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Probabilistic stress variation studies on composite single lap joint using Monte Carlo simulation

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ABSTRACT

The work presented in this paper involves the stochastic finite element analysis of composite-epoxy adhesive lap joints using Monte Carlo simulation. A set of composite adhesive lap joints were prepared and loaded till failure to obtain their strength. The peel and shear strain in the bond line region at different levels of load were obtained using digital image correlation (DIC). The corresponding stresses were computed assuming a plane strain condition. The finite element model was verified by comparing the numerical and experimental stresses. The stresses exhibited a similar behavior and a good correlation was obtained. Further, the finite element model was used to perform the stochastic analysis using Monte Carlo simulation. The parameters influencing stress distribution were provided as a random input variable and the resulting probabilistic variation of maximum peel and shear stresses were studied. It was found that the adhesive modulus and bond line thickness had significant influence on the maximum stress variation. While the adherend thickness had a major influence, the effect of variation in longitudinal and shear modulus on the stresses was found to be little.

1. Introduction

The widespread use of composite materials has propelled the use of structural adhesives to execute the assembly of structures in automotive and aerospace industry. The strength of a bonded joint is influenced by many parameters like the bond-line thickness, surface preparation of the adherend, joint geometry, the type of adhesive and adherend, boundary conditions, service temperature and moisture, etc. These factors also influence the stress distribution in the bondline region, particularly at the edge where the stresses are high [1,2]. Many analytical models have been developed to study the stress distribution in adhesive joints [3–5]. A detailed literature survey on major analytical models for adhesively bonded single lap joints has been provided by da Silva et al. [6]. They have further done a comparative study on different analytical models to comprehend the accuracy and time requirements for different cases [7]. However obtaining an exact solution becomes difficult if the joint geometry is complex or the number of factors to be considered is large. Though stresses can be measured conducting mechanical tests, taking into consideration the number of parameters involved, it becomes expensive in terms of cost and time. These limitations can be overcome using numerical methods like finite element analysis (FEA). It is convenient to study the influence of a change in different parameters on the behavior of a bonded joint using FEA. This reduces the number of tests to be conducted during prototyping and also helps in reducing the time and cost involved during the process.

Numerous studies on the analysis of bonded joints with composite adherends have been published [8–12]. Linear and nonlinear finite element analyses have been carried out on different types of adhesive joints and stresses and strains in the bonded region have been evaluated [13–19]. Banea and da Silva [19] have given a detailed illustration of the contributions made towards finite element analysis of adhesively bonded joints with composite adherends. Haghani et al. [20] carried out a parametric study to investigate the effect of tapering length and the material properties of joint constituents on stress distribution in adhesive joints. Experimental and numerical analysis of single lap joints were also carried out by Grant et al. [21]; they investigated the effects of various parameters such as the overlap length, the bond line thickness and the spew fillet on the bond line stresses. Diaz et al. [22] carried out a benchmark investigation of 3D finite element models of CFRP single lap joints. Pereira et al. [23] studied the effect of geometrical and manufacturing parameters on the strength of adhesively bonded single lap joints with the aim of optimizing shear strength. Neto et al. [24] studied composite single lap joints with different types of adhesives and different overlap lengths using an experimental approach. The results were compared with analytical models to find the suitability of each model to evaluate different joints.

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Many of the previous attempts to study the performance of an adhesive joint have been associated with the development of appropriate failure criteria for improved joint strength predictions [8–12]. The continuum mechanics based approach has been used by many researchers to predict the joint strength [13–16]. This approach is much simpler and uses a maximum stress or strain as a basis for strength prediction. However, a significant amount of uncertainty is associated with the measured peak stresses due to the variation in the influencing parameters. This randomness in the bond line peak stresses have been studied in the present work using finite element based Monte Carlo simulation. A finite element model of the composite epoxy single lap joint was developed and studied using a commercial software ANSYS 10. The stresses computed using the FE model were verified against the experimental stresses obtained using digital image correlation (DIC). The FE model was further used in the Monte Carlo simulation to study the variation in the peak stresses due to variation in the influencing parameters.

2. Materials and samples

Single lap shear joints were prepared as per ASTM D 5868 standard [25] with carbon fiber reinforced plastic (CFRP) as adherend and an epoxy adhesive. The CFRP adherend was fabricated using 14 layers of unidirectional carbon prepreg CP150ns, each having a thickness of 0.18 mm. All the layers were oriented along the same direction to obtain a unidirectional laminate cured in an autoclave as per the curing cycle recommended by the prepreg manufacturer (60 °C for the first 30 min, 125 °C for 90 min and 7 bar external pressure with vacuum). The laminate was then cut to the required size of 101.6 mm × 25.4 mm. Surface preparation in the region to be bonded was carried out according to ASTM D 2093 standard [26]. An area of 25.4 mm × 25.4 mm was bonded using the two part epoxy adhesive system (Araldite AV138M/Hardener HV 998). The resin and hardener were mixed in the ratio of 100:40 as per the manufacturer's recommendation and cured for 24 h at room temperature. The required material properties of the adherend and the adhesive were measured using mechanical tests and ultrasonic inspection [27] and are summarized in Table 1. A uniform bond line thickness of 0.76 mm was maintained using a mold as per the requirement for ASTM D 5868 standard [25]. The dimensions of the resulting composite lap shear joint are shown in Fig. 1. A total of six samples were prepared and further tested to determine their strength.

3. Determination of bond line stresses using digital image correlation

Digital image correlation (DIC) is a non-contact optical method that involves capturing of digital images of a surface and performing the image analysis to obtain full-field deformation measurements [28]. This can be accomplished using different types of

Table 1
Material properties of CFRP adherend and epoxy adhesive.

Material property	CFRP adherend	Epoxy adhesive
Longitudinal modulus E_1 (GPa)	140	4.7 (E)
Transverse modulus $E_2 = E_3$ (GPa)	12	–
Poisson's ratio ($\nu_{12} = \nu_{13}$)	0.32	0.38 (ν)
Poisson's ratio (ν_{23})	0.28	–
Shear modulus $G_{12} = G_{13}$ (GPa)	5.4	3.0 (G)
Shear modulus G_{23} (GPa)	4.5	–
Density ρ (Kg/m^3)	1700	1548
Longitudinal strength (MPa)	1480	43
Transverse strength (MPa)	48	–
In plane shear strength (MPa)	68	–

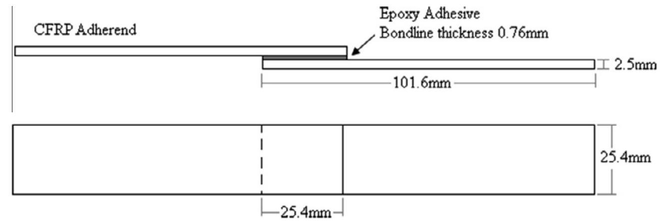

Fig. 1. CFRP-epoxy single lap shear joint.

patterns created on the surface like lines, grids, dots and random arrays. However, the most widely used pattern is called the speckle pattern which is a random distribution of dots. The technique involves image matching algorithms that take into account the deformation processes to evaluate the changes in surface characteristics and understand the behavior of the specimen while it is subjected to incremental loads. An initial reference image is captured before the application of any load and then a series of images are captured at different load levels. The images of a deformed surface show a different speckle pattern compared to the pattern in the reference image. These differences between patterns can be calculated by correlating the pixels of the reference image and any deformed image, and a full field displacement measurement can be obtained. The strain distribution can further be obtained by interpolating the displacement field and applying the derivatives.

Attempts have been made in the past to measure stresses and strains in the adhesive joints. Tsai and Morton [29] have experimentally obtained the stress distribution in the bond line region of a composite single lap joints using moiré interferometry and have compared the results with a 2D nonlinear finite element method. Ruiz et al. [30] have carried out numerical and experimental investigation of three-dimensional strains in adhesively bonded double lap shear joints subjected to tensile load using neutron diffraction and moiré interferometry. Some attempts to use DIC to evaluate composite structures and adhesive joints have also been reported [31–33]. Colavito et al. [31] have given a detailed presentation on refinements to be made to DIC technique to extract adhesive strains in lap joints. Katnam et al. [34] experimentally investigated the effect of adhesive ductility on the joint strength. They have shown that DIC can be used as an effective tool to study the damage initiation in composite bonded joints.

The adhesive joint samples were loaded in a testing machine till failure at a cross head speed of 2 mm/min. The machine was programmed to stop at incremental load of 0.5 kN, in order to capture digital images. Proper illumination was provided using fluorescent lamps. Images were recorded using a digital camera having a resolution of 16 megapixel and 10× optical zoom. The images were then processed in a commercial DIC software viz., VIC-2D to obtain strains in the adhesive bond line. Figs. 2 and 3 show the distribution of peel strain and shear strain respectively for the adhesive lap joint at different levels of load. It can be observed that as the load increases the strains in the adhesive layer also increases and attains a maximum value near failure. Further, the magnitude of peel and shear strain is very high at the bond line edges as compared to the other regions.

Fig. 4 shows the variation of adhesive strain along the bond line region of the adhesive lap joint. The percentage peel and shear strain are plotted against the ratio 'y/c', where 'y' is a coordinate value which is zero at the center of bond line and attains a maximum value of 12.7 and −12.7 at the right and left edges respectively, 'c' is half the total bond line length i.e., c = 12.7 mm. The peel strain values seen in the figure correspond to the strain at failure (i.e., at maximum load). It can be seen that peel strain is maximum at the bond line edge and minimum (close to zero) at the