal conditioners in the form of charge or voltage amplifier, are used to match & amplify the signals before signal analysis.

v) Analyzer: The response signal, after conditioning is sent to an analyzer for signal processing. A commonly used analyzer is called Fast Fourier Transformer (FFT) analyzer. Such an analyzer receives analog voltage signals from a signal conditioning amplifier, filter & digitizer for a computation. It computes the discrete frequency spectra of individual signal as well as cross-spectra between input & the different output signals. The analyzed signals can be used to find the natural frequencies & mode shapes either in numerical or graphical form.

6. EXPERIMENTAL RESULTS

Five joints were taken for the experiment tests & the experimental results are tabulated as below.

Table 9: Experimental Natural Frequencies for all Specimens

Mo-de	Natural Frequency (Hz)				
	Sp. 1	Sp. 2	Sp. 3	Sp. 4	Sp.5
1	31.25	37.5	37.5	43.75	43.79
2	206	225	256	281.2	312.5
4	568.75	618.7	681.2	731	775
6	1102	1212.2	1372.5	1581.6	1842.3

7. RESULTS & DISCUSSION

In the current work, experimental modal testing of adhesively bonded single lap joint has been carried out in various conditions & natural frequencies are obtained. The experimental results are validating with ABAQUS 6.4 software. The comparison of natural frequencies from experimental analysis & FEM analysis are carried out & result is shown here for specimen no. 1.

Table 10: Comparison of Experimental & FEM results for specimen 1

Mode	Natural Frequency (Hz)		% Variation
	Exp.	FEM	
1	31.25	32.537	- 4.12
2	206	202.04	+ 1.92
4	568.75	569.64	- 0.16
6	1102	1114.5	- 1.13

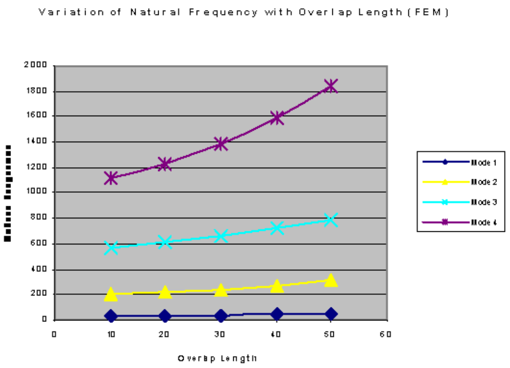

Fig.2: Variation of Natural Frequency with Overlap Length (FEM)

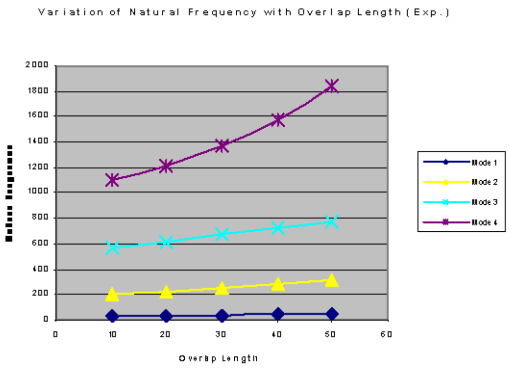

Fig.3: Variation of Natural Frequency with Overlap Length (Experimental)

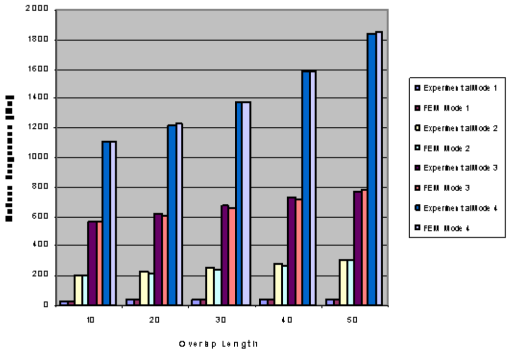

Fig. 4: Comparison of Natural Frequencies with increasing overlap lengths for all Specimens

All the five specimens were analyzed in FEM & compared with experimental results. The natural frequencies were found to be in close agreement with experimental results. The variation was between – 0.16 % to + 6.6 %. Graph 7.8 shows the comparisons between the experimental & FEM results.

Also from fig 2,3 & 4 it is observed that natural frequency increase with increase in overlap length for higher modes for both experimental & FEM results.

8. CONCLUSION

The transverse vibration of an adhesively bonded single lap joint has been investigated in this dissertation work. The experimental & finite element methods have been used for free vibration under fixed boundary conditions. A study has been conducted to observe some general trends regarding the variation of natural frequencies with certain structural & geometric parameters of the joint system.

Some general conclusions have been drawn from the study.

* The natural frequency of the system increase with the increase in overlap length of the joint. This trend is logical because of the tendency of joint system to become stiff with increasing the overlap length.

* This particular fact can be used as design tool to avoid a particular natural frequency.

From the Graph 5.6 displacement is nearly constant for overlap lengths 30 mm & above & hence for optimum condition 30 mm overlap length can be choose.

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