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Comparison of Natural Frequency & Mode Shapes of Rectangular Plates & Lap Joints by Modal Analysis

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ABSTRACT

The need of the study is to analyze the dynamic behavior of structures like a rectangular plate, bolted lap joint, and single lap epoxy adhesive joint subjected to impact or shock loads using Finite Element Analysis (FEA) and experimental modal analysis. The various factors that affect the response of single rectangular plate, bolted and adhesive joint structures are studied, such as natural frequencies, mode shapes, damping ratio etc. The aim of this paper is to provide efficient techniques using software analysis for the prediction of the dynamic response of single rectangular plate with lap joints and to validate the predictions by experimental modal analysis. The finite element method is used to predict the natural frequencies, mode shapes and frequency response functions of the beams. The dynamic test software i.e. NI-Lab View and the data acquisition hardware used in experimental measurement of the dynamic response of the joints. The frequency response functions of different joints and single rectangular plate are measured. The three different specimens are used which consist of aluminum material. The finite element analysis i.e. Ansys software is used for modal analysis of all joints. The initial case study is focused on a simple rectangular plate of cantilever beam subjected to impact force. The second case study is focused on bolted lap joint and single lap adhesive joint. The main objective of this work is to determine the natural frequency and mode shape of all three specimens at cantilever beam condition and first to compare the result of all joints with the single rectangular plate and then compare it with experimental modal analysis. In practical application this kind of modal analysis can be used to analyze various structures to find natural frequency & mode shapes such as cantilever bridge, frame of bicycle, automobile product, Industrial robots (manipulator), building structures, heavy machineries and aircraft industry etc. From these studies it is found that the analyzed results by finite element analysis are comparable with experimental analysis. The method is more accurate and can be used for various applications.

Keywords— Modal Analysis, Lap Joints, Natural Frequency, Mode Shapes, Finite element analysis.

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I. INTRODUCTION

Vibration problems are often occurred in mechanical structure. It is important to prevent such problems because it can cause structural fatigue and damage. The structure itself has a certain properties so it is necessary to understand its characteristics. For this there are different methods, In this work a modal analysis by finite element method is used. The main purpose of modal analysis is to study and predict the dynamic properties of structures like natural frequency, damping and mode shapes. This can also be used for some purposes such as, troubleshooting i.e. direct insight into the root cause of vibration problems, find structural flexibility properties quickly to monitor incremental structural changes, design optimization-design according to noise and vibration targets, enhance performance and reduce component and overall vibration & fast, test based evaluation of redesign for dynamics etc. So it is important to determine dynamic properties of a cantilever beam rectangular plate, bolted lap Joint and single lap adhesive joints of a aluminum material to study the structural response of these joints after loading or impact. The modal analysis of a rectangular plate, bolted lap joint and single lap adhesive joint is done using FEA software considering cantilever beam conditions to predict the dynamic response of all specimens and to find natural frequency and mode shapes. The araldite epoxy resin adhesive is used as bonded material for single lap adhesive joints. The fasteners used for bolted joints are hex screw (M8x16) and nut M8. Then the finite element analysis results of these three components are compared with each other and then with experimental modal analysis to find the error between software and experimental results.

The main objective of this paper is to determine the natural frequency and mode shape of a single rectangular plate, bolted lap joint and single lap adhesive joint at cantilever beam condition. The first step of the work is to do the modal analysis using ansys 13.0 software for determining the dynamic properties of the beam. The modal analysis is used to understand the dynamic properties of structure such as natural frequency (resonant frequency), damping ratio and mode shape. The finite element analysis results are compared with the obtained experimental results to verify the modal analysis. With modal analysis, we can extract the modal parameters (dynamic properties) of a structure. The modal parameters, including natural frequency, damping ratio, and mode shape, are the fundamental elements that describe the movement and response of a structure to ambient excitation as well as forced excitation. Knowing these modal parameters helps to understand the structure's response to ambient conditions as well as perform design validation.

The adhesive bonding become importance in structural bonding in aircraft industry. The subject of adhesives became even more interesting to scientists when the application of synthetic resins as adhesives for wood, rubber, glass and metals were discovered. Adhesive bonding as an alternative method of joining materials together has many advantages over the more conventional joining methods such as fusion and spot welding, bolting and riveting. Adhesive bonding is gaining more and more interest due to the increasing demand for joining similar or dissimilar structural components, mostly within the framework of designing light weight structures.

The current trends are to use visco-elastic material in the joints for passive vibration control in the structures subjected to dynamic loading. These components are often subjected to dynamic loading, which may cause initiation and propagation of failure in the joint. In order to ensure the reliability of these structures, their dynamic response and its variation in the bonded area must be understood. In adhesive joint the major function of adhesive is to transmit loads from one member of joint to another. It allows a more uniform stress distribution than is obtained by another mechanical joining process such as welding, bolting, riveting, etc. Thus, adhesive often permit the fabrication of structures that are mechanical equivalent or superior to conventional assembles and furthermore cost and weight benefits.

The conventional joining process increase the weight of the structure by adding extra material such as bolt, screws, extra filler material. If you want to joint two plate by bolting then hole is created in the plate which result in stress concentration or if you joint by weld then there is localized heating of the component take place which alter its mechanical properties. In adhesive joining process you do not need to create the hole in the plate or there is no localized heating take place. Thus adhesive bonding gaining more importance in joining process where you have to avoid stress concentration and avoid localized heating. In addition adhesive can produce joints with high strength, rigidity, dimensional precision in the light metals, such as aluminum and magnesium, which may be weakened or distorted by welding. Adhesive can also prevent electrochemical corrosion between dissimilar metals.

Adhesive bonding is a material joining process in which an adhesive, placed between the adhered surfaces, solidifies to produce an adhesive bond (Figure1). When we bond components together the adhesive first thoroughly wets the surface and fills the gap between, then it solidifies. When solidification is completed the bond can withstand the stresses of use. The strongest adhesives solidify through chemical reaction and have a pronounced affinity for the joint surfaces. Adhesives come in several forms thin liquids, thick pastes, films, powders, pre-applied on tapes, or solids that must be melted. Adhesive can be designed with a wide range of strengths, all the way from weak temporary adhesives for holding papers in place to high strength structural systems that bond cars and airplanes. Now a day's adhesive compete with mechanical fastening systems such as nuts, bolts, and rivets, or welding and soldering. In the practical application this kind of modal analysis can be used to analyze some structure such as cantilever bridge, frame of bicycle, automobile product, Industrial robots (manipulator), building structures, heavy machineries etc that can be simplified as beam and so on.

II. FINITE ELEMENT ANALYSIS

The finite element analysis (FEA) is a computational technique used to obtain approximate solution of boundary value problems in engineering. Simply stated, a boundary value problem is mathematical problem in which one or more dependent variables must satisfy a differential equation everywhere within a known domain of independent variables and satisfy specific conditions on the boundary of the domain.

The modal analysis of aluminum material rectangular plate, bolted and single lap epoxy adhesive joint is done by finite element method using ansys 13.0 software. The properties of aluminum material used are given in table 1. The analysis is done for 3D element and the type of element used in this analysis is solid 185. The required properties of the aluminum material as well as adhesive used are required for the finite element analysis is given in below table1 & 2.

Table 1: Material Properties of Aluminum Material

Material Properties	Notation	Aluminum	Unit
Modulus of Elasticity	E	7.00E+10	N/m^2
Poisson Ratio	ν	0.3	-
Density	ρ	2700	Kg/m^3
Length	l	1	m
Width	b	0.05	m
Thickness	h	0.005	m

Table 2: Properties of Epoxy Adhesive Material

Material Properties	Notation	Aluminum	Unit
Modulus of Elasticity	E	4.00E+04	N/mm^2
Poisson Ratio	ν	0.33	-
Length	l	50	mm
Width	b	50	mm
Thickness	h	0.2	m

There are certain common steps in formulating a finite element analysis of a physical problem, whether structural, fluid flow, heat transfer, vibration and some other problem. These steps are usually embodied in commercial finite element software packages. There are three main steps, namely: preprocessing, solution and post processing. The preprocessing (model definition) step is critical. This step includes; define the geometric domain of the problem, the element types to be used, the material properties of the elements, the geometric properties of the elements (length, area and the like), the element connectivity (mesh the model), the physical constraints (boundary conditions) and the loadings. The next step is solution, in this step the governing algebraic equations in matrix form and computes the unknown value of the primary field variables is assembled. Actually the features in this step such as matrix manipulation, numerical integration and equation solving are carried out automatically by commercial software. The final step is post processing, the analysis and evaluation of the result is conducted in this step. The specimens used for this analysis are given in below fig.1. So by using the finite element analysis techniques the natural frequencies and mode shapes are calculated with the help of parameters and properties given in table 1& 2 and the below configuration of the specimen which being used in this analysis.

III. Validation of FEA Techniques by Experimentation

In order to validate the effectiveness of the finite element analysis results or techniques used with experimental analysis results in the study of the forced vibration analysis and characteristics of the material used. Experimental tests are carried out by NI-Lab View software for measuring the natural frequencies and mode shapes of the single plate and all joints. The adhesive used for single lap adhesive joint is very common there two components araldite which is commercially available. The mechanical properties of the specimen and adhesive are given in the table 1 & 2. The adhesive is applied on the degreased surfaces of the both the specimen and the two sheets or specimen pressed together in order to squeeze sufficient adhesive out to avoid undue quilting of the finished joint which probably affects the natural frequencies of the joint. For getting expected adhesive layer thickness, the joint is bonded under constant pressure by using the clips and cured at room temperature for at least 3 hours.

The experimental set ups used for vibration measurements of the all three specimen is shown in the fig. 2. The NI-Lab View software is used in conjunction with the data acquisition hardware of four channel (QDAC) i.e. vibration analyzer for the dynamic tests. For measuring the natural frequencies and mode shapes of the single plate, bolted lap joint and adhesive bonded lap joint. One end of the joint is clamped in a heavy support with the help of c-clamp. The accelerometer is fixed at 20 % of the length of the beam from its clamped end or from its free end. Connection of all the wires and cables are done with the data acquisition hardware, accelerometer, and Impact hammer and with PC or Laptop loaded with NI-Lab View software as shown in fig. 2. The power supply is given to the system and software is opened and given all necessary inputs and make all required settings in the software to perform experimental tests. Now we apply impacts by the impact hammer on the nodes marked on the cantilever beam one by one. Total six nodes are marked on each cantilever beam for accurate readings. Signals from the accelerometer and impact hammer are received by the data acquisition hardware for each impact provided one after the other and that compared and analyzed by the software. After this with the help of Ni-Lab View software the natural frequencies and mode shapes at required nodes are computed by performing some operations in the software. Then obtained results i.e. natural frequencies and mode shapes are compared with the predicted results of finite element analysis. This shows a good agreement between the experimental and FEA results.

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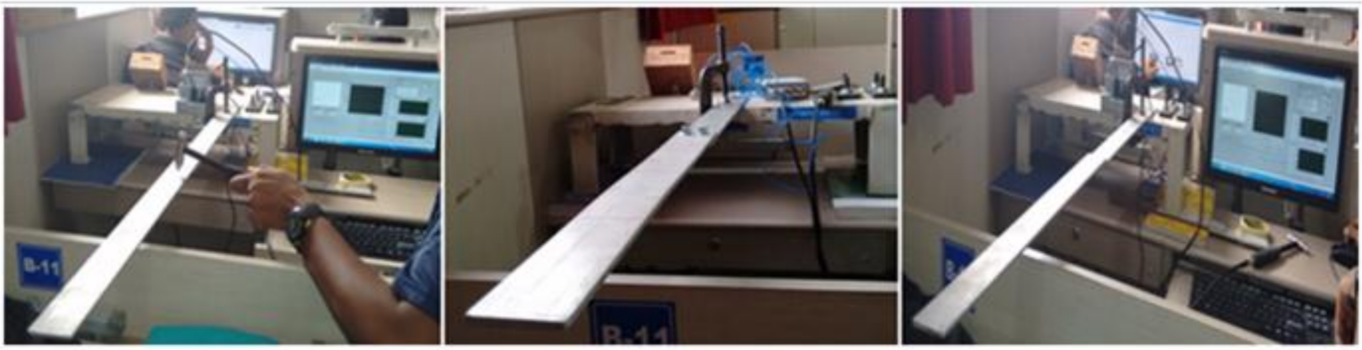

a b c

Fig.2 Experimental set up of a) single rectangular plate b) Bolted lap joint and c) adhesively bonded lap joint.

IV. Results and Discussion

Comparison of predicted and measured frequencies of the beams.

In this analysis, the modal properties of the single plate and both the lap joints are first predicted using FEA software and measured using experimental test rig are compared. The natural frequencies obtained by FEA and Experimental tests are almost close to each other and shown in table 3. Although only the first 10 natural frequencies are extracted and first five natural frequencies are more important for all the specimens. Thus, it can be said that the table 3 and figure 3 shows good agreement between the measured and predicted natural frequencies of the bonded beams. The table 3 and figures also show that the natural frequencies from experiment are lower than those predicted using FEA. This is because of the support, which clamp the beams is not infinitely rigid, which is causing a finite stiffness of the support on the measured modal characteristics. In addition to this, the variation in the natural frequencies attributed to force transducer or accelerometer mass contributions to the overall system mass. In FEA, however, the beams are clamped with infinite rigidity and no any additional masses attached on.

Table 3. Comparison of FEA and experimental natural frequencies.

Modes	Natural Frequency (Hz)					
	Single Rectangular Plate		Bolted Lap Joint		Single Lap Adhesive Joint	
	FEA	Experimental	FEA	Experimental	FEA	Experimental
1	0.29774	0.67	0.28115	0.44	0.20229	0.385
2	1.3296	1.705	1.445	1.132	1.382	1.45
3	1.8632	2.98	1.7527	1.66	1.4432	1.86
4	5.2034	3.92	4.9879	4.375	4.1426	3.845
5	8.2374	8.32	8.6378	8.74	7.9265	7.56
6	10.172	9.36	9.5469	9.29	8.7888	8.368
7	12.254	11.67	11.582	11.31	9.5233	8.939
8	16.817	15.013	15.808	14.779	13.16	12.913
9	22.658	23.617	23.753	23.475	19.779	19.032
10	24.999	23.944	24.929	23.794	24.726	23.67

The result show in fig. 3 that the natural frequencies of all lap joints are almost close to each other and if we compare it with a single rectangular plate that also comes to be satisfactory. The result show that the natural frequencies are depends on young's modulus, Poisson's ratio and density of the material.

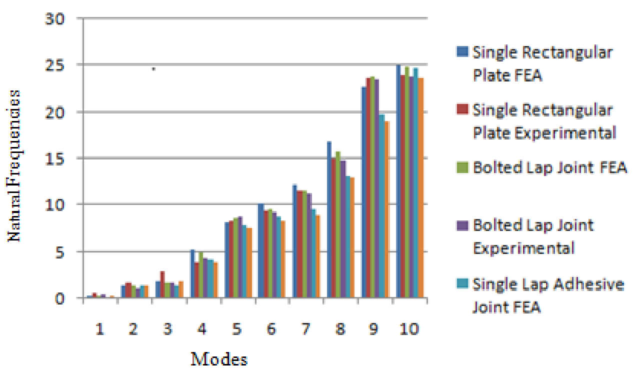

Figure 3: Comparison of natural frequencies with respect to modes

We observed that the material of the lap joint is same but the kind of joint is only different but then also the natural frequencies and mode shapes are nearby same which is shown by table 3. In table 3 we also compared the experimental and software analysis solution with each other and found that the natural frequencies at first 10 modes are nearby same that means the results are satisfactory as per the expectation.

Comparison of predicted and measured modal shapes

Mode shapes are very important in the dynamic response analysis of single plate, bolted and adhesive lap joint. If they are known at the design stage, the nodes can be place in the proper region of the structures. In this study, the FEA and experimental measurements are carried out of single plate and both the lap joints. There are total 10 natural frequencies and 10 mode shapes are extracted in this analysis. First 4 mode shapes of the experimental as well as FEA are compared with each other and shown in fig. 4. In this, it is seen that all corresponding mode shapes are similar. The dynamic response of the beams depends on the transducer or accelerometer and impact of hammer on the specimen locations. Some complexity in the mode shapes can be attributed to accelerometer mass contribution to the overall system mass. In fig. 4 only first 4 FEA and experimental mode shapes of the single rectangular plate are compared with each other and other mode shapes of the joints will remain the same.

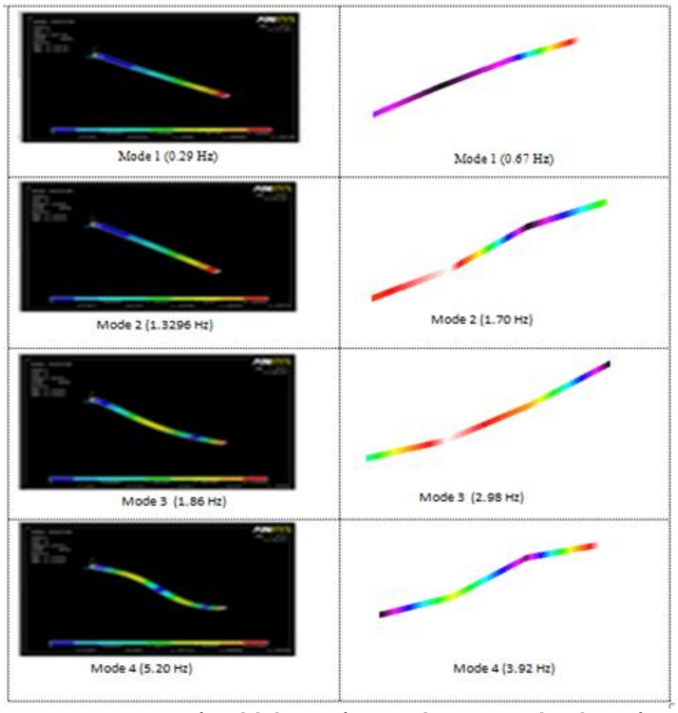

Fig. 4 Comparison of modal shapes of FEA and experimental analysis of a single rectangular plate.

V. CONCLUSION

In this work the modal analysis of a single plate, bolted lap joint and adhesively bonded lap joint is done using FEA software and experimental test rig. The dynamic response of all the specimens are investigated numerically (FEA) and experimentally and compared both the results with other. The Ansys 13.0 software is used for finite element analysis to predict the natural frequencies and mode shapes of all the specimen at cantilever beam condition. The NI-Lab View Software and data acquisition hardware is used for the experimental modal analysis to find natural frequencies and mode shapes. Then, the finite element analysis predicted results are compared with the experimental results and found to be satisfactory. These are almost close to each other. The natural frequencies and mode shapes obtained by the both method are compared and shown in table 3 and fig. 4. It is seen that the natural frequencies obtained experimentally are lower than the predicted (FEA); it is because of the accelerometer or transducer mass and impact of the hammer on the specimen. It is concluded that the FEA of dynamic response of the bonded beams with a single lap joint will help future applications of adhesive bonding by allowing different parameters to be selected to give as large a process window as possible for bonded beams vibration analysis. From this work it can also be conclude that the adhesive bonding of joints is an alternative method of joining materials together which has many advantages over the conventional joining methods such as welding, bolting and riveting. The corrosion and vibration stress associated with mechanical fasteners and welds can be reduced or eliminated by forming adhesive joint. It is important to study modal analysis of all joints to understand the dynamic nature of the systems and also in design control.

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