INCAST 2008-096

FAILURE PREDICTION OF ADHESIVELY BONDED LAP JOINTS BETWEEN METAL AND COMPOSITE ADHERENDS

P. K. Sahoo[1, *], C. M. Manjunatha[2], B. Dattaguru[3]
[1] Structural Integrity Group, Structural Technologies Division, National Aerospace Laboratories, Bangalore, India, pks@css.nal.res.in
[2] Structural Integrity Group, Structural Technologies Division, National Aerospace Laboratories, Bangalore, India, manjucm@css.nal.res.in
[3] Aerospace Engineering Department, Indian Institute of Science, Bangalore, India, datgur@aero.iisc.ernet.in

ABSTRACT: Most of the modern civilian or military aircrafts use advanced composite materials for their primary structural components, in addition to metals. The components are joined together by using either fastener or adhesively bonded joints. But with the introduction of composite materials in aircraft industries, adhesively bonded lap joints are most preferred. This is due to the fact that they develop smooth load transfer and fewer points of stress concentration as compared to fastener joints. The failure prediction of such joints is extremely important, to avoid catastrophic failures during aircraft service period. In the present investigation, an adhesively bonded lap joint between metal-composite (i.e., Al 2024-T3/CFRP) adherends bonded with Redux 319-A adhesive has been analyzed using finite element method considering geometric non-linearity and incorporating adhesive material nonlinear behavior. The failure has been predicted using plastic zone size criterion of adhesive material, which is innovative approach of this study. Also, experimental program is carried out on such joints to correlate with the predicted failure load obtained from numerical model. In this study, the failure of joint is assumed to take place due to adhesive failure only. Plastic zone size in adhesive at failure load of joint is taken as 15 % of the lap length as established from the previous work of the authors. It is observed that the failure load of the adhesively bonded lap joint between composite-metal adherends as obtained from numerical model is well compared with that obtained from experimental study. Results are discussed.

Keywords: Adhesively bonded lap joint, Composite-metal Adherends, Geometric and material non-linear finite element analysis, ASTM D3165, Elastic-perfectly plastic model and Plastic zone size.

1. INTRODUCTION

Most of the modern civilian or military aircrafts use the composite material for their primary structural components, in addition to metal. The components are joined together by using either fastener or adhesively bonded joints. Adhesively bonded lap joints are most preferred, because they develop smooth load transfer and have fewer points of stress concentration as compared to fastener joints. The failure prediction of such joints is extremely important since their failure might lead to catastrophic accidents of aircraft during its service period. Hence, failure prediction of such joints supplemented by testing is required to ensure the safety of aircraft.

Maximum point stress criterion using linear elastic material model to predict the failure has been used by many investigators in the past[1]. They had used 1D, 2D or 3D approximations of joint configuration. Among these 2D and 3D idealization of the joint could give better estimates of the joint strength. Gopalan [2] used average shear stress criterion up to a characteristic distance from the bond end to predict failure of single lap joints. Maximum Von Mises stress criterion at a characteristic distance away from the lap end has been used by the authors in their previous work [3]. Further, there is a need to include both geometric

* Corresponding Author: Tel: 080-25086342: Email: pks@css.nal.res.in / p_sahoo@hotmail.com

non-linear behaviour arising due to eccentricity of load path and material non- linear behaviour of adhesive due to non-linear stress-strain behaviour at high load levels.

In the present investigation, an adhesively bonded lap joint between metal/composite (i.e., Al 2024-T3/CFRP) adherends bonded with Redux 319-A adhesive has been analyzed using finite element method considering geometric non-linearity and also incorporating adhesive material nonlinear behavior. The failure has been predicted using plastic zone size criterion of adhesive material, which is innovative approach of this study. In this study, the failure of joint is assumed to take place due to adhesive failure only. Plastic zone size (PZS) in adhesive at failure load of joint is taken as 15 % of the lap length as established from the previous work of the authors[4]. ASTM D3165 test specimen geometry and dimensions, as shown in Fig. 1 is followed for generating the model. In this investigation, it is assumed that the joint failure takes place in adhesive layer only as the desired mode of failure.

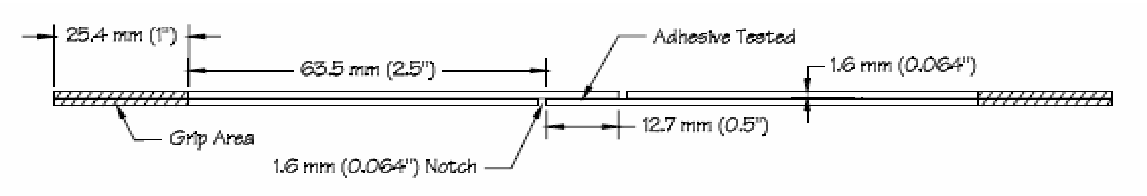

Fig. 1. ASTM D3165 specimen

2. THEORITICAL FORMULATION

A geometric and material non-linear finite element analysis has been carried out for composite-metal adhesively bonded joint following test specimen geometry and dimensions as shown in Fig. 1. 2D plane stress idealization was carried out for composite-to-metal joint with Redux 319 A adhesive. Materials for metal and composite used in analysis are respectively Al 2024-T3 and CFRP T 300/914C as shown in Table 1 and 2.

Table 1. Material Properties of Aluminum Adherend and Redux 319 A Adhesive

Component	Material	Properties		
		E (MPa)	ν	σ_{yp} (MPa)
Adherend (Metal)	Al-2024-T3	73103.5	0.3	324
Adhesive	Redux 319 A (400 gsm)	2189.2	0.3	43.2

Table 2. Mechanical Properties of T 300/914C CFRP Lamina and Laminate

Material	Properties								
	E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	G_{12} (MPa)	G_{23} (MPa)	G_{31} (MPa)	ν_{12}	ν_{23}	ν_{31}
CFRP T 300/914C UD composite lamina	130000	10000	10000	5000	3270	5000	0.35	0.5	0.027
Laminate ([+45/-45/0/90/0] $_{S,}$ 0.15 mm thick/lamina	66610	43990	12420	16430	3962	4308	0.32	0.41	0.067

2.1 Composite Laminate Elastic Properties

Composite laminate is made out of 10 layers of CFRP T 300/914C lamina of thickness 0.15 mm following stacking sequence [+45/-45/0/90/0] $_S$. The material properties of metal and adhesive are shown in Table 1 and those of lamina and laminate are shown in Table 2. Laminate 3D homogeneous orthotropic properties have been derived using average stiffness coefficients of laminas using following relation[4]:

$$\left[\overline{C}_{ij}'\right] = \frac{1}{N}\sum_{k=1}^{N}\left[\overline{C}_{ij}\right]^{k} ,$$

Where, $\left[\overline{C}_{ij}'\right]$ = Stiffness matrix for laminate

N = Number of layers (Here N=10), $\left[\overline{C}_{ij}\right]^{k}$ = Stiffness matrix for k^{th} lamina

Among derived 3D homogeneous orthotropic properties as tabulated in Table 2, only 2D orthotropic properties such as E_1, E_3, G_{13} and ν_{13} have been considered, since the problem is of 2D idealization. It may be noted that subscripts 1, 2 and 3 in property symbols represents longitudinal, transverse and thickness direction of laminate.

2.2 Finite Element Analysis

Finite element models have been generated using 2D plane stress Quad-4 elements. The boundary conditions u_x and u_y =0 are imposed at the left edge of the model (simulating fixed end of testing machine), u_y=0 is imposed at both bottom and top corner of the right edge and equal displacement in x-direction is imposed across the right edge (simulating actuator end of the testing machine) using MPC (RBE2 as per MSC.NASTRAN). The 2D mesh generated is shown in Fig 3 and details of the mesh are given in Table 3.

Nonlinear FEA has been carried out applying load in 10 equal increments. Elastic-Plastic analysis assumes Von Mises yield function and isotropic strain hardening flow rule. The analysis is carried out using MSC.NASTRAN code, which uses standard methods [5,6, 7].

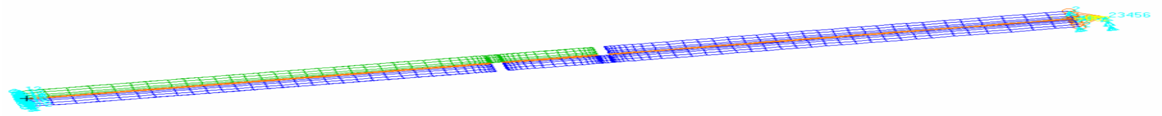

Fig. 2: 2D FE model with boundary conditions and constraints

Table 3: Details of the 2D Finite Element mesh

FE Mesh	2D Mesh
Element type	Quad 4
Number of elements in the model	1144
Number of elements in adhesive	80
Number of elements through adhesive thickness	4
Total number of nodes	1280
Total number of DOFs	2560

3. EXPERIMENTAL WORK

Aluminum 2024 T-3 and CFRP laminate adherends were cut to the required size as per ASTM D 3165 standards. Surface of Aluminum 2024 T-3 specimens were prepared following aluminum etching process. Composite laminate surface was prepared by scuffing lightly the surface such that upper layer of epoxy matrix would be removed. Then 2 layers of Redux 319 A (400gsm) film adhesive having thickness 0.12 mm per layer were put between substrates to be bonded. To maintain glue line thickness of 0.24 mm, shims were used in all the specimens for supporting the substrate. Then all glued specimens were kept securely on a surface plate. They were kept in a 3 phase electric oven for 1.5 hours at a temperature of 176 ^{0}C and 0.8 bar pressure. Then they were oven cooled to 80 ^{0}C for about 45 minutes and then to RT normally.

Experimental work was carried out in a 50kN computer controlled servo-hydraulic test machine for testing metal/composite adhesively bonded lap joint specimens. The specimens were held in hydraulic grips as shown in Fig. 3. Tests were performed as per ASTM D3165 standard specifications (1995). Load, displacement and strain data were acquired synchronously on data acquisition system. Tests were performed under stroke control mode at a cross-head speed of 0.1 mm/min, in RT lab air atmosphere and data on failure loads were obtained. Failure load was obtained and found to be 3.4kN.

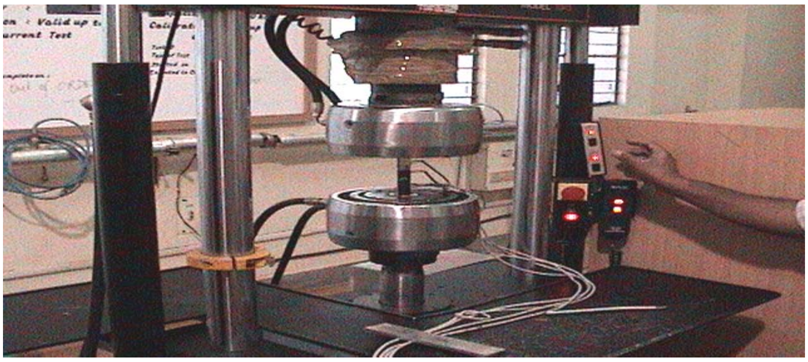

Fig. 3: Experimental set-up

4. RESULTS AND DISCUSSION

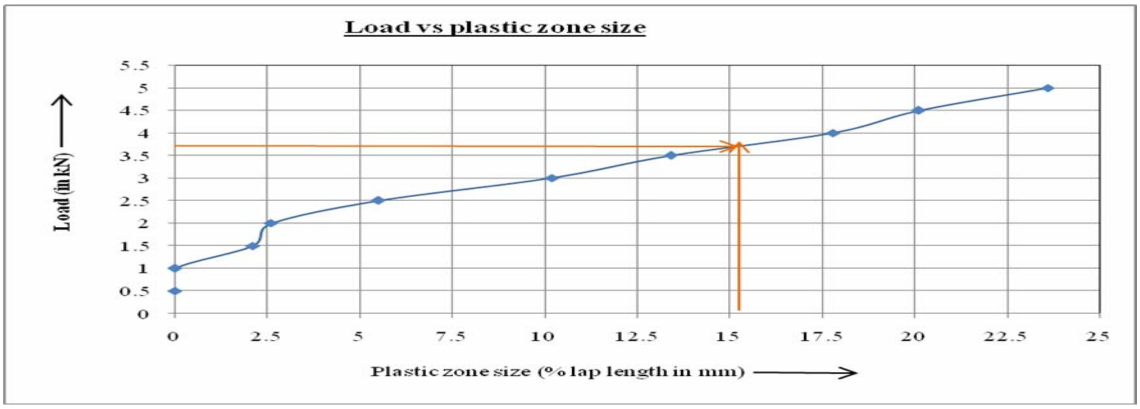

Fig. 4: Plastic zone size variation for CFRP–Al adhesively bonded lap joint at different loads

Fig. 4 shows load variation for a CFRP-Al bonded joint as a function of plastic zone size in adhesive measured in terms of % lap length. Failure load of such joint is obtained by noting the load corresponding to the plastic zone size of 15% lap length, which was established from authors' previous work [4]. Failure load so obtained for this joint is 3.65kN.

It is observed from fig. 4 that plastic zone development starts at 1kN load. Then the load increases linearly up to 1.5kN at a rate of 0.25kN/mm plastic zone size and abruptly increases to 2kN at a rate of 1kN/mm of PZS. Then the same initial rate of 0.25kN/mm up to the failure load of 3.65kN is retained.

Table 4. Failure load comparison between FEM and Experiment

Solution Methods	Failure Load (kN)	Mode of failure	% deviation
Finite Element Method	3.65	Adhesive	7 %
Experimental Method	3.4	Adhesive + Interface between metal and adhesive	

Table 4 shows the failure load comparison between FEM and experimental technique. It is observed that failure load obtained from FEM is higher than that of experiment by about 7 %. This error might be due to the assumption being made in FEM that only adhesive failure occurs in the joint. However, it is seen from experiment that the failure is due to contribution of two different modes, i.e., both adhesive failure as well as failure at interface between metal and adhesive material as shown in fig. 5. The interface failure can be controlled to a greater extent if metal surface to be bonded is grit blasted during surface preparation, as has been established in authors' previous work [2]. The grit blasted metallic surface in joint may lead to a value closer to that obtained from numerical model.

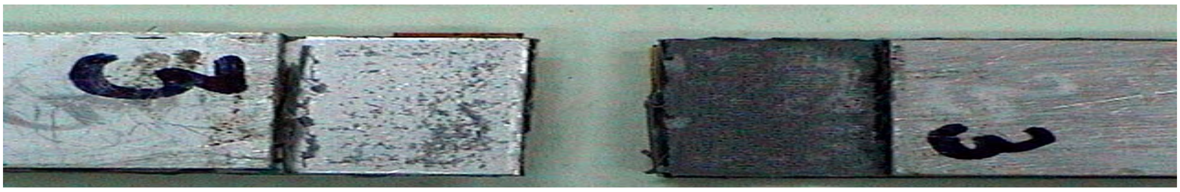

Figure 5: Failure surface of Metal-Composite adhesively bonded joint (Left: Al 2024 T3, Right: CFRP Laminate)

5. CONCLUDING REMARKS

Failure load of adhesively bonded lap joint between metal-composite adherends is predicted using geometric and material non-linear finite element approach. For the joint of identical configuration failure loads are available with experimental program. The numerical prediction is within 7% of the experimental results and can be considered satisfactory. The ability to predict failure loads to this accuracy significantly reduces the need for very expensive testing activities. It is recommended that the metallic bonding surface be grit blasted during surface preparation in order to have more strength as well as failure to occur in adhesive material only.

ACKNOWLEDGMENTS

The first author would like to thank the Director, National Aerospace Laboratories (NAL), Bangalore for permitting him to present this paper at INCAST-08 conference. He would like to thank Mr. DV Venkatasubramanyam, Head, STTD for his valuable comment, support and encouragement. Also, he would like to thank Dr. VR Ranganath, Scientist, Structural Integrity Group, Structural Technologies Division, NAL for his support and valuable discussion. He would also like to acknowledge the support of Advanced Composite Division of NAL in fabrication of the specimens.

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