Numerical Analysis of Adhesive Joints with Bi-Layered Adherends

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***Abstract*—Improvement of joint quality has always been a call for concern in an assembled component due to numerous application of such components in immense industrial sectors such as aerospace and automotive industries, electrical/electronic industries etc. With this in mind quite a vast research had been carried out and still on going to enhance the characteristics of various parts that makes up an assemble and the complete assemble itself. Part of the research carried out fixated on adhesive bonded joint of different geometrical designs such as L-shape, single-lap, double-lap, tubular, T-shaped, stepped and scarf joints etc. Focusing on single –lap joint due to the simplicity of the design geometry and their ease of fabrication, various forms of arrangement have been researched on. But owing to its untimely failure, caused by high strength concentration in the overlapping areas and some other parts that are delicate to peel damage various forms of design geometry have been adopted ranging from tapering, stepping and wavy lapping of overlapping layers in order to reduce or mitigate the stress concentration for an improved load bearing ability. Due to a lot of challenges being faced with difficulty in fabrication, this study focused on double layer single-lap joint. Its harmonic response when subjected to external dynamic loading was investigated with the use of Ansys finite element analysis. The numerical analysis was carried out on various forms of adhesive-adherends arrangement, and from the harmonic response obtained it showed that the double layer single-lap joint have improved load bearing capacity as compared with other geometrical designs.**

***Index Terms*—Adherends, Ansys Finite Element Modelling (FEM), Double Adhesive Single Lap Joint, Harmonic Response.**

I. Introduction

With the zeal to enhance the quality of joints in an assembled component, and due to an extensive application of adhesive bonded joint in vast industrial sectors such as aerospace and automotive industries, electrical/ electronic industries, there have been an increase in the approaches used to study the response of adhesively bonded joints. Different geometries can be obtainable for adhesively bonded joints depending on the area and type of application. Some of them are L-shape, single-lap, double-lap, tubular, T-shaped, stepped and scarf joints [1]

There are a lot of advantages of adhesively bonded joint over traditional mechanical fasteners. Some of the advantages can be seen in aircraft where fibre reinforced polymer matrix composites (FRPCs) are used for improved damaged tolerance and lower structural weight designs [2]. The most common disadvantage associated with adhesively bonded joint is the fatigue damage they experience which may be due to continuous vibration, crash and impact and for this reason it became necessary to study their dynamic response or behavior.

The approach for the dynamic behavior analysis may be experimental, numerical or analytical [3], but in this study one out of the three approach will be considered which is the numerical finite analysis.

II. Literature Review

Adhesively bonded joints have found usage in many industrial and even non-industrial applications in order to merge together similar materials like every other mode of joining and non-similar materials; a very peculiar advantage [4]. Industrial sectors like automobile, marine, railway and specifically, aircraft [5] to build complex structures of whose dimensions are immense.

Researchers over the years have studied how adhesively bonded joints behave under stressed situations and how to reduce stress concentrations in adhesively bonded joints which often times lead to fatigue and consequent damage of the joint and adherends because moving machinery are subjected to vibrations, collisions and impact [6-7]. These manners put by these joints can be researched in the analytic way [8-3], studied numerically [9-11] and examined experimentally [12-15].

Different analysis, studies and examinations have gone ahead since Volkerson’s first work when he derived the shear-lag model [16]. Further analytical research was done which tends to consider the adherend’s bending manner and this lead to the proposition of a model by Goland and Reissner [17] which was based on the stress analysis of beams. Also, the classical work of Hart-Smith [18-20] which was one of the breakthroughs in the analytical approches to this study, simplified the complex stress-strain behaviour by the application of elasto-plastic or bilinear curve.

Since then, lots of analytical research has been done for example Delale et al. derived a two-dimensional solution for assemblies bonded together [21]. Also, shear and peel stresses in both metallic and composite adherends have been studied and analytical models like that of Zou and others have been developed [22]. By considering double lap bonded geometry as an overlaminate joint, Osnes and MacGeorge [23] under loaded condition investigated the shear stress on the joint. Their work was later extended by themselves to take account the adhesive’s elastomeric behaviour [24].

Concerted efforts have also been made not only on

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analytical method as highlighted above but also analysis using a very powerful and efficient tool like the Finite Element Analysis (FEA) to show how adhesively jointed single lap joints behave and how their strength have been affected under the influence of shear and peel stresses by Magalhaes and co. [25], failure mechanisms by Kim K. and others [26], overlap length by Campilho et al. [27,28], adhesive damage by Benyahia and co-workers [29], influence of cohesive variables by Fernández-Cañadas and others [30] and patch dimensions which was carried out by Fekih et al. [31]. It has been found that joint strength can be increased when uniform load transfer occurs which can be brought about by the plastification of ductile adhesives. This research was carried out by Keller [32] when he evaluated how full-scale double-lap joints comprising of brittle protruded GFRP laminates' strength and hardness is affected by adhesive ductility. With the help of the Cohesive Zone Model (CZM), Campilho et al. [33] developed a FEM model of single-lap joint and explained the effect of cohesive law parameter of a triangular CZM. A 3D FEM model of the single lap joint was also developed by Khalili and others [34] and results showed that near the ends of the adhesive region, the peel and shear stress values were the greatest. Not more than two years ago, William and Jialai [35] also developed a 3D model which is based on the Finite Element Analysis to cater for the setback of the 2D model by Goland and Reissner [36] and using functionally graded materials as substrates. William and Jialai's work was geared because of the fact that the two parameters, elastic foundation (2-PEF) model cannot capture the boundary conditions where the shear stresses are significantly more and different. Their work was a success and the three parameter, elastic foundation was developed to cater for the flaw and his results showed that stress concentrations near the ends of the joint can be brought down by bringing down Young's modulus of the adhesive layer, increasing the adhesive layer thickness, and/or making sure that the FG adherends are configured to make the stiffer part is nearest to the adhesive layer [35].

A lot of research based upon experimental analysis have been examined for example, recently, Prabhakar and Garcia found out that using 3D printed reinforcement (i.e. infusing structural strengtheners to the adherends through fused deposition modelling (FDM) additive technique, the visible shear strength of adhesively bonded single lap joints can be improved to about 832% [2]. Also, research on bonded adhesives by exploring the field of nano-science was carried out by Salih, Iclal and others [37] based on their experimental analysis on adhesively bonded single lap joint by nano-composite adhesives which were obtained by adding nanostructures, they varied the concentration of three different nanostructures in the adhesive and experimental failure loads imparted on them. They observed that the nanocomposite adhesive manufactured increased the joint's load failure and the rate of increase depended on the structural make-up of the adhesive and the type of nanostructure used. However, the result at 0.01 ratio is the best.

All the researches highlighted above be it numerical, analytical and experimental, the author to the best of his knowledge has not come across the study of how an adherend will behave when subjected to vibrations while the other adherend is fixed at the other end. This study will be done by exploring the harmonic response of singly supported double adhesive single lap joint. The only similar study that was found was that done by Khalid and Ramzi when they subjected single-lap and double-lap joints to axial loads while the other end was fixed [1]. While one of the adherend's end will be fixed, the other will be struck with a hammering gesture. This will set up a vibration in the system. The response as earlier said will be analysed numerically using the Finite Element Analysis (FEA) approach.

III. Methodology

Numerical Model

With the use of ANSYS finite element software package a numerical analysis had been carried out to show the harmonic response of the double similar/ or dissimilar adherent single lap joint when subjected to harmonic load.

The model design has a z-direction (width) that is much greater than its thickness, therefore it is assumed to be plane strain with a 2-dimensional configuration. This also means that the strain along the cross section is much more than z-directional plane strain.

With the adoption of a 2-dimensional model design, the adhesive is a single layer thickness of 1mm with a double layer adherent of 1mm each. The adherent is made up of Aluminum and Steel arranged in two different ways in order to achieve varying response when subjected to harmonic loads.

The adhesive used has a young modulus of 4.1E8Pa with a Poisson ratio of 0.4 and a density of 1800 kg/m3. The properties of the adherents used is given in table I.

The geometrical design is done in such a way that the overlap region of the adhesive/adherent joint have a length of 50mm while the extended parts are of length 100mm each. With this, the length of the adherents is 150mm.

TABLE I: Properties of Adhrends used in Model design.

S/N	Adhesive Properties	Aluminum	Steel
1	Thickness (mm)	1	1
2	Length (mm)	150	150
3	Density (kg/m3)	2800	7550
4	Poisson ratio	0.34	0.3
5	Young's modulus (Pa)	6.9E11	2E11

The sensitivity of resonance frequency with respect to change in mesh size was observed by conducting convergence analysis which shows that a slight variance in mesh size from 0.1mm to 1mm has little effect on the outcome of the values of natural frequencies obtained. Due to this, a fine mesh of element size 0.25mm was applied on the adherends while that of the adhesive was 0.1mm. Figure 1 shows the meshing of the model design.

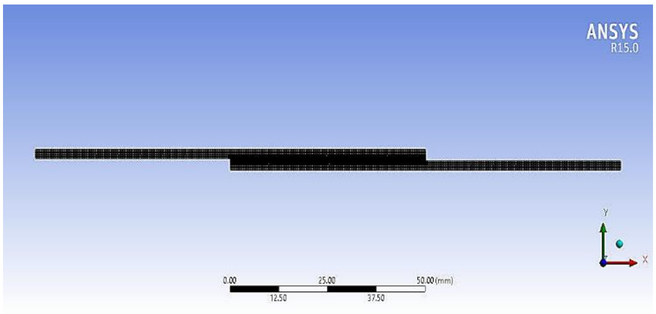

Fig. 1. 2D finite element mesh of the model design.

A SURF 153 element was used. This element has three nodes and two degrees of freedom per node with axial and transverse displacement. The boundary conditions is subjected in such a way that left corner of the upper layer of the adherend is fixed while the lower layer of the adherend is subjected to harmonic force of 1N. This is achieved by ensuring that the two adherend layers (upper and lower) are prevented from moving in transverse direction. Figure 2 shows the boundary condition imposed on the model design.

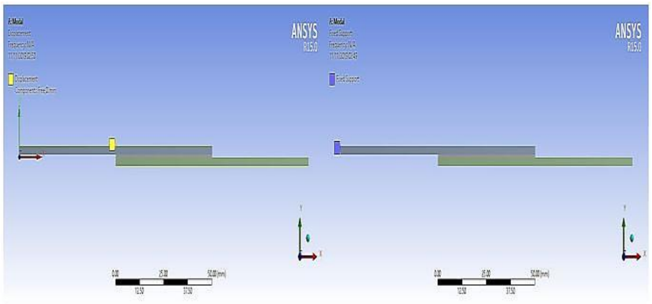

Fig. 2. The boundary condition for the 2D finite element model design

The steps carried out while performing finite element analysis with the use of Ansys workbench platform was to firstly assign material properties to the adherends and adhesive. Afterwards, the design geometry was produced with the use of bonded contact conditions applied between each layer of adherends and adhesives. Then meshing and modal analysis were carried out to generate the first six (6) resonance frequencies and mode shapes. Finally, with the use of generated frequencies and mode shapes, the frequency response graphs were plotted using mode superposition technique.

IV. Result and Discussion

A. Validation

So as to authenticate our model which is based on frequency response of the joint to harmonic loads, several simulations were carried out. With the use of multilayers of Aluminum and steel as adherends arranged sequentially in different fashion, the properties of both Aluminum and steel can be seen as shown before in Table 1. While the adhesive used has a young modulus of 410Mpa, Poisson's ratio of 0.4 and a density of 1800kg/m^3. Two different dissimilar joints of arrangements of Aluminum and steel are studied and various frequency responses are recorded and analyzed. Table II shows the two different arrangement of the double layer single lap joint and all frequency response were calculated from the range of 1000Hz to 100 kHz.

The frequency response of the first double layer arrangement (Al-St-Ad-Al-St) can be seen as illustrated in Fig.3. The first natural frequency for numerical modal analysis is 7202 kHz. The second double layer arrangement (Al-St-Ad-St-Al) was also analyzed for frequency response which is shown in Fig.4. The first natural frequency for numerical modal analysis is 7205 kHz. Shown in Table III below is the results of the first, second, third and fourth natural frequencies studied and the error margin between the two arrangements of the double layer single lap joint.

TABLE II: Material and Geometric Properties of the Two Different Arrangement of Double Layer Single Lap Joint.

Joint #		1		2	
Arrangements		Al-St-Ad-Al-St		Al-St-Ad-St-Al	
Adherend 1	Material	Al	St	Al	St
	Young modulus (GPa)	70	200	70	200
	Poisson ratio	0.34	0.3	0.34	0.3
	Density (Kg/m3)	2800	7800	2800	7800
	Thickness (mm)	1	1	1	1
Adherend 2	Material	Al	St	St	Al
	Young modulus (GPa)	70	200	200	70
	Poisson ratio	0.34	0.3	0.3	0.34
	Density (Kg/m3)	2800	7800	7800	2800
	Thickness (mm)	1	1	1	1

TABLE III: Results of the First, Second, Third and Fourth Natural Frequencies of the Two Joints Arrangement and Error Between the Two

	Joint # 1	Joint # 2	Error
1st Natural Frequency (kHz)	7202	7205	0.04
2nd Natural Frequency(kHz)	22060	22073	0.06
3rd Natural Frequency(kHz)	36448	36501	0.15
4th Natural Frequency(kHz)	42374	42429	0.13

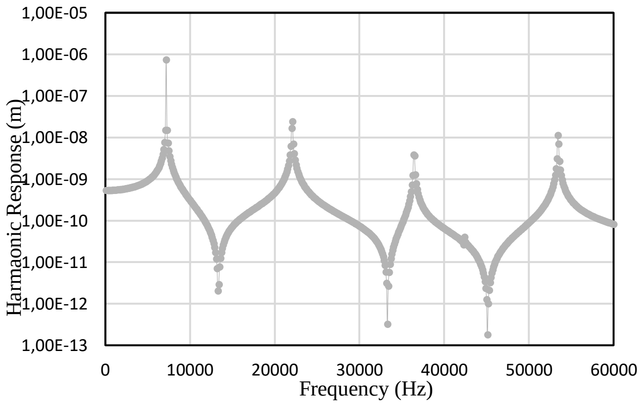

Fig. 3. Frequency response for Al-St-Ad-Al-St arrangement

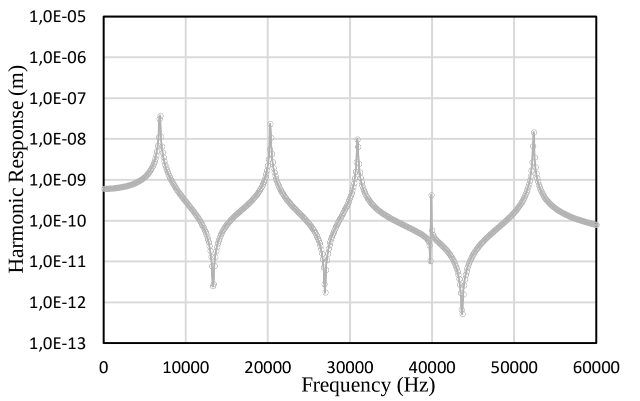

Fig. 4. Frequency response for Al-St-Ad-St-Al arrangement

B. Discussion

From the validation result shown above, it can be seen that the numerical analysis which was carried out on the double layer single lap adhesively bonded joints were developed in order to model its harmonic response when subjected to external force. In this case of dissimilar joints arrangement, the natural frequencies depend on the order of substrates. The several configurations which were examined as shown in table III shows a steady increase in the values of Natural frequency obtained which indicates stability of the arrangement. With this, the double layer single lap joint can be said to be able to withstand a considerable load. Also, as the natural frequency increases from 1st natural frequency to 4th natural frequency for the two different configuration, there is an increase in error margin between the two arrangements (i.e. Al-St-Ad-Al-St and Al-St-Ad-St-Al). This shows that the more the natural frequency increases the less stable the harmonic response. It can also be seen from table III that, the 1st (Al-St-Ad-Al-St) and 2nd (Al-St-Ad-St-Al) arrangement have similar natural frequencies with little error which signifies that the effect of external force irrespective of the arrangement of the second layer between Al and St is insignificant.

V. Conclusion

Using double layer single lap joint model of different adhesive arrangement, the harmonic responses of the joints were derived. The Numerical approach was generated with ANSYS finite element software. The numerical analysis is in conformity they showed that the double layer single-lap joint has improved load bearing capacity from the results of the harmonic response obtained.

From the numerical analysis carried out in this research, it can be said that the natural frequencies generated is dependent on the order of substrate or adherends arrangement. Also, judging from the numerical analysis results shown and discussed in the previous chapters, it can be said that the double layer single lap joint is stable since the four (4) natural frequencies obtained from the 1st (Al-St-Ad-Al-St) and 2nd (Al-St-Ad-St-Al) arrangement increases in a consistent manner. For future reference, it may be desirable to do more different adhesive arrangement as these may get improved results.

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