Modelling of Harmonic Response of Scarf Adhesive Joints

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Abstract — Adhesives are used for attaching structures to various spacers such as tubular and scarf joints to replace the traditional joining methods of welding, brazing, soldering, etc. Many of the unique features associated with adhesives are low manufacturing cost, long component life, and lightweight. Accordingly, a considerable amount of study has been carried out and is still underway to develop. The main objective of this study is to investigate the response of the scarf joints when exposed to a harmonic load. The finite element method (FEM) using ANSYS is availed to study and analysis the natural frequencies, mode shape, and frequency response. Additionally, the influence of the adhesion angle is examined.

Index Terms — Adherends; Ansys; Finite Element Modelling (FEM), Scarf Adhesive Joints.

I. INTRODUCTION

Scarf joints involve complex deformation states especially when using the traditional attachment techniques [1]. As a result, the use of adhesives in the joining of scarf structures has been steadily increasing [2], [3]. This use of adhesives comes amidst the urge to replace these old methods, such as brazing, welding, and soldering. The utilization of adhesives has been found to reduce the production cost, as well as to make components' life longer by decreasing the response to vibrations.

The characteristics of these adhesive materials are remarkable. As a result, these significant weaknesses led to the need to produce better adhesives and appropriate surface processing equipment to make adhesive surfaces effective [4], [5]. Also, scarf joints are believed to have defects, such as gaps, voids, ineffective surface, and curing, which may affect the quality of the bond, as well as both dynamic, and static responses [16].

With all these advantages, the application of adhesives is often used with cautious especially that concerned with long-term impact, when subjected to various environmental conditions [6]. Due to the need to study the dynamic response and behavior of the scarf adhesive joint under a harmonic load, this study comes to understand and analyze that.

At the beginning of the 20th century, the technological creation of an adhesive joint started with Volkersen's work [28], and several others followed, such as Charalambides [29], Goland [30], and others. The adhesively bonded joints currently play an important role in the industry and civil engineering, as they achieve resistant and robust joints [13]. Because of the ease of production and the lack of any technical expertise in the development process, the single-lap joint is also the most commonly used one.

The geometry is straightforward, but the stress distributions are very complex. Double lap joints, step joints, and scarf joints are among other common joint arrangements. Scarf joints, however, can be found highly fascinating because they do not induce adhesion bending, which adversely influences the strength of the joint, unlike single-lap joints [1]. Thanks to their ability to assemble a wide variety of components, adhesive joints seem to be an interesting tool for minimizing the weight and expense of structures in diverse manufacturing fields. However, adhesives are significantly underused because of the lack of faith in non-destructive quality assessment. The need to suggest testing to assess the durability of assembly choices that can be used for the construction of adhesively bonded structures is another important point. The experimental characterization of the potential assemblies is not a simple task because of the severe edge effects (linked with a geometrical and material mismatch between the adhesive and the substrates) and the complex failure dynamics that could be produced [2].

Due to a large amount of material and geometric variables affecting the efficiency of scarf repair, the design of the optimum scarf repair for a given application (especially for composite structures) is complicated. There are also different experiments to find exact design instruments for the static power of scarf joints or replacements because of this. They can be analytical, numerical, or experimental. The early work of Jones and Graves is an example of experimental experiments on scarf repairs [1].

The study of adhesive-bonded joints involves knowledge of the structural adhesive's stress-strain nature, and there are many test methods for this reason [15]. To promote this experimental characterization, some experiments have been normalized, such as the single-lap joint test. However, the estimation of a consistent intensity is not negligible because of the pressure concentrations at the ends of the overlap. Although, some studies suggest some solutions and ideas to reduce the edge effects. In addition, this test is dedicated to determining the strength of a given peel/shear stress ratio that is believed to be a quasi-pure shear, while high peel stresses are produced at the ends of the overlap, some studies suggest some modifications by subjecting the adhesive to variable combinations of peeling and shearing stresses [2].

During the treatment of surfaces, the efficiency of bonded CFRP joints has been enhanced by various methods. Mechanical, plasma, chemical, and laser surface applications can be loosely categorized into methods. Mechanical surface treatments, such as grit, grinding, or baking, improve

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ruggedness, reduce corrosion, and expose the new materials to a new layer [3]. Surface treatment with chemicals and plasma has been documented in order for usable groups to be taken to the surface. Plasma surface therapy may also be used to eliminate release agents. [3].

Khashaba [5,8] addresses the use of nanoparticles in functional applications such as laminated composites, adhesive joints, and hybrid joints as entirely new subjects, and enhancing the efficiency of the mantle joint in composite structures by using Al_2O_3 or SiC nanoparticles have not yet been studied, but there are some attempts on single-coil metal joints, so great attention should be paid to [5].

Andrea Dorigato and Alessandro Pegoretti [6], showed that the temperature of the glass transformation of the nano-filled adhesives increased to maximum filler filling and then decreased, possibly due to the parallel and opposing effects of blocking the chain and decreasing the degree of crosslinking. The presence of untreated alumina nanoparticles at an acceptable filler content has positively influenced the tensile modulus, split stress, and crack strength of the bulk adhesive [6].

Korayem et al. [18] found that the CNT-reinforced epoxy has Young's modulus 20% higher than the neat epoxy. The reinforced epoxy has also a tensile strength 30% higher than the neat epoxy. However, the elongation-to-failure is reduced by about 41%. Studying, analyzing, and simulating all these details has been difficult historically, but now the methodology of finite elements takes the lead in the analytical processes in this century. In only a few decades, this technology has evolved, from the first use of a large scale and richly different electronic solution for many science and technology fields in 1941 in aircraft structural analysis and structural engineering. Stress analysis is often complicated and for many engineering challenges in the field of structural mechanics; theoretical solutions are exceedingly difficult and repetitive [15]. Approximate and sufficient ways to solve most functional problems are found in numerical methods. With the introduction of computers, one of the best methods that emerged in the area of engineering research is the finite element approach and a general method for the study of structures that are solid in complex shapes and complicated bounds. FEM splits a structure into several elements (structure parts), then reconnects elements to "nodes" as if nodes were pins or drops of glue binding elements together, resulting in a sequence of algebraic equations concurrently [14].

It is possible to divide the current theoretical analyses on complex activities into two categories: finite element analysis (FEA) and empirical science. Through the advent of industrial FEA methods, modeling the bonded joint and simulating the joint's mechanical behaviors has become simpler [19].

Through studying the stress of an independent lap joint with FEM, Baylor and Sancaktar showed that, when a mesh density along the transverse path of an overlap reaches 3 elements per mm, it will essentially eliminate the variation of maximal main stress and of mesh density in Misses. 25 elements per mm in the peel direction were also found to contribute to the decoupling of these stresses with mesh densities with an adhesive thickness of 0.2 mm [17].

II. METHODOLOGY

The finite element analysis was performed through several steps using ANSYS workbench. First, we have assigned the material properties to the adherents and adhesive. Afterward, the design geometry was produced with the use of bonded contact conditions applied between each layer of adherents and adhesives. Then meshing and modal analysis.

Next, we have also assigned the material that makes up each part, and the position and amount of force applied during the test. Finally, we need to select the results that will be processed. Here our goal is to obtain the first four natural frequencies, the mode shape, and the frequency response.

The study will be carried out on a rectangular geometric shape, with external dimensions (length 200 mm, width 10 mm, adhesive thickness 0.5 mm), the center of the scarf joint is in the middle of the shape and the dimensions of the shape are changed in order to change the angle of contact. In table III, we can see the dimensions of all cases of the study. The dimensions are given in millimeters. The structure is clamped from one edge and free from the other.

During the study of the frequency response, there is a load of 1 N at a distance of 30 mm from the left edge of the body's as shown in Fig. 1. The frequency response will be taken as the displacement along the Y-axis

In this work we considered that adherends are aluminum and adhesive part is epoxy, the mechanical properties of these materials in Table I.

TABLE I: MECHANICAL PROPERTIES OF MATERIALS

Material	E (Gpa)	ρ (kg/m ³)	ν
Aluminum	70	2770	0.34
Epoxy	2	1800	0.4

Fig. 1. 2D scarf joints with adhesive in the middle and shows the position of the force 30 mm from the beginning of the installation on.

The behavior of the natural frequency under this case will be studied by changing the angle of the scarf joint and the adhesive is always of constant thickness.

The finite element method (FEM) will be implemented using ANSYS to investigate the response of the scarf joints. For simplicity purposes, the numerical approach will be dealt considering the problem as a 2-D finite element model. Adherent and adhesive are assumed isotropic.

The accuracy that can be obtained from any FEA model is directly related to the finite element mesh that is used. As these elements are made smaller and smaller, the mesh is refined, and the computed solution will approach the true solution. The study of convergence requires the selection of an appropriate mesh refinement metric. Mesh element size is varied between 0.1 and 10 mm. The convergence for a mesh size of 0.5 mm. The process of mesh refinement is a key step in validating any finite element model and gaining confidence in the software, the model, and the results.

Fig. 2. Mesh element size at 5 mm.

TABLE II: GEOMETRIC DIMENSIONS

Case	L1	L2	L3	L4	t	w
1	100	100	100	100	0.5	10
2	100.5	99.5	99.5	100.5	0.5	10
3	101	99	99	101	0.5	10
4	102	98	98	102	0.5	10
5	104	96	96	104	0.5	10
6	106	94	94	106	0.5	10
7	108	92	92	108	0.5	10
8	110	90	90	110	0.5	10
9	115	85	85	115	0.5	10
10	120	80	80	120	0.5	10
11	125	75	75	125	0.5	10
12	130	70	70	130	0.5	10
13	135	65	65	135	0.5	10
14	140	60	60	140	0.5	10
15	150	50	50	150	0.5	10
16	160	40	40	160	0.5	10
17	170	30	30	170	0.5	10
18	180	20	20	180	0.5	10
19	200	0	0	200	0.5	10

III. RESULT AND DISCUSSION

A. Result

The goal of this work is to obtain the first four natural frequencies, the mode shape, and the Frequency response of all cases shown in Table II.

For the (Clamped-Free) Aluminum scarf joint, we have studied the effect of scarf angle on the natural frequencies. From the Fig. 3, we can conclude that the natural frequencies are maximum at 90° for all first four natural frequencies. However, the minimum is variable depending on the natural frequency. For the first natural frequency, the smallest value is reached at the angle (2.83 °), while for the second natural frequency the smallest value is reached at (18.43° and 14.04°), and for the third natural frequency, the lowest value is achieved at (4.76°). Finally, for the fourth natural frequency the smallest value is obtained at 3.57° (see Table III and Fig. 3).

We can also notice that the difference between the maximum and minimum value of a normal frequency is not significant, NF1= 2.31Hz, NF2 = 10.9 Hz, NF3 = 34.6 Hz, and NF4 = 16.3 Hz. The difference between the maximum and the minimum values is not significant and does not exceed 0.35% for all cases.

After studying the natural frequencies, we also studied the mode shapes (Fig. 4, 5, and 6). Through this study, it becomes clear that the effect of the angle of the mantle joint is very small. We compared the response of the presence of the scarf joint and a bulk aluminum beam. We found that the displacement was not significantly affected.

Three angles were chosen because results are close for all angles (Fig. 4, 5, and 6).

TABLE III: FIRST FOUR NATURAL FREQUENCIES FOR EACH ANGLE (ALUMINUM (C-F))

Angle (Degree)	Natural frequency (Hz)			
	first	second	third	fourth
90°	220.62	1332.8	3670.9	6687.5
84.29°	220.61	1332.6	3670.7	6687.3
78.69°	220.57	1332.2	3670.2	6686.7
68.2°	220.42	1330.5	3668.4	6684.6
51.34°	220.09	1327.1	3663.8	6680.2
39.8°	219.82	1324.5	3660.1	6677
32°	219.65	1323	3657.5	6675.1
26.56°	219.55	1322.2	3655.7	6673.9
18.43°	219.42	1321.5	3652.3	6672.5
14.04°	219.35	1321.5	3649.5	6671.9
11.31°	219.31	1321.9	3646.8	6671.6
9.46°	219.26	1322.4	3644.2	6671.4
8.13°	219.21	1323	3641.7	6671.4
7.125°	219.16	1323.7	3639.7	6671.3
5.7°	219.05	1325.2	3636.9	6671.3
4.76°	218.92	1326.6	3636.3	6671.2
4.08°	218.77	1327.8	3637.3	6671.2
3.57°	218.62	1328.6	3639	6671.2
2.83°	218.31	1329	3640.2	6671.3

Fig. 3. First four natural frequencies of Aluminum with (C-F).

Fig. 4. Mode Shape of Aluminum with (C-F) At Angle 90°.

Fig. 5. Mode Shape of Aluminum with (C-F) At Angle 32°.

Fig. 6. Mode Shape of Aluminum with (C-F) At Angle 2.83°.

We have studied the frequency response of the (Clamped-Free) Aluminum scarf joint for different angles and there is also no significant effect (Fig. 7).

Fig. 7. Frequency Response of Aluminum (Clamped-Free).

B. Discussion

Now, the same geometric shape is tested by using aluminum and without the scarf joint, and the natural frequency is compared with and without the joint and the effect of that (Table IV).

TABLE IV: NATURAL FREQUENCIES WITH ONE BODY

Natural frequency (Hz)	
first	214.66
second	1328.3
third	3647.2
fourth	6676.2

From Fig. 8. It is clear that the effect of the scarf joint on the first natural frequency is greater than the rest of the other three frequencies, at angle 90° we notice that the effect is large, but it gradually decreases to be approximately one at 2.83°.

Fig. 8. The ratio of the impact of the scarf joint on the natural frequency.

IV. CONCLUSION

Adhesives are increasingly for attaching structures to various spacers such as tubular and scarf joint to replace the traditional joining methods of welding, brazing, soldering, etc. Many of the unique features associated with adhesives are low manufacturing cost, long component life, and lightweight. Due to various applications of such components in huge industrial sectors such as aerospace and automotive industries, electrical and electronic industries, the development of joint performance will always be a call for attention in an integrated component. Accordingly, a considerable amount of study has been carried out and is still underway to develop.

The main objective is to investigate the response of the scarf joints when exposed to a harmonic load. The finite element method (FEM) using ANSYS is availed to study and analysis the natural frequencies, mode shapes, and frequency responses. The obtained results show that the effect of the scarf angle on the natural frequency is limited.

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