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Mechanical behavior of interlocking multi-stepped double scarf adhesive joints including void and disbond effects

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ABSTRACT

Surface topographical effects on the mechanical behavior of interlocking multi-stepped double scarf adhesive joints under tensile load were studied. For this purpose, finite element analysis (FEA) of the joint geometry at 10 different step angles was carried out. In the second stage, the effects of substrate voids and adhesive delaminations on the interfacial strength were studied for the scarf angle of 32.2° by FEA simulation as well as experimentally. For the cases of the missing steps (voids) and delamination (absence of bonding induced by release agent) the ratios of maximum stresses (principal, von Mises, normal, shear and transverse) between the completely bonded and altered (void or delaminated) joints were compared with the failure load ratios for the same joints to interpret the mechanism of failure. The results revealed that except for the normal stress, the maximum stress ratios reach a maximum value and then decrease with increasing scarf angle. FEA analysis with the voids showed that the strength of the joint not only depends on their size, but also on their location in the joint. When the experimental results were compared with the FEA using the stress ratio between the unmodified (completely bonded) and modified (void or disbond) cases, the results indicated that the normal stress dominates the failure behavior of the 32.2° scarf angle joint. Comparison of the experimental results for the void, and disbond cases revealed that the disbond cases can possess higher joint strength in comparison to the void cases. This finding could not be predicted by FEA, and was attributed to the presence of friction at the interface subsequent to delamination.

1. Introduction

Wide applicability of adhesives means that their adherends vary widely both chemically and physically. Scanning electron microscopy (SEM) and profilometry on adherend surfaces can easily show that most engineering material surfaces are rough, to a degree, as we examine them at larger magnifications. Furthermore, surface treatments used to improve adhesion typically result in roughening of adherend surfaces.

Not only the average roughness but also the geometry of the adherend surface topographies are expected to affect the resulting joint strength. For example, Keisler and Latailade [1] reported that “the micro-geometry of the substrate surface needs to be taken into account if one is interested in the influence of the roughness”. Their results showed that the shear strength of the adhesive joint was maximum when their substrates possessed “an optimum surface morphology”. Such optimum surface morphology was related to “the average roughness R(a), the width of valleys, and the dominance of valleys or peaks”. The interphase, which exists between the adhesive and the adherend, has properties different from those of the bulk adhesive, or the adherend [2,3], because of the action of the mechanical and chemical adhesion processes, adherend surface treatment, and surface topography. In most engineering joints the adherend surfaces have distinct topographies [4–8], which result in a collection of miniature joints in micron, and even nano scale when bonded adhesively. Numerical simulations have been performed on the effects of surface roughness and the influence of geometry on adhesive bond strength and performance of structural adhesive joints [9]. These simulations considered roughness, stress distribution, and contact area to discern qualitative influence of substrate topography on the adhesion of a joint and interpenetration of materials on the mechanical properties of the interphase by assuming continuity of displacements at the substrate/adhesive interface. If the interphase is not considered as a discrete collection of individual chemical bonds, the methods of continuum mechanics can still be applied to this collection of miniature joints by assuming continuous, or a combination of continuous/discontinuous interphase zones [6–8,10]. Thus, the displacement at the interphase need not be continuous at every location. The analysis of a miniature joint contributing to the overall adhesion in a macro joint can be performed in a fashion similar to that for the macro joint itself [2,3], which is usually studied with the employment of the methods of elasticity, viscoelasticity, plasticity, fracture, damage, and/or failure, mechanics.

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This investigation also has significance in understanding the state of stress in interlocking stepped-butt joints as it relates to macroscopic cases, for example, as seen in aircraft applications, at the same time as it relates to the understanding of the bonding effects with or without voids and/or delaminations in mechanical adhesion. For these purposes optimization of the geometry of such interlocking stepped-butt joints is done by using different FEA models. Experiments are also conducted to validate the results of the simulations. The effects of substrate voids on the state of stress in the stepped-butt joint is also investigated. The states of stresses are studied for bonded stepped joints containing different void levels, and the stress levels are evaluated for different locations and verified experimentally. In this way a rigorous analysis of interlocking stepped-butt joints, and the surface topography they represent is performed including any void and/or delamination effects.

Such a study is significant in further development of aircraft or primarily lightweight structures as well as in assessment of different surface preparation techniques for optimum adhesion. Typical macro applications of these cases involve the F-18 aircraft and its wing joints. Graphite reinforced epoxy is used for the wing bending material in the form of top and bottom wing cover plates or skins. These are bonded to the titanium fittings at the sides of the fuselage. The joint is similar to the stepped-butt configuration considered in this study. Furthermore, based on our earlier observations on surface profiles obtained from hot rolled and cold rolled steel specimens treated by chemical etching or sand blasting [11], we propose to approximate such topographies by a collection of single and/or multiple scarf, lap, or butt sections, which can be in stepped and/or straight configurations. Such multi-stepped double scarf joints containing voids, and disbonds can be used to shed more light into the behavior of joints, which are not fully wetted, and contain void and/or disbond sections as a result. Thus a fundamental basis can easily be established for the present study on the effects of changing the joint geometry to optimize an interlocking stepped-butt joint. The use of this work lays down a framework from which different improvements and ideas could be implemented in any application utilizing adhesive bonding since, ultimately, the results can be related to surface preparation effects when the interlocking geometries are considered in a smaller scale.

1.1. Statement of purpose

In this paper, novel analysis techniques are presented to help us to incorporate the effects of the adherend surface topography as a discrete entity in the adhesive joint composite. For this purpose, examples of multi-stepped double scarf joints with void, and disbond effects will be illustrated to shed more light into the behavior of joints, which are not fully wetted, and contain void and/or disbond sections as a result. This study also sheds light into the surface topographical effects in mechanical adhesion when considered in a smaller scale.

The main objective of this study is to assess surface topographical effects on mechanical adhesion for the case of stepped joints under tensile load. For this purpose, finite element analysis (FEA) of interlocking stepped-butt joints is performed for a variety of conditions. The effect on the state of stress in the adherend–adhesive interface along the joint is evaluated for 10 different interlocking butt joint scarf angles by making use of the FEA pre and post processor ALGOR® and the Superview III Model generator, and verified experimentally. The effects of the change in the substrate volume i.e., void effects, are also investigated both by FEA and experimentally. Finally the effect of delamination (absence of bonding induced by release agent) of the adhesive is studied again using the FEA as well as experimentation. For the cases of the missing steps (voids) and delamination, the ratios of maximum stresses (principal, von Mises, normal, shear and transverse) between the completely bonded and altered (void or delaminated) joints are compared to the intensities of failure loads for the same joints to access the cause of failure. The ultimate goal is to shed light into the surface topographical effects in mechanical adhesion of stepped interlocks loaded under tension, and with or without voids and/or delamination.

2. Materials, experimental and analytical procedures

2.1. Finite element analysis

2-D finite element models were constructed using the finite element method for aluminum substrate stepped-joints bonded with epoxy adhesive. The stress distributions were obtained in different configurations of adhesive joints. Preprocessing, solving and post-processing were done using the software package, ALGOR®. The joints were under a tensile distributed load and the state of stress was assumed to be plane stress. All models incorporated 2-D, quadratic, isotropic elements with six degrees of freedom per node and a few triangular elements to fit the geometry. Thus, finite element models were developed and validated for stepped-butt joints at different scarf angles (0°, 3.6°, 14.1°, 23.8°, 32.2°, 39.3°, 50.1°, 57.5°, 69.7° and 73.9°) having an adhesive thickness of 0.2 mm, and subjected to tensile loading and various geometrical conditions to include void and delamination phenomena boundary conditions. Void effects were studied using FEA models for 32.2° stepped-butt joints having different substrate volumes with 2.37, 5.2, 9.95, 15.6, 27.7, and 40.7% reduction in substrate volume to simulate void conditions in bonded joints by using missing steps.

2.1.1. Loading conditions and materials

A uniformly distributed tensile load of 1 kN was applied across end meshes of the joint. The model adherend and adhesive materials used were aluminum (6061-T6) (Table 1) and Shell EPON® 815C epoxy resin containing bisphenol A and *N*-butyl glycidyl ether (Table 2). The curing agent for this resin was Shell EPI-CURE® 3223, also known as DETA—diethyleneamine, which was added to the adhesive formulation 11% by weight.

For the nonlinear analysis, the material is considered to be in the elastic region with a linear stress–strain curve. The first slope in the stress–strain curve is referred to as Young's modulus. Beyond the yield point a second modulus is utilized referred to as E2. The two elastic moduli values, E1, E2, the yield stress, S_y,

Table 1
Material properties for aluminum adherend 6061-T6.

Mass density	2.65×103 kg/m^3
E1	71 GPa
E2	9.5 GPa
S_y yield stress	275 MPa
Poisson's ratio	0.33

Table 2
Material properties for epoxy based EPON 815 adhesive.

Mass density	1.25×10^3 kg/m^3
E1	3.098 GPa
E2	1.6 GPa
S_y yield stress	37 MPa
Poisson's ratio	0.39