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Investigation of Vibration Modes of Double-lap Adhesive Joints: Effect of Slot

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ABSTRACT

Adhesive joints represent a viable alternative to traditional joining methods. The analysis of frequencies and modal shapes is fundamental to predict the vibrational behaviour of a structural component subjected to dynamic stress. There are numerous studies in the literature to determine the trend of stresses in the bonded region. It has been proved that the introduction of a slot in the inner adherend allows to reduce the stress concentration at the edges of the adhesive region. In this paper, the influence of imperfections in the central adherend is investigated by FEM analysis. The FE software ANSYS©19 is used for the modal analysis of the double lap adhesive joints and the first five modes are considered. The results show the influence of Young's modulus and density ratio on the natural frequencies, varying with the material. Moreover, the introduction of the imperfection is found to influence the vibrational behavior as the frequency increases. It is also observed that the mass reduction due to the introduction of the crack does not change the shape and modal frequency for the most significant modes, while it causes more important changes for the last vibrational mode. Therefore the introduction of the crack does not significantly change the dynamic behaviour of the joint and allows to realize a more even distribution of stresses, reducing the stress peaks values.

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NOMENCLATURE

EPX	Epoxy Adhesive	T0	Perfect inner adherend configuration
Tslot	Slot thickness	T1	1 mm thick slot configuration
Et	Young Modulus in tension	T2	2 mm thick slot configuration
ρ	Density	T3	3 mm thick slot configuration
$\boldsymbol{\nu}$	Poisson ratio	DLJ	Double-Lap joint
EPX	Epoxy Adhesive	T0	Perfect inner adherend configuration

1. INTRODUCTION

The use of structural adhesives has increased considerably in the field of civil engineering. Adhesive joining offers numerous advantages, including the possibility of joining different materials, reducing overall weight, uniform stress distribution, sealing capacity, and vibration dampening [1-7]. Adhesive joints find widespread applications in various industrial fields. The reliability of adhesive type joints depends on an accurate analysis of the mechanical properties as well as on the design, materials, and production methods [8-10]. Some of the best-known types of adhesive type joints are represented by the following: Single-Lap Joints (SLJ), Double-Lap Joints (DLJ), Strap Joints (SJ), Double-Strap Joints (DSJ), Scarf Joints (ScJ), single-L joints, T-joints and T-peel joints [11]. Among these types, the most used to experimentally evaluate mechanical performance are Lap Joints [12, 13]. For a correct design of adhesive joints, a thorough knowledge of both static and and dynamic characteristics is necessary to determine the correct distribution of stresses, as is the case in recent research developments [14]. Numerous studies have been carried out by performing dynamic analyses on both theoretical and FEM joints.

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To determine the free vibrations in adhesive joints, double lap joints are the most widely used due to their simple geometry. Miles and Reinhall [15] studied a model for the vibration behavior of a layered beam considering both the effects of shear and thinning of the adhesive layer. Ko et al. [16], Lin et al. [17] used FEM analysis to determine the free vibration behavior of adhesive joints. Saito and Tani [18] studied the natural frequencies and loss factors of adhesive joints subjected to both longitudinal and transverse coupled vibrations. Praveen and Reddy [19] studied the dynamic response of functionally classified ceramic-metal plates taking into account transverse shear deformations, rotational inertia, and moderately large rotations in the direction of von Karman. Loy et al. [20] studied the free vibration of functionally classified (St-Ni) cylindrical shells and the influence of constituent volume fractions on natural frequencies. Hamdan [21] investigated the effects of non-dimensional geometric parameters on stress concentration factors (SCFs) of circular hollow section CHS brace-to-H-shaped section T-connections under axial compression. The results showed that SCFs in the brace and chord increases. Ettefagh et al. [22] tested a flexible joint via explicit model predictive control method. First, the equations are derived and linearized, then the algorithm is applied. The results confirmed that the method was able to control the vibrations of the flexible joint. Balamuralikrishnan et al. [23] assessed the behaviour of beam-column joint reinforced with GFRP reinforcements using the FEA analysis. The experimental results obtained are compared with the analytical ones for both the beam-column joints reinforced with steel and GFRP reinforcements. Döner [24] studied the corrosion behavior of bare titanium and titanium dioxide. The main result showed that higher polarization resistance was obtained on porous TiO_2 than that of bare titanium.

The aim of this research is to optimize the use of materials in the field of civil engineering, in particular in the field of structural adhesives. As mentioned above, the introduction of imperfections in the joint is able to even out the stresses distribution in the bonding region.

For a proper design it is also necessary to consider the vibrational behaviour of a structure. Therefore, the effect of imperfections on the oscillations of the structure is analysed in detail. In this paper, a numerical investigation of the influence of geometrical adherends' imperfections on the free torsional vibration of double lap adhesive joints is presented and discussed. Different materials–among the most representative in structural adhesive applications–are considered. In particular, the effect of a slot introduction, as shown in Figure 1, in the middle adherend is analysed. In the following, the results obtained and the comparison with perfect middle adherend are shown and discussed. The numerical analysis are carried out with FE method using the ANSYS$^{©}$19 commercial software. The flowchart shown in Figure 2 summarizes the research program which is discussed in the following.

2. PROBLEM STATEMENT

The free oscillation of a structural system is evidence of its mechanical oscillatory behavior. The harmonic motion of a system is the result of the cyclic interchange of kinetic and potential energies between the components of the system itself. To guarantee a high level of structural performance compared to the demand for external actions, an accurate design phase of the

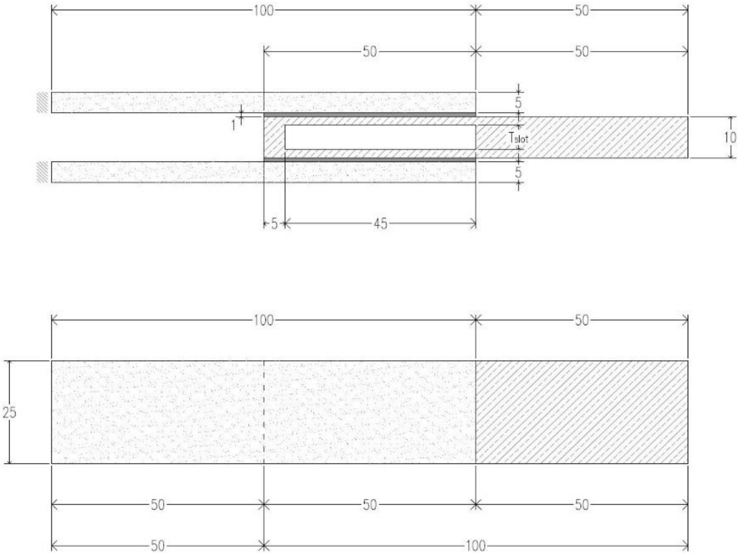

Figure 1. Double-lap joint geometry: section and plan view (measures in mm)

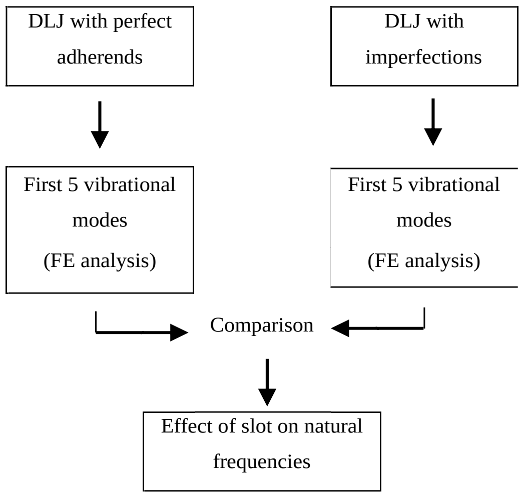

Figure 2. Research methodology

structural elements is necessary. For this purpose it is necessary to consider and predict the oscillatory behavior of a structural element. A generic structural element if not subject to external damping, when subjected to an initial disturbance, will tend to perpetuate its oscillation according to its own frequency while maintaining a particular geometric shape. This is the "natural frequency" of the system, and its shape is called a "modal shape". The object of modal analysis mainly concerns the determination of the natural frequencies and modal forms of a dynamic system. Once the modes are determined, they could be used in understanding the dynamic nature of systems, and in design and control.

In the case of adhesive joints, due to the involvement of geometrical, mechanical characteristics, it is difficult to determine the correct mechanical behavior of the joint. Several studies have been carried out regarding the stress distribution. Chen and Cheng [25] analyzed the stress distribution in a ScJ junction. The butt joint analysed is treated as a special case. Cheng et al. [26] analyzed the case of joints with different adhesive layers. In Lin and Lin's paper [17] a finite element model for stress analysis in the adhesive of a single lap joint is presented. Many studies in literature have proposed different methods in order to increase the joint structural efficiency. This is obtained by reducing the normal and shear stresses concentration by changing the geometry of the adhesives and of the aderends. The effects of tapering adherends were investigated by Sancaktar and Nirantar [27]. Hou et al. [28] have shown that the insertion of a defect in the internal adhesion of a double lap type joint led to a reduction of the stress peaks recorded at the edges of the adhesive region while reducing the overall weight of the joint.

In this paper the dynamic behavior of a DLJ is investigated, using an epoxy adhesive with both normal and cracked adherends, considering the geometries considered in literature [28]. The geometry is shown in Figure 1. The models analyzed are labelled as follows: T0-T1-T2-T3, where 0, 1, 2, 3 indicate the dimension in height (in mm) of the slot in the middle adherend, respectively. The joints are made of outer glass adherends and inner ones made of aluminum, GFRP, or S235JR steel.

Tables 1 and 2 summarize the mechanical parameters of the materials considered.

3. MODAL ANALYSIS

Adhesive joints find many applications. In some of these (e.g. naval or aeronautical applications) the vibrating component is fundamental in evaluating their mechanical performance. Modal analysis makes it possible to determine the vibration characteristics of structural components.

4. RESULTS AND DISCUSSION

This section reports on the modal dynamic analysis of the double-lap epoxy adhesive joints illustrated in

TABLE 1. Materials' characteristics for the FEA model

	Glass	
E_t [GPa]	ρ [N/m^3]	ν [-]
75	27000	0.30
	Aluminium[1]	
E_t [GPa]	ρ [N/m^3]	ν [-]
69	27100	0.30
	GFRP[2]	
E_t [GPa]	ρ [N/m^3]	ν [-]
26	26300	0.30
	Steel S235JR	
E_t [GPa]	ρ [N/m^3]	ν [-]
69	78000	0.30

[1] According to EN 755-2

[2] According to ASTM D904-99.

TABLE 2. Adhesive's characteristics for the FEA model

	Epoxy Adhesive	
E_t [GPa]	ρ [N/m^3]	ν [-]
3.25	12500	0.40

section 2. Different combinations of inner and outer adherends (i.e. Aluminium-Glass, GFRP-Glass, Steel-Glass) and of slots of different sizes inside the inner adherend are considered. The modal analysis is carried out using the commercial software ANSYS©19, with the "Modal" analysis. The geometry is meshed with PLANE 182 elements, a 4-node structural solid and a maximum element size of 0.10 mm.

Figures 3 to 6 show the first five modal shapes for each combination. Table 3 summarizes the frequency value for each modal form of the T0 configuration for the number of modes considered for the different combinations. Tables 4 to 6 show the frequency value for each modal form of the T1-T3 configurations concerning the number of modes considered.

The Steel-Glass combination shows the lowest natural frequencies of any other configuration; the Aluminium-Glass combination shows the highest ones. The difference is due to the different density of the materials. In fact, the ratio between the density of Steel and Aluminum is 2.87. The ratio between the frequencies of the first mode is about 1.5, remaining almost the same for the following modes. The natural frequencies of the Aluminum-Glass and GFRP-Glass joints are almost the same for the first two modes of vibration, while there is a deviation for the remaining modes, especially modes 3 and 5. In particular, the T1 configuration sees the greatest amount in terms of frequency in 4th mode for the GFRP-Glass combination.

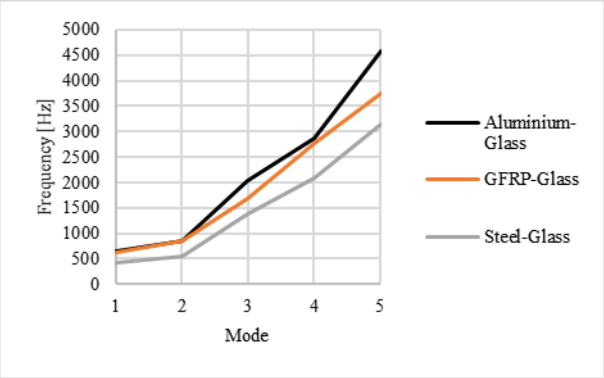

Figure 3. T0 DLJ modal analysis

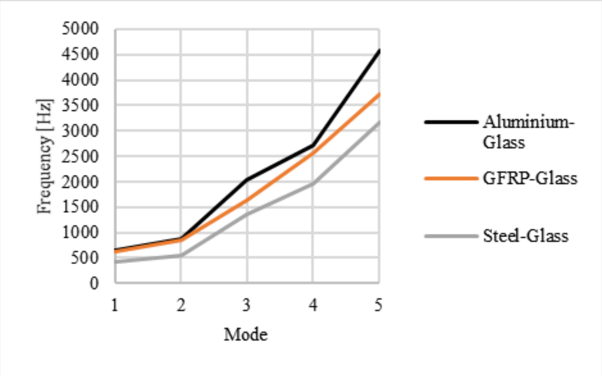

Figure 4. T1 DLJ modal analysis

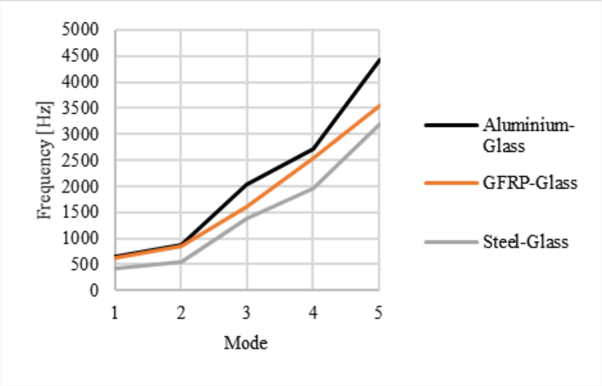

Figure 5. T2 DLJ modal analysis

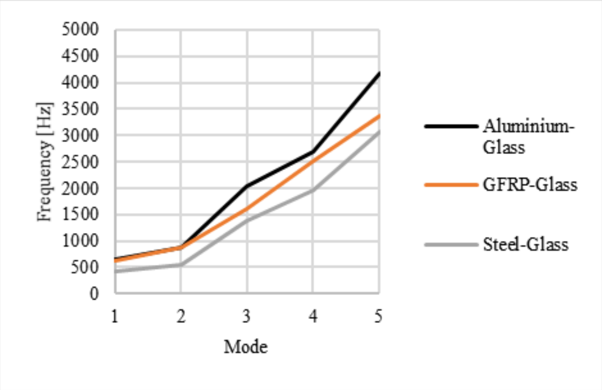

Figure 6. T3 DLJ modal analysis

TABLE 3. Modal frequencies for T0 configuration

Materials	f_1 **[Hz]**	f_2 **[Hz]**	f_3 **[Hz]**	f_4 **[Hz]**	f_5 **[Hz]**
Aluminium – Glass	641.81	861.51	2046.50	2863.30	4589.50
GFRP – Glass	633.02	855.43	1681.00	2759.10	3739.80
Steel - Glass	421.53	540.62	1373.90	2086.60	3151.20

TABLE 4. Modal frequencies for T1 configuration

Materials	f_1 **[Hz]**	$\Delta f_1/f^{T0}_1$ **[%]**	f_2 **[Hz]**	$\Delta f_2/f^{T0}_2$ **[%]**	f_3 **[Hz]**	$\Delta f_3/f^{T0}_3$ **[%]**	f_4 **[Hz]**	$\Delta f_4/f^{T0}_4$ **[%]**	f_5 **[Hz]**	$\Delta f_5/f^{T0}_5$ **[%]**
Aluminium Glass	641.55	0.04	866.93	-0.63	2034.00	0.61	2721.30	4.96	4574.70	0.32
GFRP Glass	622.81	1.61	859.44	-0.47	1633.60	2.82	2566.80	6.97	3723.70	0.43
Steel Glass	422.51	-0.23	544.30	-0.68	1364.30	0.70	1973.50	5.42	3165.70	-0.46

TABLE 5. Modal frequencies for T2 configuration

Materials	f_1 **[Hz]**	$\Delta f_1/f^{T0}_1$ **[%]**	f_2 **[Hz]**	$\Delta f_2/f^{T0}_2$ **[%]**	f_3 **[Hz]**	$\Delta f_3/f^{T0}_3$ **[%]**	f_4 **[Hz]**	$\Delta f_4/f^{T0}_4$ **[%]**	f_5 **[Hz]**	$\Delta f_5/f^{T0}_5$ **[%]**
Aluminium Glass	645.69	-0.60	872.45	-1.27	2036.00	0.51	2707.40	5.44	4425.60	3.57
GFRP Glass	623.51	1.53	863.97	-1.00	1620.60	3.59	2547.10	7.68	3557.20	4.88
Steel Glass	425.36	-0.91	548.09	-1.38	1371.30	0.19	1967.30	5.72	3183.90	-1.04

TABLE 6. Modal frequencies for T3 configuration

Materials	f_1 **[Hz]**	$\Delta f_1/f^{T0}_1$ **[%]**	f_2 **[Hz]**	$\Delta f_2/f^{T0}_2$ **[%]**	f_3 **[Hz]**	$\Delta f_3/f^{T0}_3$ **[%]**	f_4 **[Hz]**	$\Delta f_4/f^{T0}_4$ **[%]**	f_5 **[Hz]**	$\Delta f_5/f^{T0}_5$ **[%]**
Aluminium Glass	649.05	-1.13	877.77	-1.89	2035.30	0.55	2691.30	6.01	4180.10	8.92
GFRP Glass	623.12	1.56	868.17	-1.49	1603.50	4.61	2526.30	8.44	3383.60	9.52
Steel Glass	429.76	-1.95	551.70	-2.05	1376.00	-0.15	1959.50	6.09	3063.60	2.78

The variation in T1-T3 configurations compared to T0 configurations is always within 10%. In particular, for the first three modes the variation is always whithin -1.0 and 2.05 %. Greatest variations could be observed in T3 configurations for the GFRP-Glass and Aluminum-Glass combinations (8.92 and 9.52, respectively). An increase in terms of natural frequencies with regard to T0 configuration is similar due to comparable values of density and Young's modulus. Steel-Glass combination does not show a significant increment (2.78%).

The results obtained show that the introduction of an imperfection, which could reduce the stress distributions in the bonded area, does not affect the modal behavior significantlly, especially for the first three modes.

5. CONCLUSIONS

The adhesive joints represent a viable alternative to the classic joining methods. In the design and control of a structural element, the modal analysis (frequency and modal shape) of the adhesive joint is of great importance. The study of the modal analysis of the adhesive joint is necessary in the design and monitoring process of the joint. The study of natural frequencies provides the designer with an indication of how the joint will respond to different dynamic loads. This aspect finds several applications (e.g. naval, areonautical), where dynamic behaviour plays a fundamental role in the design and service life phase. The modal analysis makes it possible to avoid resonance phenomena at a specific frequency. Previous studies, concerning static load conditions, aimed to determine how to reduce the stress peaks commonly present in the edges of bonded regions. It has been demonstrated that the introduction of a slot in the middle adherend enables these stress peaks to be reduced. The novel concept introduced in this study is to consider not only the static response of the joint, but the dynamic behavior as well. The main aim of this study is to consider the modal analysis of a double-lap joint both in the perfect adherends configuration and in the one with imperfections (i.e. slot) in the inner adherend. The results illustrated in this paper show the correlation between natural frequencies and mechanical (i.e. elastic modulus) and material (i.e. material density) parameters.

The similarity between elastic modulus and density characteristics is reflected in the frequencies and modes of vibration. It has also been observed that the introduction of imperfections makes it possible to reduce the stress peaks at the edges of the bonded region without modifying either the shapes or the natural frequencies for the most significant modes of vibration (i.e. the first modes of vibration).

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Persian Abstract

چکیده

اتصالات چسب جایگزین مناسبی برای روشهای اتصال سنتی است. تجزیه و تحلیل فرکانس ها و اشکال معین برای پیش بینی رفتار ارتعاش یک جزء ساختاری در معرض استرس پویا اساسی است. مطالعات بسیاری در ادبیات برای تعیین روند استرس در منطقه پیوندی وجود دارد. ثابت شده است که ورود یک شکاف در چسبندگی داخلی باعث کاهش مقدار استرس در لبه های منطقه چسب می شود. در این مقاله ، تأثیر نواقص موجود در پیوند مرکزی با تجزیه و تحلیل FEM بررسی شده است. از نرم افزار FE ANSYS © 19 برای آنالیز مفاصل اتصالات چسب دو دامان استفاده می شود و پنج حالت اول در نظر گرفته می شود. نتایج نشان می دهد که تأثیر مدول و نسبت چگالی یانگ در فرکانسهای طبیعی متفاوت است. علاوه بر این ، معرفی نقص با افزایش فرکانس ، بر رفتار ارتعاشی تأثیر می گذارد. همچنین مشاهده می شود که کاهش جرم به دلیل معرفی ترک باعث تغییر شکل و فرکانس مودال برای مهمترین حالت ها نمی شود ، در حالی که باعث تغییرات مهم تر برای آخرین حالت ارتعاشی می شود. بنابراین معرفی ترک باعث تغییر چشمگیر رفتار پویا در مفصل نمی شود و امکان تحقق توزیع گسترده تر تنش ها را کاهش می دهد و باعث کاهش مقادیر قله های استرس می شود.