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ScienceDirect

Procedia Engineering 173 (2017) 1635 – 1641

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Symposium on Plasticity and Impact Mechanics, Implast 2016

Strength prediction of adhesively bonded joints using plastic zone size criterion

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Abstract

The prediction of the strength of adhesively bonded joints has been an issue of considerable interest in literature. This exercise requires numerical techniques combined with experimental programs and matching the two to arrive at a viable criterion. The configurations used for the study are single lap adhesively bonded joints between (i) aluminium (Al) – aluminium (Al) and (ii) carbon fibre reinforced composite (CFRP) and aluminium adherends with Redux-319A epoxy. Geometric and material non-linear finite element analysis was conducted using the NASTRAN software package to establish the proposed plastic zone size (PZS) failure criterion. On the same configuration both experimental program for joint strength and numerical analysis were conducted. The plastic zone size corresponding to failure load was initially estimated from Al-Al joints. The same value was used to predict failure load for CFRP-Al bonded joint. The average experimental value and numerical predictions for CFRP-Al joints matched within 7%. This study suggests an alternative method of strength prediction of adhesively bonded single lap joint in presence of inelastic behaviour of adhesive material.

Keywords: Lap joint, Composite-metal adherends, Geometric and material non-linear analysis, Plastic zone size (PZS)

1. Introduction

Modern airframes are built with significant amount of fibre reinforced plastic composite materials for their primary and secondary structural components, in addition to conventional metallic alloys. The structural

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doi:10.1016/j.proeng.2016.12.259

components are joined together by using either fastener or adhesive bonds. Adhesively bonded joints are preferred over fastener joints due to various advantages like smoother load transfer, fewer points of stress concentration, less weight, good fatigue and corrosion resistance. Strength prediction of such joints is important to ensure the structural integrity and hence safety of the aircraft during its service period. In the recent years there is a rise in the use of adhesive bonded joints in general aviation industry in metallic and composite airframe structures, and so the ability to make failure predictions as accurately as possible is assuming significance.

There were several attempts in the past to predict strength of adhesive joints using maximum point stress criterion and computed with one-dimensional approximations of the adherends and the adhesive starting with Volkersen referred from Adams et.al [1] and Goland & Reissner [2]. There were contradictory conclusions on the effect of adhesive thickness on the strength of joints till it was shown by experiments that thinner adhesives provide higher strength [3-5]. Later it was found that 2D and 3D idealization of the joint have given better estimates of the joint strength.

The techniques for failure prediction using average stress or point stress criteria have been tried in the past [6-7]. However, both these criteria deal with only elastic stress states. Gopalan [6] used average peel stress criterion up to a characteristic distance from the bond end to predict failure of single lap bonded joints. Most of the adhesives exhibit material nonlinear behaviour. Analyses based on the elastic behaviour lead to singularities at the end of the lap length whereas incorporation of material nonlinearity mitigates the singularities.

It is necessary to use different criterion to predict failure in the cases involving material yielding near the ends of the lap length. In the present work, a failure criterion based on the plastic zone size (PZS) is proposed and an attempt is made to establish this as a possible criterion for strength prediction of bonded joints in the presence of the material nonlinear behaviour of the adhesives. The size of the plastic zone (PZS) at failure is obtained by matching the numerical non-linear estimations with experimental results on static strength value obtained from tests on several specimens of aluminium (Al) - aluminium (Al) and carbon fibre reinforced (CFRP) composite -Al joints.

2. Strength prediction using PZS criterion

When a single lap bonded joint is subjected to monotonically increasing tensile load, the plastic deformations initiate at both the ends of lap region (these regions have elastic singularity) simultaneously and grow progressively along the adhesive bond towards the centre of the joint. This is due to the inclusion of materially no-linear property of the adhesive. The extent of lap length over which plastic deformation is spread in adhesive material at any load level is known as plastic zone size (PZS) and becomes critical at failure load of the joint. PZS is defined as the percentage of lap length over which plastic strain occurs in the adhesive. The static failure of the joint is assumed to occur at critical PZS. Therefore, the failure criterion for such a joint is that the static failure of a single lap adhesively bonded joint occurs, when

$$PZS \geq Z\ \%\ \text{of lap length} \tag{1}$$

Where, Z is a number corresponding to critical PZS. To establish the PZS criterion, an integrated numerical-experimental approach is used in this investigation.

3. PZS estimation in Al-Al joint

3.1. Failure load determination by experiments

Tensile tests were carried out on Al-Al adhesively bonded single lap joint with Redux-319A epoxy adhesive. A schematic of the test specimen used as per ASTM D3165 [8] is shown in Fig. 1.

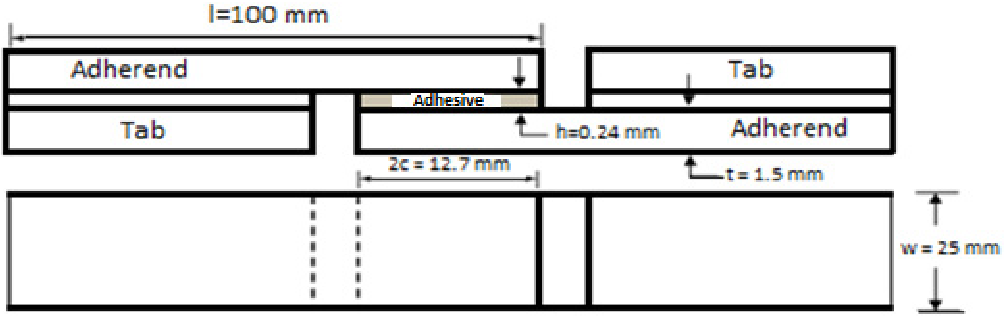

Fig.1. A schematic of adhesively bonded single lap joint specimen

Firstly, aluminium 2024 T-3 adherends were cut to the required size and surfaces were etched. Then 2 layers of Redux-319A (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 90 minutes 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.

Tensile tests were carried out in a 50kN computer controlled servo-hydraulic test machine. Load, displacement and strain data were acquired simultaneously by system-5000 data acquisition. Tests were performed under stroke control mode at a cross-head speed of 0.1 mm/min, in RT lab air atmosphere. Five tests were carried out and average failure load determined was 3.59 kN.

3.2. FE analysis

A combined geometric and material nonlinear finite element analysis was carried out on Al-Al single lap adhesively bonded joint specimen with Redux-319A adhesive having geometry and dimensions as shown in Fig. 1. The FE model was generated using 2D plane stress Quad-4 elements. Three different meshes were used to perform a convergence study and finally a model with 2786 degrees of freedom with Quad 4 elements is selected. This contains 4 elements across the thickness of the adhesive. 2D FE model of mesh 2 with boundary conditions, multi-point constraints and load is shown in Fig. 2.

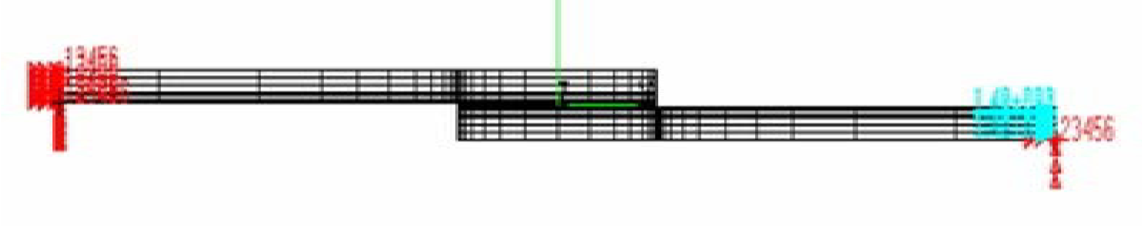

Fig.2. 2-D FE model with boundary conditions, MPC and load

Table1. Mechanical properties of materials used for FEA [9-11]

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

The mechanical properties of materials used for FE analysis are shown in Table 1 [9-11]. For nonlinear FE analysis, the stress-strain diagram of Redux-319A adhesive considered is shown in Fig. 3. This data was obtained from the manufacturer which was derived by the standard torsion test. The stress–strain relation as given is bilinear, with the tangent modulus E_T beyond the yield stress is about 2% of the Young's Modulus E in the elastic region. This has been approximated to an elastic–perfectly plastic curve since the tangent modulus is extremely small.

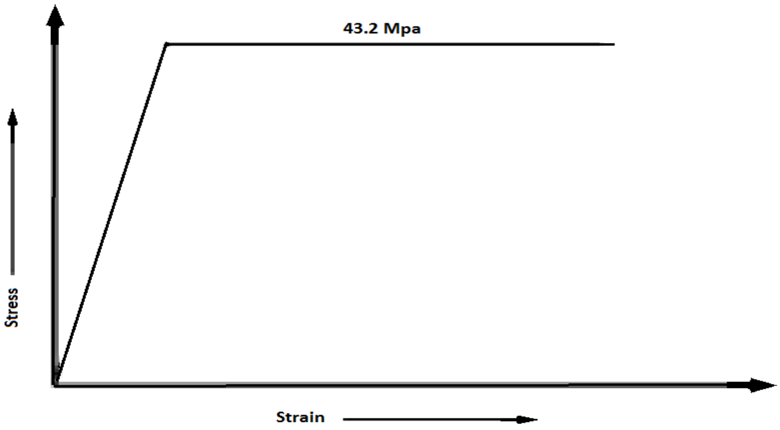

Fig.3. Stress-strain curve of adhesive Redux-319A [10,11]

The boundary conditions $u_x = 0$ and $u_y = 0$ are imposed at the left edge of the model, $u_y=0$ is imposed at both bottom and top corner of the right edge and equal displacement in x-direction is imposed across the right edge using MPC (RBE2 element in NASTRAN software).

Nonlinear FEA of Al-Al bonded joint was performed by applying the experimental failure load of 3.59 kN in 5 equal load increments. Elastic perfectly plastic material non-linear behaviour of the adhesive was assumed. Elastic-Plastic analysis assumes von Mises yield function and isotropic strain hardening flow rule. Modified Newton-Raphson technique was used in nonlinear analysis for faster convergence. The analysis was carried out using NASTRAN FEA code [12]. Plastic zone size (PZS) was determined from the results of FE analysis at a load of 3.59 KN.

4. Strength prediction in CFRP-Al joint

4.1. FE analysis of CFRP composite-Al joint

The material properties of CFRP composite lamina and laminate used in FE analysis are shown in Table 2 [13]. Composite laminate is made out of 10 layers of CFRP T 300/914C lamina of thickness 0.15 mm following stacking sequence $[+45/-45/0/90/0]_S$.

Laminate 3D homogeneous orthotropic properties were derived using average stiffness coefficients of laminas using the following relation [14]:

$$\left[\bar{C}'_{\mathrm{ij}}\right] = \frac{1}{NL}\sum_{k=1}^{NL}\left[\bar{C}_{\mathrm{ij}}\right]^k \tag{2}$$

Where, $\left[\bar{C}'_{\mathrm{ij}}\right]$ = Stiffness matrix for laminate, NL = Number of plies, $\left[\bar{C}_{\mathrm{ij}}\right]^k$ = Stiffness Matrix for k^{th} lamina

Table 2 Mechanical properties of T 300/914C CFRP Lamina and Laminate [13,14]

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* lamina	130000	10000	10000	5000	3270	5000	0.35	0.5	0.027
CFRP Q-I** laminate	66610	43990	12420	16430	3962	4308	0.32	0.41	0.067

*Uni-directional ** Quasi Isotropic

The same mesh used for modelling Al–Al bonded joint is used in modelling CFRP-Al single lap joint. Also all other modelling parameters such as materials, boundary conditions and MPC as described earlier for Al-Al joint, remain the same except that material of one of the adherends in this case is CFRP and applied load is 5 kN. Non-linear analysis of CFRP-Al adhesively bonded joint with Redux-319A adhesive was carried out applying load of 5kN in 10 equal increments.

4.2. *Experimental program*

CFRP laminate adherends were cut to the required size according to ASTM-D3165 standard [10]. Composite laminate surface was prepared by scuffing lightly the surface such that upper layer of epoxy matrix would be removed in order to ensure proper bonding [15]. The same adhesive Redux-319A was used for bonding the composite and metal adherends. Curing procedure which was explained earlier for Al-Al joint was followed in preparing CFRP-Al single lap joint specimen also.

CFRP-Al bonded joints were tested using the similar procedure as adopted for Al-Al joint mentioned in previous section. The average value of failure loads for same set of five specimens was obtained to be 3.4 kN.

5. Results and Discussion

5.1. *Failure criterion*

Real adhesive has a finite yield stress. The results based on linear adhesive behaviour imply that the adhesive yield stress is assumed to be infinitely large or there is no yielding of the adhesive material. So, while material non-linearity is included it is necessary to include criterion based on plastic deformation of the adhesive.

Plastic deformation or yielding will start from the left end point of upper bond line and also from the right end point of lower bond line of the adhesive layer. Then it progressively propagates from both sides towards the centre of the mid bond line as load increases (Table 3). It is observed that plastic zone size from left bond end is equal to that from right bond end. But, however, it is likely that these zones may differ depending on the boundary conditions or and material of the adherends used. When yielding is propagated through nearly 15.2% of the bond length catastrophic failure of the joint takes place.

Table 3 Plastic zone size corresponding to failure load for Al-Al adhesive lap joint

Analysis type	Failure load (kN)	Plastic zone size			
		From left bond end (*l*) in mm.	From right bond end (*r*) in mm.	Total in mm.	% lap length
2D Plane Stress	3.59	0.965	0.965	1.93	15.2

5.2. *Plastic zone size (PZS) criterion for CFRP-Al Joints*

Load variation in CFRP-Al bonded joint as a function of plastic zone size in adhesive measured in terms of % of lap length is shown in Fig. 4. It is observed from the figure that plastic zone development starts at 1 kN load. Numerical prediction of failure load of the joint is obtained by the load corresponding to the plastic zone size of 15.2% lap length, which was proposed by correlating plastic zone size at failure load of Al - Al bonded joint (Table 4). The failure load so obtained for CFRP-Al joint is 3.65 kN. This value is more than the failure load (3.59 kN) of aluminum-aluminum (Al-Al) bonded joint. The two joints have nearly the same failure load since the failure is primarily in the adhesive and is not significantly affected by the adherend property.

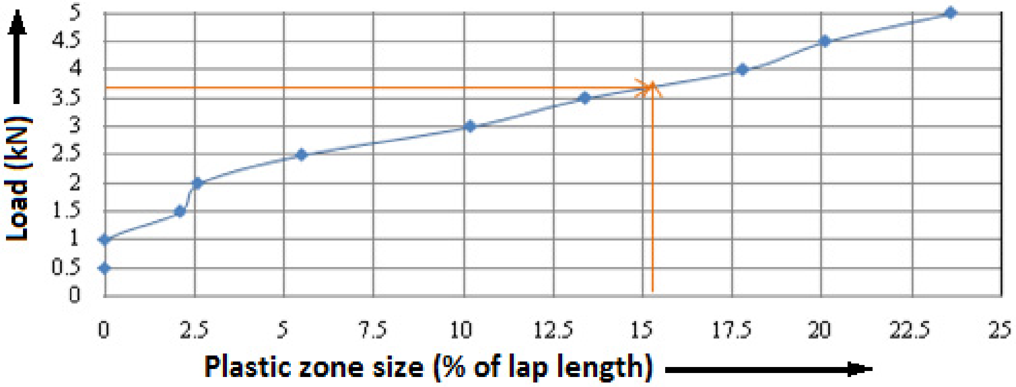

Fig.4. Plastic zone size variation for CFRP-Al adhesively bonded lap joint with load

Table 4 Failure load comparison between FE and experiment

Solution Methods	Failure Load (kN)	Mode of failure
Finite Element Method	3.65	Adhesive
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 %. One reason for this deviation 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 also occurs over some small extent along the interface between metal and adhesive material as shown in Fig. 5. Another reason might be due to possibility of imperfect bonding between the adherend and adhesive interface during the surface preparation process.

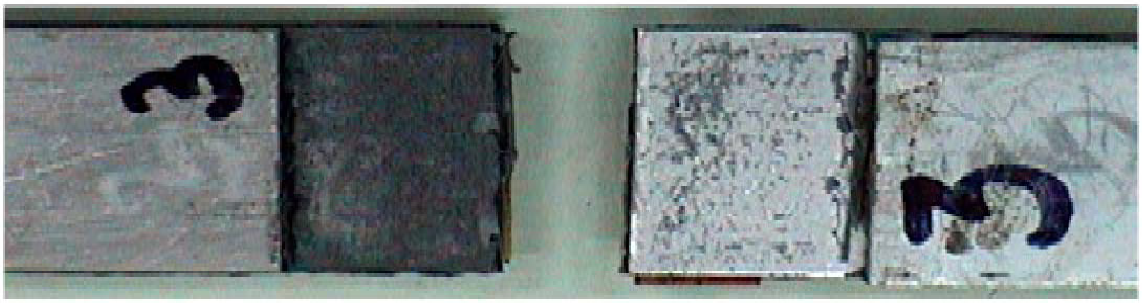

Fig.5. Failure surface of CFRP-Al adhesively bonded joint

6. Conclusions

Plastic zone size as a measure of failure prediction of adhesively bonded single lap joint has been established by correlating plastic zone size with experimental failure load for aluminum-to-aluminum single lap bonded joint. The same extent of plastic zone size was used to predict the failure load of Al-CFRP single lap joint. The comparison between experimental and numerical prediction showed that experimental values for failure load are 7% less than those predicted by numerical computation. This can be attributed to possible imperfections in bonding the composite adherend and also the failure was observed to be partly along the mid-bond line and also along the interface between the composite and adhesive. The PZS criterion has promise to be an acceptable criterion in cases where plastic deformation in the adhesive is included in the analysis.

Acknowledgements

The authors, P.K. Sahoo and C.M. Manjunatha would like to thank the Director, CSIR-National Aerospace Laboratories, Bangalore for encouragement and permitting them to publish the work. They would like to thank Dr. Satish Chandra, Head, Structures Technology Division (STTD) for his support and encouragement. Dr. V.R. Ranganath, Scientist, Structural Integrity Group, STTD is thanked for the valuable discussions. The support of colleagues at FSIG, STTD and that of Advanced Composite Division of CSIR-NAL in fabrication of the specimens are also acknowledged. All the authors acknowledge the contribution of Prof. C.R.L. Murthy, Professor, Department of Aerospace Engineering, Indian Institute of Science, Bangalore who was also one of the supervisors for the work presented and is no more at this time.

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