A Study Of Interphases Of Adhesive Joints By Ultrasonic Guided Waves

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Abstract

The interlayer between the adhesive and the adherend in an adhesive joint termed the interphase is a critical region responsible for the strength and durability of the joint. A study of this region through non destructive evaluation techniques helps understand the bond quality during in service of the component. The effect of the bonding quality on ultrasonic guided waves is considered here through the dispersion spectra of symmetric waves for different values of the stiffness constant.

Keywords: *guidedwaves, adhesive-adherend, adhesive bonds, dispersion spectra*

1. Introduction

Layered elastic structures are being used with increasing frequency in aerospace and automobile industries. The interface quality between layers in a layered structure is critical in fracture and fatigue analysis [1]. These layered structures are generally formed/fabricated by bonding the two adjacent layers with a layer of adhesive material. Adhesive bonding is attractive as it distributes stress over the entire bond area and thus avoids stress concentrations in a layered composite [2]. The quality of the interfaces of adhesive joints is crucial to these systems and this has led to a large number of studies to understand the nature of the mechanical bond at the interfaces [3]. It is necessary to model the interface more precisely, including the adhesive layer and the possible presence of imperfect bonding resulting in partial slippage between the materials across the interface. The influence of these additional factors on the velocity and other properties of guided waves in the solid needs to be determined theoretically before a reliable Non-destructive evaluation (NDE) technique can be developed [4]. Hence a proper modelling of the imperfect interfaces is of great importance.

In general, an interface can be modelled as a thin layer with certain material properties. For a perfect bond both the upper and lower boundaries of this layer are assumed to transmit continuous displacements and stresses. For imperfect interfaces the stresses and/or displacements are discontinuous across the interface and a jump in these quantities is assumed to model different types of imperfections through adjustable parameters [5]. Despite numerous studies on imperfect interfaces, the nature of the interlayer/interface between the adhesive and the adherend in adhesive joints still needs to be probed as this is one of the major determinants of the strength and durability of the joint.

The imperfect interface between the adhesive and the adherend formed due to inadequate surface preparation of the adherend or due to environmental degradation of the adhesive bond is considered to be a common cause of premature failure of bonded components. Using conventional modelling technique, Cawley [6] introduced a homogeneous isotropic layer of finite thickness between adhesive and adherend. In it the degradation of the interlayer was simulated numerically and was correlated it with two ultrasonic techniques. The properties of this interlayer were assumed to vary as a result of different surface propagation procedures during manufacture or as a result of in-service degradation. To account for the porous nature of the oxide layer, the density of the interlayer was taken to be 33% of the native Al_2O_3 density. Variation in the thickness, shear velocity of the interlayer was carried out to simulate the degradation of the interlayer [6]. In [7] the damaged interfaces were modelled as an array of circular water filled disbond with disbond thickness approaching zero. The disbond was characterized by slip boundary conditions while the non damaged area corresponds to welded boundary conditions. A parameter that describes the homogenized distributed springs over the entire adhesive-adherend interface was used to study the degradation of the interface. A model that helps study the possibility of utilizing measurements on guided wave propagation to detect the interfacial weakness between an adhesive and adherend was presented in [8]. They assume that the normal stress and displacement are continuous across the interface but using a quasi static approach model the shear mechanical behaviour of the interface by a density of springs with stiffness constant (κ) between the adhesive and adherend.

In the present paper we model the adhesive-adherend interface using approach presented in [8] but assuming that the fractional area of disbonding is low, the estimate for (κ) [7] is used to study how the guided wave propagation characteristics are affected by the bonding quality.

2. Theory

The geometry of the adhesively bonded structure considered is shown in fig1. We consider two dimensional harmonic motion of the adherend semi space/ interlayer/ adhesive/ interlayer/ adherend semi space in the x-z plane so that the guided wave has no y dependence in the xyz Cartesian frame. The adherend and adhesive are assumed to be linear, homogeneous and isotropic solids. The harmonic wave is propagating in the x direction with OXZ plane coinciding with the middle of the adhesive layer. The adherend plates are assumed to be semi-infinite. We use ρ^a, λ^a, μ^a to denote the density and lame constants respectively of the material of the adhesive while the ρ^p, λ^p, μ^p to denote the corresponding quantities for the adherend plate. We denote the wave speeds by V_1^p, V_2^p in the adherend plates and by V_1^a, V_2^a in the adhesive. The displacement vector is denoted by U^p, U^a in the plates, adhesive and the corresponding stresses by T_{ij}^p, T_{ij}^a.

The wave equation in elasticity theory for homogeneous isotropic media in terms of the displacement U is

$$\mu^i \nabla^2 U^i + (\lambda^i + \mu^i)\nabla\nabla \bullet U^i = \rho^i \ddot{U}^i \quad \text{-----(1)}$$

where we have assumed that there are no body forces with

$$\mu^i \geq 0,\ (3\lambda^i + 2\mu^i) \geq 0,\ \ i = p, a$$

The stresses are given by

$$T_{ij}^m = \lambda^m \upsilon^m \delta_{ij} + 2\mu^m e_{ij}^m, m = p, a \quad \text{------(2)}$$

The harmonic guided wave propagation in the symmetric wave guide structure with circular frequency θ and phase velocity V (= θ / γ) where γ is the wave number can be split into symmetric and anti symmetric modes. It is to be noted that we have taken identical adherend plates and the symmetric or anti symmetries is with respect to the centre of the adhesive layer. Solving (1) and (2) we write the expressions for the displacements and stresses in the plate and adhesive.

For $Z \geq t^a$

$$U_x^p = (i\gamma A_1 e^{-\alpha_1 z} + \beta_1 B_1 e^{-\beta_1 z}) e^{i(\gamma x - \theta t)} \quad \text{---- (3)}$$

$$U_z^p = (-\alpha_1 A_1 e^{-\alpha_1 z} + i\gamma B_1 e^{-\beta_1 z}) e^{i(\gamma x - \theta t)} \quad \text{----(4)}$$

$$T_{zz}^p = \{\mu^p(\gamma^2 + \beta_1^2) A_1 e^{-\alpha_1 z} - 2\ \mu^p i\gamma\beta_1 B_1 e^{-\beta_1 z}\} e^{i(\gamma x - \theta t)} \quad \text{-----(5)}$$

$$T_{zz}^p = \{-2\mu^p i\gamma\alpha_1 A_1 e^{-\alpha_1 z} - \mu^p(\gamma^2 + \beta_1^2) B_1 e^{-\beta_1 z}\} e^{i(\gamma x - \theta t)} \quad \text{----(6)}$$

where

$$Z = z - t^a, \alpha_1^2 = \gamma^2 - \frac{\theta^2}{(V_1^p)^2}, \beta_1^2 = \gamma^2 - \frac{\theta^2}{(V_2^p)^2}$$

For the upper-half of the adhesive layer, i.e., for

$0 < z < t^a$ we have (dropping $e^{i(\gamma x - \theta t)}$)

$$U_x{}^a = i\gamma[A_0\cosh(\alpha_0 z) + B_0\sinh(\alpha_0 z)] - \beta_0[C_0\sinh(\beta_0 z) + D_0\cosh(\beta_0 z)] \quad \text{---(7)}$$

$$U_z{}^a = \alpha_0[A_0\sinh(\alpha_0 z) + B_0\cosh(\alpha_0 z)] + i\gamma[C_0\cosh(\beta_0 z) + D_0\sinh(\beta_0 z)] \quad \text{----(8)}$$

$$T_{zz}{}^a = \mu^a(\gamma^2 + \beta_0{}^2)[A_0\cosh(\alpha_0 z) + B_0\sinh(\alpha_0 z)] + 2\mu^a i\gamma\beta_0[C_0\sinh(\beta_0 z) + D_0\cosh(\beta_0 z)]$$

----(9)

$$T_{zx}{}^a = 2\mu^a i\gamma\alpha_0[A_0\sinh(\alpha_0 z) + B_0\cosh(\alpha_0 z)] - \mu^a(\gamma^2 + \beta_0{}^2)[C_0\cosh(\beta_0 z) + D_0\sinh(\beta_0 z)]$$

----(10)

where $\alpha_0{}^2 = \gamma^2 - \frac{\theta^2}{(V_1{}^a)^2}$, $\beta_0{}^2 = \gamma^2 - \frac{\theta^2}{(V_2{}^a)^2}$

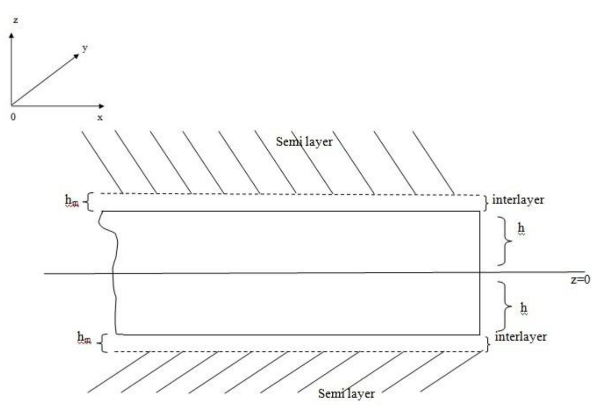

Fig 1

Following [8] the interface between the adhesive and adherend is modelled as a spring-mess structure. The damaged interlayer can be represented as an array of circular water filled disbonds with disbond thickness approaching zero. The properties of the interlayer as a whole can be modelled by spring boundary conditions with the stiffness constant (κ) describing the homogenized distributed springs over the entire adhesive-adherend interlayer [7]. For the simple disbond pattern as shown in **Fig 2** the stiffness constant has been estimated in [9] when the fractured area of disbonding is low.

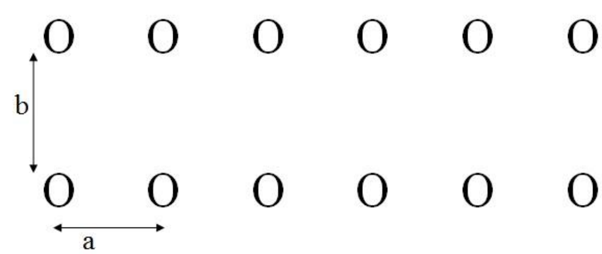

Fig 2

It has been estimated as

$$\kappa = (\frac{2-\nu}{2})\frac{\pi}{8}\frac{E}{1-\nu^2}\frac{1}{a}(1.299723A^{\frac{1}{2}}$$

$$-0.9952365A + 0.66720233A^{\frac{3}{2}} - 0.423089A^2$$

$$+0.1406982A^{\frac{5}{2}} - 0.02954016A^3 + \frac{0.149058A^{\frac{1}{2}}}{1+A^{\frac{1}{2}}}$$

$$-108686\log(1+A^{\frac{1}{2}}) - 0.419904\log(1-A^{\frac{1}{2}}))^{-1}$$

where A is the disbond area fracture given by $A = (a-b)^2/4a^2$ and a is the distance between centres of disbonds. ν is the poisons ratio which is the average of the poisons ratio of adherend and adhesive. E is the effective Young's modulus given by

$$E = \frac{2E_1E_2}{E_2(1-\gamma_1{}^2) + E_1(1-\gamma_2{}^2)}$$

Where E_1, E_2 and γ_1, γ_2 are the Young's moduli and Poisson's ratio of the adherend and adhesive. Further assuming that the ultrasonic wavelength (λ) is much larger than the dimension of the interlayer (h_m). The interface conditions at the interface Z = h are

$$T_{zz}{}^p = T_{zz}{}^a; \;\; U_z{}^p = U_z{}^a$$

$$T_{zx}{}^{p} = -(\kappa + \frac{m}{4}\theta^2)U_x{}^{a} + (\kappa - \frac{m}{4}\theta^2)U_x{}^{p}$$

$$T_{zx}{}^{a} = -(\kappa - \frac{m}{4}\theta^2)U_x{}^{a} + (\kappa + \frac{m}{4}\theta^2)U_x{}^{p}$$

Substituting the expressions for displacements and stresses in the interface conditions. We obtain the dispersion matrix equation

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ A_0 \\ C_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Where

$$a_{11} = \mu^{p}(\gamma^2 + \beta_1{}^2)$$

$$a_{12} = -2\mu^{p} i\gamma\beta_1$$

$$a_{13} = -\mu^{a}(\gamma^2 + \beta_0{}^2)\cosh(\alpha_0 h)$$

$$a_{14} = -2\mu^{a} i\gamma\beta_0 \sinh(\beta_0 h)$$

$$a_{21} = -\alpha_1$$

$$a_{22} = i\gamma$$

$$a_{23} = -i\gamma\cosh(\alpha_0 h)$$

$$a_{24} = \beta_0 \sinh(\beta_0 h)$$

$$a_{31} = [-2\mu^{p} i\gamma\alpha_1 - (\kappa - \frac{m}{4}\theta^2) i\gamma]$$

$$a_{32} = [-\mu^{p}(\gamma^2 + \beta_1{}^2) - (\kappa - \frac{m}{4}\theta^2)\beta_1]$$

$$a_{33} = (\kappa + \frac{m}{4}\theta^2)\alpha_0 \sinh(\alpha_0 h)$$

$$a_{34} = (\kappa + \frac{m}{4}\theta^2) i\gamma\cosh(\beta_0 h)$$

$$a_{41} = -(\kappa + \frac{m}{4}\theta^2) i\gamma$$

$$a_{42} = -(\kappa + \frac{m}{4}\theta^2)\beta_1$$

$$a_{43} = \sinh(\alpha_0 h)[2\mu^{a} i\gamma\alpha_0 + (\kappa - \frac{m}{4}\theta^2)\alpha_0]$$

$$a_{44} = \cosh(\beta_0 h)[-\mu^{a}(\gamma^2 + \beta_0{}^2) + (\kappa - \frac{m}{4}\theta^2) i\gamma]$$

3. Numerical results and discussion

The numerical solution of the dispersion equations for the symmetric modes are graphically presented and discussed in this section. The two semi-spaces i.e. aluminium plates in this case are of type *Al*2024 bonded by the *FM*73 adhesive. The adhesive layer is of 100 µm thicknesses initially and the interlayer between the adhesive and the adherend is of 2.6 µm thicknesses with density 0.87g/l. The physical mechanical properties of the aluminium plate and adhesive are shown in **table1.**

Table 1

	type	Density (g/cc)	Wave velocities (mm/ μ s)		Thickness
			Longitudinal	shear	
adherend	Al2024	2.7	6.32	3.13	Semi-int
adhesive	FM73	1.18	2.25	0.98	100 μ m

The interlayer between the adhesive and the adherend is usually composed of two thin layers and its thickness is therefore varied from 2.6µm to 3.5µm of the two thin layers one is the aluminium oxide layer and the other is the primer layer. The morphology of

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the oxide produced generally resembles a honey comb structure. It is also observed [10] that adhesive often flows into the pores of the oxide structure during the curing process, so forming a micro composite layer. For a simulation we modelled the mechanical properties of this layer with effective properties of aluminium oxide and primer and varying the thickness of the interface. Further assuming that the fractural area of disbonding is low and fining the distance between disbonds (a); the fracture of disbond area (*A*) was varies from 1% to 50% and for this κ varied from 10^{13} to 10^{17} N/m^3. The dispersion spectrum are shown for κ =5.5 x 10^{12} N/m^3 and κ =5.5x 10^{16} N/m^3 that corresponds to 1% and 50% of disbond area.

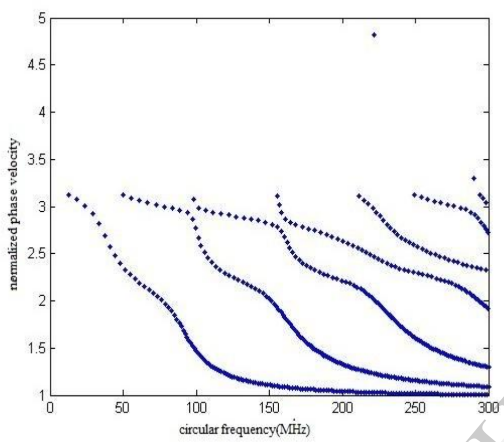

Fig 3: h_m = 0.0026, κ = 5.5 x 10^{12}N/m^3

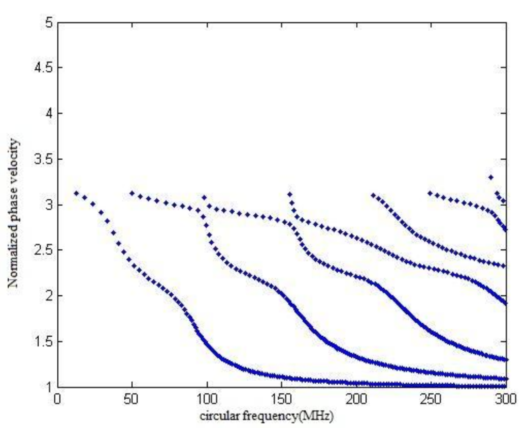

Fig 4: h_m = 0.0035, κ = 5.5 x 10^{12}N/m^3

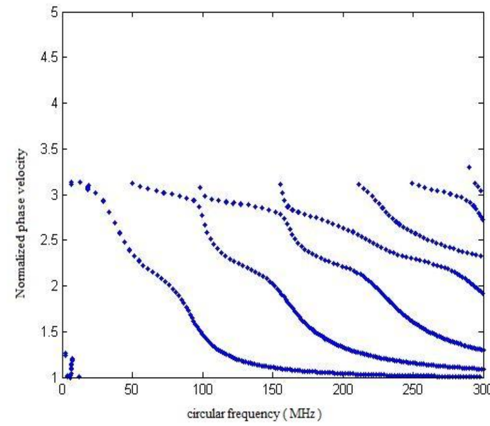

Fig 5: h_m = 0.0026, κ = 5.5 x 10^{16}N/m^3

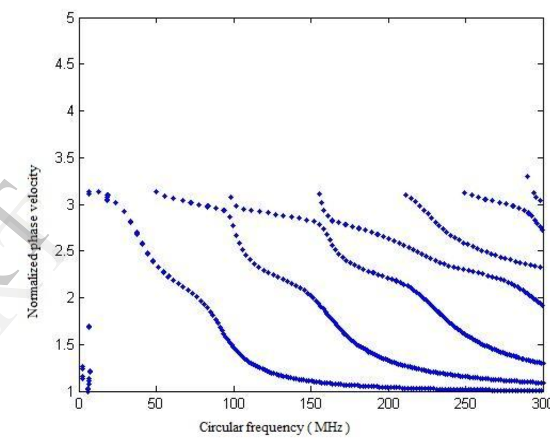

Fig 6: h_m = 0.0035, κ = 5.5 x 10^{16}N/m^3

4. Conclusion

The interlayer between the adhesive and adherend is a major determinant of the strength and durability of the adhesive joint. Ultrasonic non-destructive techniques are a means of evaluating the strength of the bond and characterizing this thin interlayer. The study shows that symmetric guided waves are sensitive to degradation of the thin interlayers and offer a means of characterizing this layer.

5. References

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