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Stress Analysis of Adhesively Bonded Double-Lap Joints Subjected to Combined Loading

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***Abstract*—**Adhesively bonded joints are preferred over the conventional methods of joining such as riveting, welding, bolting and soldering. Some of the main advantages of adhesive joints compared to conventional joints are the ability to join dissimilar materials and damage-sensitive materials, better stress distribution, weight reduction, fabrication of complicated shapes, excellent thermal and insulation properties, vibration response and enhanced damping control, smoother aerodynamic surfaces and an improvement in corrosion and fatigue resistance. This paper presents the behavior of adhesively bonded joints subjected to combined thermal loadings, using the numerical methods. The joint configuration considers aluminum as central adherend with six different outer adherends including aluminum, steel, titanium, boron-epoxy, unidirectional graphite-epoxy and cross-ply graphite-epoxy and epoxy-based adhesives. Free expansion of the joint in x direction was permitted and stresses in adhesive layer and interfaces calculated for different adherends.

***Keywords*—**Thermal stress, patch repair, Adhesive joint, Finite-element analysis.

I. Introduction

In many applications adhesively bonded joints are more suitable than traditional joining techniques such as mechanical fastening, especially for components made from composite or polymeric materials, because they can provide uniform distribution of load, resulting in better damage tolerance and excellent fatigue life. Whereas adhesively bonded joints and bonded repairs made to cracked metallic structures have been continuously receiving attention in the aerospace industry for the purpose of enhancing fatigue resistance and restoring the stiffness and strength of damaged/cracked structures, the effective use of adhesive bonding technology in primary structural members is still in its infancy. Because of the involvements of many geometric, material and fabrication variables, and complex failure modes and mechanics presented in the joints, a deep understanding of the failure behaviour of adhesively bonded joints, particularly under combined loading conditions, is needed in order to fully achieve the benefits of adhesive bonding. There are several typical failure modes associated with adherends and adhesive in adhesively bonded composite repairs including substrate yielding, patch fibre breaking in tension, fibre failing in compression, adhesive shearing, substrate-adhesive peeling, patch-adhesive peeling, patch interlaminar peeling, and patch interlaminar shearing. Since substrate yield is not a catastrophic failure mode, an optimal design will focus on other failure modes associated with the patch and adhesive [1-9].

The failures in adhesively bonded joints are mainly of two types, adhesive and cohesive; occurring mainly due to interfacial (adhesive) cracking, also called debonding, at geometric boundaries due to stress concentrations, or resulting from faulty joining in fabrication. Well-bonded joints should fail within the adhesive (cohesive) or within the adherends (interlaminar failure) when broken apart. Failure at the adherend-adhesive interface (interfacial failure) generally indicates that the bond was not performed properly. Stress-based concepts provide a realistic description of the stresses and strains and information on the physical cause for material rupture. In order to explain the mechanical behaviors of adhesively bonded joints and develop a failure prediction method it is useful to be able to predict the stresses acting in the joint. Nominal adhesive peel and shear stresses are related to mode-I and mode-II deformation of the adhesive layer, respectively. Stress-based approaches, which focus on indicating both shear and normal (peel) stresses through standard lap shear tests, have been the subject of a vast amount of researches [2, 3, 9-11].

Adhesive bonding usually requires curing of adhesive at temperature higher than applied condition. When two adherend have dissimilar material properties and subsequently having mismatch coefficients of thermal expansions, the curing process create residual stress in jointed materials, such situations generally are produced when one adherend is made of composite material and another is metallic material. Composite patch commonly used in aerospace industry particularly in cracked metallic structures, are subjected to thermal loading due to difference in the operating temperature of the aircraft in flight time or bonding process due to curing of the adhesive. Accurate computational thermal stress analysis is particularly important for estimation of the servicelife of bonded joints and repairs [6-11]. In this study, a finite element thermal stress analysis was conducted in order to investigate the behavior of adhesively bonded joints using double-lap joints.

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II. Stress Based Analysis

J-integral and stress intensity factors concepts do not provide a realistic description of the stresses and strains and information on the physical cause for material rupture. Two dimensional stress analysis approaches have been proposed for double-lap bonded joints with and without tapered patches. These two dimensional models have good accuracy in stress calculations including the effects of shearing and peeling stresses. The behaviour of bonded joints is examined based on the results of stress analysis and failure prediction using a quasi two-dimensional model. In this study, double-lap joint configurations which simulate the problems of bonded patch repair such as fatigue enhancement and crack patching were considered.

III. Description of Material Properties

This study examined a number of different substrates including aluminum, steel, titanium, boron-epoxy, unidirectional graphite-epoxy and cross-ply graphite-epoxy. Epoxy-based adhesives, FM®73 were investigated.

The thermoelastic constants of adherends and adhesives used in FEM analyses are summarized in Table I [9, 11]. For composite materials, 1 is the direction parallel to the fibre and 2 and 3 are the directions transverse to the fibres, while the direction of the x coincides with the fibre direction. The adhesives and adherends were chosen because of their use in aerospace applications. The double-lap joints considered in Fig. 1 are composed of three adherends bonded by an adhesive.

The upper and lower adherends, the central adherend and the adhesive layer are assumed to have thicknesses of t_1, t_2 and t_3, respectively. The patch length and the overall length were L_2 and L_1 respectively. The adherends are made of materials with thermoelastic constants E_1, ν_1, $\alpha 1$ and E_2, ν_2, $\alpha 2$ and the adhesive has properties of E_3, ν_3 and α 3. A uniform stress of σ^{∞}=200 MPa was applied at the free end and uniform temperature variation ΔT=-55C° was applied at whole model. Geometric variables are given as the following: t_1=3.5 mm, t_2=6.4 mm, t_3=0.4 mm, L_2=100 mm, L1= 200 mm.

IV. Finite Element Model

The double-lap joints considered in Fig. 1 are composed of three adherends bonded by an adhesive. The adhesive and adherends are assumed to be linear elastic. The 0.4 mm thick adhesive bond line was divided into eight layers. Finite element analyses of double-lap joints were performed to calculate stresses in the joints using ABAQUS software. The respective patterns of full finite element meshes of double lap joints are shown in Fig. 2. The entire specimen was modeled using an eight nodes quadrilateral element and the mesh was refined in the adhesive layer. To simulate stress variation through adhesive thickness, nine elements were placed across the 0.4 mm thick adhesive layer. The size of the smallest elements in the adhesive layer was found almost 0.04 mm. Further away from the adhesive layer, the adherend element was changed gradually and the aspect ratio of elements was kept below 3. It has been found that the calculated stresses in the joint used here did not vary when the number of the bond line thickness elements was doubled. The dimensions and material properties of the double-lap joint considered here are listed in Table I and Fig. 1. All calculations were performed under plane strain conditions.

V. Results and Discussion

The effects of adherends on the stresses were studied using double-lap geometry. The central adherend was aluminum and the adhesive was FM®73. The problem was solved by considering joints with various lower and upper adherends. This study examined a number of different substrates including aluminum, steel, titanium, boron-epoxy, unidirectional graphite-epoxy and cross-ply graphite-epoxy. The effects of adherend properties on the stresses distribution of the double-lap joint are shown in Fig. 3 which the simple protracted lines in this fig indicate minimum of magnitude and the solid protracted lines indicate maximum of magnitude. The maximum peel and shear stresses for different adherends are summarized in Tables II–VII. Isotropic adherends with different properties were found to have significant effects on the maximum shear and peel stresses, so that maximum peel stresses in combined and thermal loading and shear stresses in pure thermal loading increases, maximum shear stress in combined loading decreases for adhesive layer as the adherend modulus increases (Table II). Maximum shear and peel stresses in combined and thermal loading for interfacial line into central adherend increases as the adherend modulus increases (Table VI). For interfacial line into upper adherend maximum peel stress decreases and shear stress increases as the adherend modulus increases (Table IV). Cracks always initiated in the fixed end into upper and lower adherends in the cases which upper and lower adherend made of isotropic material. Therefore the stiffer adherend leads to a decrease in strength of the joint .The effect of composite adherend lay-up on the stresses in the joint is shown by comparing the maximum stresses along the adhesive and interface bond lines (Table III and VII). It can be seen that increasing the stiffness of the adherend (in the longitudinal direction) has increased significantly the stress concentration in the interface in the fixed end within interface between adhesive and central adherend. This indicates an increase in strength of the joint when multidirectional adherend is used. The maximum peel and shear stresses along critical line(interface between central adherend and adhesive) decreases as the adherend modulus increases for combined loading and increases for pure thermal loading. The cracks always initiated in the fixed end within interface between central adherend and adhesive.

TABLE I
THERMOELASTIC PROPERTIES OF ADHESIVE AND ADHERENDS

Material	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]	$\alpha 1$ $\times 10^{6}/^{\circ}C$	$\alpha 2$ $\times 10^{6}/^{\circ}C$	$\alpha 3$ $\times 10^{6}/^{\circ}C$	υ_{12}	υ_{13}	υ_{23}
FM®73	2.295	2.295	2.295	0.8	0.8	0.8	80	80	80	0.35	0.35	0.3
Steel	207	207	207	79.6	79.6	79.6	11	11	11	0.3	0.3	0.3
Titanium	110	110	110	42	42	42	10	10	10	031	0.31	0.3
Aluminum	72	72	72	27	27	27	23	23	23	0.33	0.33	0.33
Boron-epoxy	193.06	18.617	18.617	5.516	5.516	7.757	4.5	23	23	0.21	0.21	0.2
UD Graphite-epoxy	132.7	8.83	8.83	4.76	4.76	3.4	0.02	22.5	22.5	0.36	0.36	0.3
CP Graphite-epoxy	71.2	71.2	8.83	4.76	4.0	4.0	0.02	0.02	22.5	0.045	0.32	0.32

TABLE II
MAXIMUM PEEL AND SHEAR STRESSES FOR DIFFERENT ISOTROPIC ADHERENDS IN ADHESIVE LAYER

Material	**Aluminum**	**Titanium**	**Steel**
Max. Peel Stress (MPa). Combine Load	55.78	53.66	57.76
Max. Shear Stress (MPa). Combine Load	-35.02	-24.25	-29.51
Max. Peel Stress (MPa). Pure Thermal Load	44.35	43.75	50.17
Max. Shear Stress (MPa). Pure Thermal Load	-5.532	15.33	16.39

TABLE III
MAXIMUM PEEL AND SHEAR STRESSES FOR DIFFERENT COMPOSITE ADHERENDS IN ADHESIVE LAYER

Material	**CP Gr-Epoxy**	**UD Gr-Epoxy**	**Boron-Epoxy**
Max. Peel Stress (MPa). Combine Load	37.69	35.85	38.81
Max. Shear Stress (MPa). Combine Load	-10.89	-11.87	-16.88
Max. Peel Stress (MPa). Pure Thermal Load	35.72	-35.15	35.72
Max. Shear Stress (MPa). Pure Thermal Load	22.09	23.15	22.09

TABLE IV
MAXIMUM PEEL AND SHEAR STRESSES FOR DIFFERENT ISOTROPIC ADHERENDS AT INTERFACE BETWEEN UPPER ADHEREND AND ADHESIVE

Material	**Aluminum**	**Titanium**	**Steel**
Max. Peel Stress (MPa).Combine Load	103	52.88	90.34
Max. Shear Stress (MPa).Combine Load	28.64	-25.49	-29.73
Max. Peel Stress (MPa).Pure Thermal Load	72.76	42.77	49.59
Max. Shear Stress (MPa).Pure Thermal Load	-17.31	-40.36	-25.49

TABLE V
MAXIMUM PEEL AND SHEAR STRESSES FOR DIFFERENT COMPOSITE ADHERENDS AT INTERFACE BETWEEN UPPER ADHERENDT AND ADHESIVE

Material	CP Gr-Epoxy	UD Gr-Epoxy	Boron-Epoxy
Max. Peel Stress [MPa]. Combine Load	32.28	28.41	34.68
Max. Shear Stress [MPa]. Combine Load	-32.42	-33.02	-28.03
Max. Peel Stress [MPa]. Pure Thermal Load	31.4	24.3	31.4
Max. Shear Stress [MPa]. Pure Thermal Load	-25.66	-30.3	-25.66

TABLE VI
MAXIMUM PEEL AND SHEAR STRESSES FOR DIFFERENT ISOTROPIC ADHERENDS AT INTERFACE BETWEEN CENTRAL ADHEREND AND ADHESIVE

Material	Aluminum	Titanium	Steel
Max. Peel Stress (MPa).Combine Load	183.4	197.3	186.4
Max. Shear Stress (MPa).Combine Load	-118.8	-131.9	-120.7
Max. Peel Stress (MPa).Pure Thermal Load	133.8	157.3	160.4
Max. Shear Stress (MPa).Pure Thermal Load	-82.65	-103.1	-102.4

TABLE VII
MAXIMUM PEEL AND SHEAR STRESSES FOR DIFFERENT COMPOSITE ADHERENDS AT INTERFACE BETWEEN CENTRAL ADHEREND AND ADHESIVE

Material	CP Gr-Epoxy	UD Gr-Epoxy	Boron-Epoxy
Max. Peel Stress (MPa). Combine Load	222.8	218.4	209.5
Max. Shear Stress (MPa). Combine Load	-162.9	-160.7	-149.7
Max. Peel Stress (MPa). Pure Thermal Load	168.8	179.5	178.8
Max. Shear Stress (MPa). Pure Thermal Load	-120.5	-130.4	-125.8

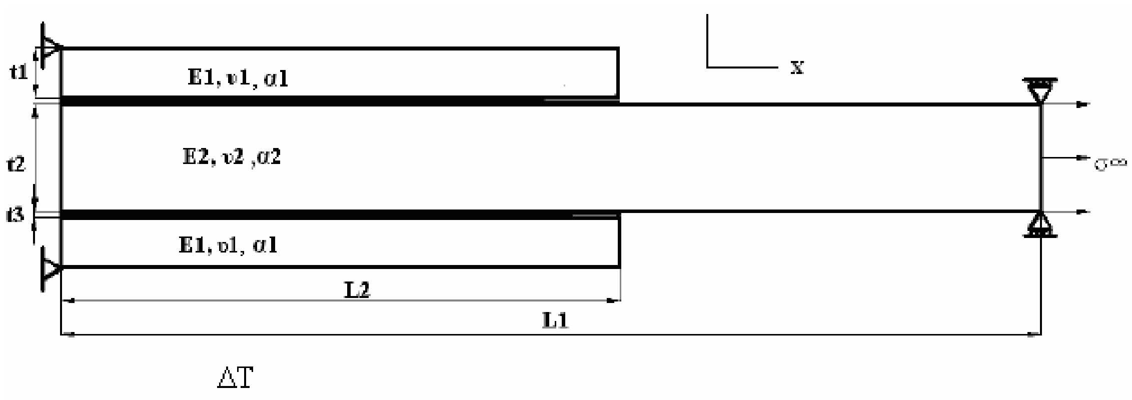

Fig. 1 Geometry of the double-lap joints

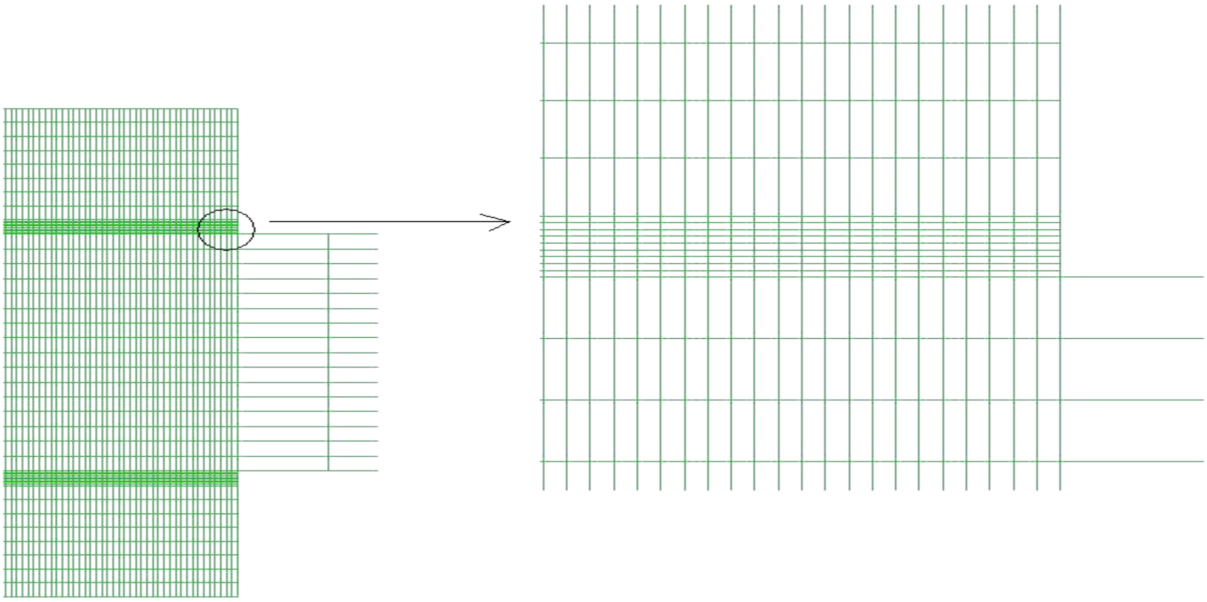

Fig. 2 Finite element mesh pattern of double lap joint

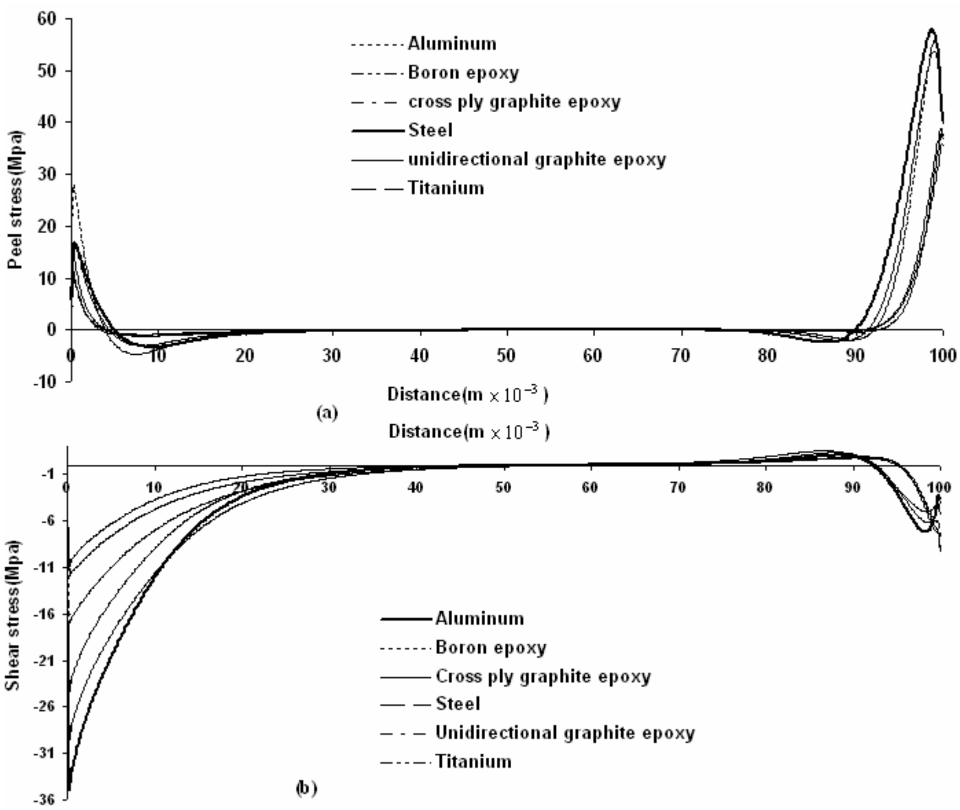

Fig. 3 (a) Peel stress (b) Shear Stress along the adhesive layer with different properties of patches versus distance measured from the patch termination for combine loading situation

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