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EFFECT OF DIFFERENT STEP-LAP JOINTS ON THE NATURAL FREQUENCIES OF DIFFERENT ADHESIVELY BONDED METALLIC MATERIALS: A NUMERICAL STUDY

Ali İhsan KAYA[1]*

[1]*Adıyaman University, Engineering Faculty, Mechanical Engineering Department, Adıyaman, 02040, Türkiye*

Abstract: Due to their many applications' benefits, adhesively bonded joints are widely utilized in nearly every industry, including space, marine, automotive, and aeronautics. Since unpredicted loadings may cause resonance in the structures, an accurate prediction of the bonded joints' dynamic characteristics is crucial. Therefore, in this study, modal analysis was performed on the two-, three-, four- and double-step adhesively bonded lap joints of Aluminum (Al), Copper (Cu), and Mild steel (Ms) materials with Epoxy Araldite adhesive. Ansys commercial program was utilized to analyze it numerically. The results showed that modeling the bonding region of single lap joints as two-, three-, and four-step adhesively bonded lap joints has no significant effect on the natural frequencies. This modeling has a minor incremental effect on the natural frequencies. However, Double-step lap joints were found to cause a considerable reduction in natural frequencies compared to not only single lap joints but also two-, three-, and four-step adhesively bonded lap joints. Double-step bonding caused a decrease of 8.82%, 8.57%, and 8.73% for Al-Al, Cu-Cu, and Ms-Ms. In general, in all models, the best increase or decrease in terms of natural frequencies was found to be Cu-Cu adhesively lap joints.

Keywords: Adhesively bonded joints, Step-lap joints, Modal analysis, Finite element method

***Corresponding author:** Adıyaman University, Engineering Faculty, Mechanical Engineering Department, Adıyaman, 02040, Türkiye
E mail: alikaya@adiyaman.edu.tr (A. İ. KAYA)
Ali İhsan KAYA https://orcid.org/0000-0002-3040-5389

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1. Introduction

An adhesive is positioned between the adherend surfaces during the process of adhesive bonding, which creates an adhesive bond. Because adhesive joints combine many types of materials and have good damping qualities, high corrosion and fatigue resistance, fracture retardation, and labor, time, and cost savings, they are widely utilized in load-bearing structures across a wide range of industries. In addition to these better qualities, adhesive joints are the subject of some research that is being conducted in the literature because of their lightweight and simplicity of application (da Silva and Marques, 2008; Shang et al., 2019). As a result, simple fixes, including adhesive joins to link materials have been proposed and are still being proposed.

Single- and double- acting adhesive types are the most commonly utilized in bonded connections. A study (Apalak and Engin, 1997) used bonding models in single and double-reinforced lap joints. Four distinct single-lap joints of hybrid AA2024-T3 aluminum alloy and carbon/epoxy composites were explored by Gültekin et al. (2017). The impact of functionalized boron carbide and boron nitride nanoparticles on the bonded joints of aluminum alloy (AA2024-T3) was examined by Gültekin and Yazici (2022). The impact of surface preparation on the strength and performance of single-lap aluminum-copper alloy joints for automotive applications was investigated by Boutar et al. (2016). They discovered that there was an inverse relationship between surface roughness and the shear strength of single lap joints, with rougher surfaces having lower wettability. The aluminum and carbon-epoxy components of hybrid adhesively-bonded single lap joints were examined by Ribeiro et al. (2016). The bonding strength of hybrid metal-fiber reinforced polymer single-lap joints was examined by Thomas et al. (2021).

Thakare and Dhumne (2015), simulated the different joint techniques of welding, riveting and adhesive bonding of Mild Steel (MS) by using the Finite Element Method (FEM) and stated that, with good fatigue and force resistance, these adhesives can offer substantial cost and weight reduction benefits. Erbayrak et al. (2017), used the FEM to investigate the impact of different adhesive types on the free transverse vibration of a single lap joint and concluded that varying the type of adhesive has a substantial impact on the natural frequency of lap joints. Hussain and Ingole (2022), surveyed the significant advancements in the field of dynamic characteristics of mechanical and structural joints, as well as the frequency domain dynamic analysis approach for nonlinear system parametric identification in structural dynamics. Aabid et al. (2021), studied a beam plate structure's adhesive joints. Aluminum 2024-T3 and Araldite 2014 were taken into consideration for the beam and adhesive bond. They concluded that the adhesive layer used in the lap joint needs to be lengthy and thick to improve the structural performance of vehicle scale models. Dhilipkumar et al. (2022), have made an effort to provide a succinct overview of the vibrational properties, such as natural frequency, damping factor, and modal strain energies, which influence the strength of joints that are adherently linked. Ramalho et al. (2022), reviewed the most current studies that focus on the numerical examination of adhesive joints' dynamic behavior. Three distinct fields were identified under dynamic behavior: modal analysis, fatigue, and variable strain rate and impact. Sindi et al. (2021), used a functionally graded adhesive with a comparison of steel and aluminum adherents in their FEM model, and it was found that it produced natural frequency predictions that were consistent with the analytical model. Using a FEM, the first 20 natural frequencies of Single Lap Joints (SLJs) were predicted by He (2012). He and Oyadiji (2001), used a FEM to investigate the effects on the adhesive mechanical characteristics' natural frequencies. They found that, in general, changes to the Poisson's ratio do not significantly affect the natural frequencies. Van Belle et al. (2018), investigated a number of joining techniques for SLJ both numerically and experimentally. It was discovered that the natural frequencies predicted by the numerical technique for the adhesive joints were comparable to those seen in the experiments. Yaman and Sansveren (2021), examined composite SLJ, SSJ, and DSJ with various geometric modifications both experimentally and numerically. For the various joint configurations, there was a good correlation between the FEA and the experiments. Additionally, it was demonstrated that the natural frequencies are significantly affected by the fiber orientation angle and adherent thickness, increasing with the latter. Conversely, as overlap duration grows and adherent thickness drops, the damping ratio gets better. Du and Shi (2014), considered how vibration fatigue affects the modal characteristics of single-lap joints and tried to determine how the modal characteristics of the jointed structure and the fatigue damage in the adhesive layer are related. Different step-lap joint’s fatigue performances subjected to tensile loading were studied by Demiral and Mamedov (2023). They studied how the step-lap joint's failure characteristics change under cyclic tensile loading because these loadings can cause adhesively bonded joints to fail, even at low percentages of their static strengths.

Although studies on the modal analysis of adhesively bonded joints have started to increase in recent decades, new studies in this field are important in terms of understanding the nonlinear dynamics and the effect of different adherents and adhesives on the dynamic characteristics of adhesively bonded joints. Therefore, in this study, modal analysis was performed on the two-, three-, four- and double-step lap joints of Al, Cu, and Ms plate materials with Epoxy Araldite adhesive. Ansys commercial program was utilized in order to analyze it numerically. To the best of the author’s knowledge, although there are studies on the modal analysis of adhesively bonded joints, there is no such comprehensive study on the change in dynamic properties of different metallic materials for the structural state of two-, three-, four- and double-step adhesively bonded lap joints in different configurations. Therefore, this study aims to fill this gap in the literature and contribute to the literature on the change of dynamic parameters of adhesively bonded joints.

2. Materials and Methods

2.1. Modal Analysis

The process of creating a mathematical model for a system's dynamic behavior by ascertaining its innate dynamic properties, such as natural frequencies, damping factors, and mode shapes, is known as modal analysis. The effectiveness of many structural dynamics applications depends only on having a precise mathematical model for a dynamic structure. Finite element modeling, which takes the form of mass and stiffness matrices, can be used to create such a model. Because of the robustness of this technique, the resulting FE model may be crucial for further applications such as prediction (He and Fu, 2001).

Numerous variables, including the type of joint, geometrical specifications, adherend materials, and adhesive properties, affect the strength and dynamic properties of bonded joints. Since unpredicted loadings may cause resonance in the structures, an accurate prediction of the bonded joints' dynamic characteristics is crucial for the appropriate characterization of their service life.

Ramalho et al. (2022), stated that numerical models currently used in the literature are becoming the benchmark for evaluating various analytic techniques. Furthermore, the studies that conducted experimental and numerical data demonstrated how accurate these models were in predicting the natural frequencies. Therefore, the modal analysis of the lap joints is performed using one of the FE programs in this study. Ansys 2023, a commercial program, was used to simulate the modal analysis of different step-lap composite joints. A thorough analysis was conducted to determine how the various step-lap arrangements, as per the geometric configurations in Demiral and Mamedov (2023), affected the metallic joints' service life.

2. 2. Validation of the Method

For validation, the study of Patil and Barjibhe (2013), was taken into consideration. Al-Al, Cu-Cu, and Ms-Ms plates with epoxy adhesives, as in the considered study, were modeled in Design Modeler. The dimensions of all plates were 140 mm x 38 mm x 5 mm, and the overlap length was 15 mm. Since the adhesive thickness is not specified in the relevant study and the thickness of adhesive material is more a determinant of the damping coefficient than the natural frequencies of bonded material, a 0.15 mm thickness was chosen as such by Du and Shi (2014). The properties of materials used for analysis are given in Table 1. “Bonded” contacts were identified on the model. “Multi-Point Constraint (MPC)”, generally the ideal contact formulation option for contacts with no separations and bonded contacts, was chosen for formulation, and “Nodal-Normal to Target” was used for detection method (Giannetti, 2020). Mesh numbers were reduced until no significant change was seen in the analysis results, as stated by Moaveni (2015). After the change in the analysis results reaches very low levels, the mesh parameters for the element are decided upon. Therefore, the default element size was utilized. The Contact sizing method was used to have more elements on the bonded areas, as could be seen in Figure 1. Then the geometry was meshed. The mesh geometry was consisted of 42842 nodes and 7814 elements. The obtained results were compared with the aforementioned study, as seen in Table 2. As can be seen from the results, the analysis results of this study are quite compatible with the results of Patil and Barjibhe (2013).

2.3. Numeric Analysis of Step-Lap joints

After the validation process, by using the same formulation, detection method and other properties, modal analysis of step-lap joints with different geometric configurations as such in the study of Demiral and Mamedov (2023), was carried out. The different geometric configurations in the study of Demiral and Mamedov (2023), were adapted into the current study accordingly. Hence, materials and thickness were altered proportionally. Because the thickness in the relevant study was different from the thickness in the current study, step-lap configurations were adapted proportionally according to the measurements given in the reference study.

The Same procedure was followed in the process of analyzing step-lap joints. “Bonded” type contact region were determined. The behavior in the analysis was chosen as “Symmetric”. Since “Symmetric” behavior is more complex and refers to both Contact and Target surfaces (URL1). Multi-Point Constraint (MPC), generally the ideal contact formulation option for contacts with no separations and bonded contacts, was chosen for formulation, and “Nodal-Normal to Target” was used for the detection method (Zhu, 2017). “Nonlinear Mechanics” was favored under the mesh module for the physics reference because of the nonlinear structure of adhesive lap joints. A Fixed boundary condition was applied for having a cantilever beam as shown in Figure 2. A mesh convergence was conducted as in the validation section. To have more mesh geometry in the contact region, contact sizing was added to the bonded areas. After meshing, the mesh quality of the mesh geometry was obtained as 0.625 which was reported as a good ratio (Çitil et al., 2019). After the solution, the participation factor summary was examined to comment on in-plane and out-of-plane modes. Besides, the “Ratio of Effective Mass to Total Mass” under the solution module was always checked to have a ratio of 90 % for the plane axes.

Table 1. Properties materials used for validation

Bonded Materials	Aluminum	Copper	Mild Steel	Araldite
Young Modulus (GPa)	70.3	129.8	200	0.93
Density (kg/m^3)	2700	8960	7850	1070
Poisson ratio	0.35	0.34	0.303	0.32

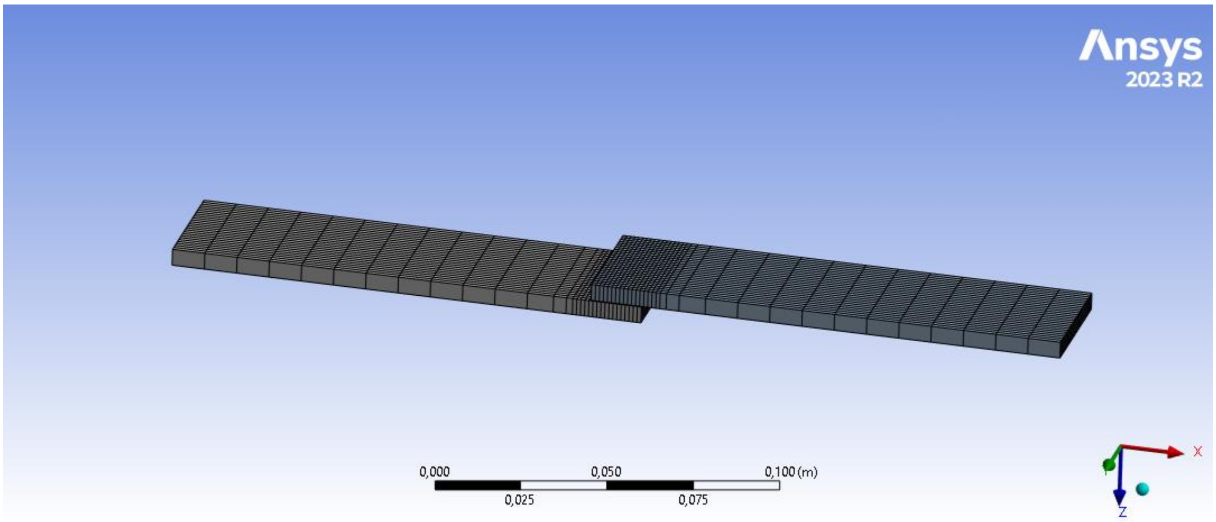

Figure 1. Mesh configuration of the single lap model.

Table 2. Natural frequencies of the analysis

Bonded Materials	Mode I[a]	Mode I*	Difference (%)
Al-Al	59.476	59.002	0.8
Cu-Cu	42.563	42.062	1.12
Ms-Ms	58.975	58.203	1.33

a This study, *Patil and Barjibhe (2013).

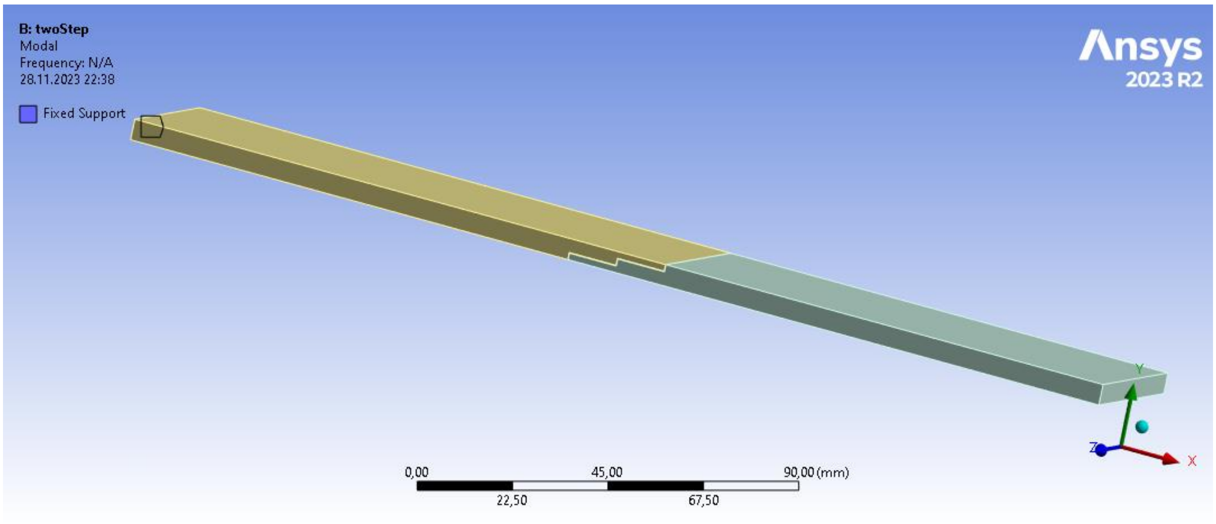

Figure 2. An example of boundary conditions for stepped lap joint.

3. Results and Discussion

Since most adhesives are viscoelastic, they have an advantage over alternative joining techniques in terms of mitigating vibration issues (Ramalho et al., 2022). In this instance, the modal loss factor tends to rise with increasing adhesive thickness and overlap length. To find the ideal adhesive thickness for a certain application, one must constantly analyze these two parameters because raising the adhesive thickness also causes a drop in natural frequencies. In the validation method section, the single-lap overlap length was 15 mm (Patil and Barjibhe, 2013). To adapt this thickness value to the reference study, a re-analysis was carried out with an overlap length of 25 mm for the single-lap joints by using the same analysis steps. The first three natural frequency analysis results are given in Table 3. By comparing Tables 2 and 3, it is possible to comment that the joint's natural frequencies increase with the overlap length. However, it was reported that its impact on joint strength becomes negligible beyond a certain length (Akpinar et al., 2022). Wani (2015), stated that as the joint's overlap length increases, so does the system's inherent frequency. Given that the joint system has a tendency to stiffen as overlap length increases, this pattern makes sense. However, for overlap lengths of 30 mm and more, it is almost constant. In terms of natural frequencies, the same outcomes were reported in other studies (Wang et al., 2019, Ingole and Chatterjee, 2011). Therefore, it could be stated that the increase in natural frequencies is compatible with the literature.

The first ten extracted natural frequency results after re-modeling the bonded area into two-step lap joints are given in Table 4. When the frequencies in the relevant table are examined, it is seen that the fundamental natural frequencies for all metallic two-step lap joints are increased. When the current analysis result is compared to single-lap joints results in Table 3, the following consequences could be deducted based on fundamental natural frequencies: While the increase for Al-Al two-step lap joints is around 0.34%, this rate is around 0.61% for Cu-Cu and 0.42%for Mild steel two-step lap joints. Therefore, it was observed that there is a minor increase, although not a significant improvement, in the natural frequencies of all metallic two-step lap joints. The improvement in fundamental natural frequencies was the best in Cu-Cu two-step lap joints; this was followed by Ms and Al two-step lap joint structures, respectively.

Table 3. The first three natural frequencies of single-lap joints for 25 mm overlap length

Bonded Materials	Mode I	Mode II	Mode II
Al-Al	63.785	402.15	456.25
Cu-Cu	47.422	300.74	340.63
Ms-Ms	62.838	397.75	451.82

The results of the first ten extracted natural frequencies of the three-step lap joints are given in Table 5. When this table is reviewed, it is seen that the natural frequencies in all metallic three-step lap joints are close to the results of two-step lap joints, and there is no substantial change in terms of fundamental natural frequencies but rather a slight increase in the case of three-step lap joints.

Table 4. Natural frequencies of two-step cantilever lap joints

	Natural Frequencies of Extracted Modes (Hz)		
Modes	Al-Araldite-Al	Cu-Araldite-Cu	Ms-Araldite-Ms
1st mode	64.001	47.71	63.102
2nd mode	400.52	298.8	395.2
3rd mode	473.41	353.15	468.15
4th mode	789.68	591.31	794.39
5th mode	1122.2	836.42	1106.3
6th mode	2214.5	1651.6	2183.4
7th mode	2396.5	1794.4	2409.6
8th mode	2704.5	2019.6	2681.4
9th mode	3701.4	2758.4	3645.3
10th mode	4084.3	3056.9	4101.4

Table 5. Natural frequencies of three-step cantilever lap joints

	Natural Frequencies of Extracted Modes (Hz)		
Modes	Al-Araldite-Al	Cu-Araldite-Cu	Ms-Araldite-Ms
1st mode	63.982	47.693	63.069
2nd mode	400.48	298.73	395.06
3rd mode	472.99	352.83	467.73
4th mode	789.19	590.93	793.86
5th mode	1122.6	836.7	1106.5
6th mode	2214.6	1651.5	2183
7th mode	2395.3	1793.6	2408.3
8th mode	2702.9	2018.3	2679.5
9th mode	3697.3	2755.2	3640.7
10th mode	4081.4	3054.7	4098.3

Table 6. Natural frequencies of four-step cantilever lap joints

	Natural Frequencies of Extracted Modes (Hz)		
Modes	Al-Araldite-Al	Cu-Araldite-Cu	Ms-Araldite-Ms
1st mode	63.894	47.63	62.997
2nd mode	399.84	298.26	394.51
3rd mode	472.7	352.62	467.45
4th mode	788.73	590.59	793.41
5th mode	1121.1	835.6	1105.2
6th mode	2214.1	1651.3	2183
7th mode	2393.7	1792.4	2406.7
8th mode	2701.7	2017.4	2678.4
9th mode	3704.5	2760.7	3648.4
10th mode	4079.7	3053.5	4096.7

When the analysis results of three-step lap joints are compared to single-lap joints' results in Table 3, the following deductions could be extracted based on fundamental natural frequencies: in the case of Al-Al three-step lap joints, the increase is found to be 0.31% while it is obtained as 0.57% for the Cu-Cu three-step lap joints and 0.37% for Mild steel three-step lap joints. Consequently, it was found that all metallic three-step lap joints have somewhat higher natural frequencies, albeit not noticeably better. Cu-Cu three-step lap joints showed the most improvement amongst fundamental natural frequencies of all metallic materials; mild steel and aluminum three-step lap joint structures came in a row, respectively. It should be emphasized that these results are compatible with the two-step lap joints.

The results of the first ten extracted natural frequencies of the four-step lap joints are given in Table 6. When this table is examined, it is seen that the natural frequencies in all metallic lap joints are almost the same in the three-step lap joints. Therefore, it could be stated that among the all fundamental natural frequencies of all metallic materials, Cu-Cu three-step lap joints demonstrated the biggest improvement; mild steel and aluminum four-step lap joint followed, respectively. It is important to note that these outcomes are consistent with the results of two- and three-step lap joints.

The natural frequency results of the first ten extracted natural frequencies of the double-step joints are given in Table 7. When this table is reviewed, unlike the analysis results of the two-, three-, and four-step lap joints, all metallic joints showed a substantial decrease in terms of natural frequency. When single-lap joints are taken into consideration for comparison to the double-step lap joint results, the following conclusion may be drawn based on the fundamental natural frequencies: Al-Al, Cu-Cu and Ms-Ms double-step lap joints showed a decrease of 8.82%, 8.57% and 8.73% respectively. Hence, it was observed that all metallic adhesively bonded structures were affected at approximately the same reduction rate in the case of the geometric configuration of double-step lap joints. Besides, it was found that the results of double-step lap joints are the geometric configuration that has the most adverse effect among the geometric lap joints considered.

When Tables 4, 5, 6 and 7 are compared, one can observe that the geometrical configurations of two-, three-, and four-step lap joints have no significant effect on the natural frequencies as per a single-lap joint. Therefore, it is possible to say that there is no point in modeling the bonding zone in a two-, three-, and four-step geometric configuration, which is more difficult in terms of production and application than single-lap, when the natural frequencies are considered. However, double-step geometric modeling is found to have a significant negative effect on the natural frequencies compared to the other geometric configurations. Although Demiral and Mamedov (2023) stated that the double-step-lap joint had a 21.8% longer lifetime comparing fatigue cycles with other models, the analysis results in this study showed that the double-step geometric model is the weakest lap joint in terms of dynamic parameters. Therefore, it is beneficial to avoid the use of this geometric model in applications where dynamic parameters are deterministic.

Utilizing a Finite Element Analysis (FEA), He (2012) and He and Oyadiji (2001) investigated the impacts on the adhesive mechanical characteristics' natural frequencies. They demonstrated that, in general, modifications to the Poisson's ratio do not significantly affect the natural frequencies. The same was noted for realistic variations in Young's modulus; however, the natural frequencies underwent a dramatic alteration when a very low Young's modulus, less than 1 GPa, was used. Therefore, these reported findings support the finding that the natural frequency results of the metallic materials analysed in this study are close to each other.

It is reported that the overlap length only slightly affects frequency by Guo and Wang (2020). Furthermore, there is a very little tendency for the natural frequency to decrease as adhesive thickness increases. The impact of bonding length and adhesive thickness on shifting resonance frequencies is still limited because of its small mass. He (2012) found comparable results regarding adhesive thickness, while Gunes et al. (2010), stated similar tendencies regarding bonding length. While it has no effect on the resonance frequency when combining materials with a high density. This finding is in line with the initial parameters of this study.

Du and Shi (2014), stated that the modal frequency changes seen in their studies require drastic decreases in modulus and contact area values, which may not always be feasible, according to their simulation data. Besides, changes in the adhesive mechanical properties—Young's modulus, density, and Poisson's ratio—did not significantly affect the natural frequencies, according to Apalak et al. (2006). Therefore, the natural frequency results for different step lap joints in Al and Ms are very close to each other, and the significant decrease in natural frequencies caused by the sudden geometric change in the bonding zone is in line with the findings of this study.

4. Conclusion

In this study, the effect of different stepped configurations of the bonding area on the natural frequencies of adhesively bonded joints of metallic materials is investigated. The conclusions drawn from this study can be summarized as follows:

Table 7. Natural frequencies of double-step cantilever lap joints

Natural Frequencies of Extracted Modes (Hz)			
Modes	Al-Araldite-Al	Cu-Araldite-Cu	Ms-Araldite-Ms
1st mode	58.161	43.358	57.351
2nd mode	363.94	271.48	359.11
3rd mode	431.06	321.55	426.26
4th mode	751	562.34	755.51
5th mode	1020.1	760.29	1005.7
6th mode	2013.4	1501.7	1985.3
7th mode	2276.9	1704.8	2289.5
8th mode	2481.7	1853	2459.9
9th mode	3370.5	2511.6	3319.6
10th mode	3784.2	2899.7	3891.1

- It was seen that commercial FEM programs could be successfully used to model the dynamic parameters of adhesively bonded joints because the compatibility was approximately 98%.
- Modeling the bonding region of single lap joints as two-, three-, and four-step adhesively bonded lap joints has no significant effect on the natural frequencies. This modeling has a minor incremental effect on the natural frequencies.
- Although the increase in natural frequency is minor among two-, three-, and four-step adhesively bonded lap joints, it is observed that there is a relatively bigger improvement in the natural frequency of Cu-Cu lap joints compared to other metallic materials.
- Double-step lap joints were found to cause a considerable reduction in natural frequencies compared to not only single-lap joints but also two-, three-, and four-step adhesively bonded lap joints.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	A.İ.K.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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