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Final Report

of

NASA Research Cooperative Agreement NCC1-70,

"Fatigue Behavior of Adhesively Bonded Joints"

Period

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A research study to characterize the fatigue damage mechanism of composite-to-composite adhesively bonded joints was initiated by the principal investigator at NASA-Langley Research Center in September 1981. This study was the first step towards the systematic investigation to identify and understand the mechanics of the possible modes of fatigue damage propagation in these joints when subjected to constant amplitude cyclic mechanical loading.

The possible failure modes in composite bonded joints may be cyclic debonding (i.e. progressive separation of the adhesive), interlaminar damage (delamination), adherend fatigue or a combination of these. An experimental program was carried on in this direction. Two composite systems - graphite/epoxy adhesively bonded to graphite/epoxy and Kevlar 49/epoxy adhesively bonded to Kevlar 49/epoxy were investigated. Both composite systems consisted of quasi-isotropic lay-ups, i.e. $[0°/-45°/+45°/90°]_S$. The two adhesives, employed in the study were (1) EC 3445 (manufactured by 3M) with cure temperature of 250°F for secondary bonding and (2) FM 300 (manufactured by American Cynamide) with cure temperature of 350°F for co-cure bonding. The secondary bonding means the joining of components that are already fabricated (cured). The co-cure bonding represents the process where components of structures are fabricated and joined simultaneously. Above mentioned composites and adhesives as well as concepts of secondary and co-cure bonding are being employed by Bell Helicopter (Fort Worth, TX) in an experimental composite airframe of the helicopter. (This program [1] is sponsored by Army's Advanced Composites Airframe Program, ACAP). The methodology based on fracture mechanics was employed to understand the fatigue failure of adhesive bond.

This research study involved several tasks. A summary of these tasks and their main conclusions are presented in the following.

1. Cyclic Debonding under Mixed-Mode Loading:

Two types of cracked-lap-shear specimen of graphite/epoxy, shown in figure 1, were tested in this task. This specimen duplicates the real life conditions where joints are subjected to mixed mode condition of failure (i.e. failure caused by shear and peel stresses; peel stress means stress normal to adhesive layer). These two types of specimens provided the different ratios of G_I/G_{II} (the strain energy release rate for mode I, G_I and mode II, G_{II}) in order to correlate the influence of G_I, G_{II} or G_T (the total strain energy release rate) on the fatigue failure of adhesive joint. This investigation showed that fatigue failure of joints occurs due to cyclic debonding of the adhesive only. No interlaminar damage or adherend failure has been observed so far. Furthermore, the cyclic debond growth rate (da/dN) correlated better with G_T than it did with either G_I or G_{II}, and this relationship can be expressed as the following:

$$\frac{da}{dN} = C(G_T)^n \tag{1}$$

A damage tolerance approach analogous to that currently employed in metal can, then, be developed for adhesively bonded joint on the availability of equation (1) for a given adhesive system in the expected service environmental conditions. This work was presented in the International Symposium on "Adhesive Joints: Formation, Characteristics and Testing" in Kansas City, Missouri, on September 13-16, 1982 and will be published in the proceedings of this conference. This work is also available as NASA TM report [2].

2. Cyclic Debonding under Mode I Loading:

The above study of task 1 was extended to investigate the cyclic debonding under opening mode I loading, to cover the broad range of fatigue loading as well as to understand the basic mechanics of cyclic debonding. A double-cantilever-beam (DCB) specimen was employed for this purpose (see figure 2). Two sets of DCB specimens (graphite/epoxy bonded with EC 3445 and FM 300 adhesives) were fatigued under constant-amplitude loading. The measured debond growth rate (da/dN) correlated well with the strain-energy-release rate (G_I). Also, the relation da/dN vs. G_I from the DCB specimen (in opening mode) and da/dN vs. G_T from the CLS specimen (in mixed mode loading) agreed with each other (see figure 3). The results of this study thus clearly show that the cyclic debond growth rate for adhesively bonded composite joint is a function of total strain-energy-release rate G_T. A report based on this work is under preparation which will be presented in the ASTM Seventh Conference: Composite Materials Testing and Design to be held in Philadelphia, April 2-4, 1984 [3].

3. Tapered Cracked-lap-shear-Specimen:

It has been observed that peel stress (stress normal to adhesive layer) is the major contributor to the fatigue failure in adhesively bonded joints [4]. The peel stress can be reduced or relieved by tapering the lap joint, as shown in Figure 4 [5,6]. It is, therefore, a practically important design consideration which should be investigated thoroughly in the fatigue failure of composite-to-composite adhesively bonded joint.

For this purpose, threshold loads for fatigue initiation in cracked-lap-shear specimens with different taper angles (α=5°, 10°, 30° and 90°) were predicted from a FEM analysis. These predictions were based on a total strain-energy-release rate threshold (G_{th}) concept. These predictions were verified by experiments. This study indicates that the total strain-energy-release rate is the driving parameter for cycling debonding and debond initiation. In addition, debond initiation and growth were found to occur with virtually no peel stress present. This work will be presented by the principal investigator in the ASTM Symposium on Delamination and Debonding of Materials at Pittsburgh on Nov. 9-10, 1983 [7].

4. Ply Lay-up in Composites:

This task involved the investigation of effect of different ply lay-ups on the fatigue failure in composite-to-composite bonded joints. Previous work in task 1 was confined to composite adherends with $[0°/\pm45°/90°]_s$ lay-up with 0° fibers on surfaces. Various lay-ups are required in composite components of aerospace structures. The fatigue damage mechanism of adhesive joints between composites having different ply lay-ups should, therefore, be characterized to broaden the range of adhesive bonding in composite structures. The following two lay-ups were tested for this purpose.

1. $[\pm45°/0°/90°]_s$
2. $[90°/0°/\pm45°]_s$

An experimental study with cracked-lap-shear specimens shown in figure 1 with above mentioned two ply lay-ups were undertaken. With both lay-ups, fatigue failure was a combination of debond, delamination and transverse cracking. In general, failure occured at end of the lap joint and penetrated in the strap portion of CLS specimen till it reached the 0° layer, and thereafter continued as d[illegible]mination on 0° interface. Threshold loads for fatigue initiation were measured for both adhesives (EC 3445 and FM 300) for both above mentioned lay-ups. A technical paper based on this work is under preparation, and it will be sent for publication in open literature upon it's completion.

5. Joint between Kevlar/Epoxy:

Task 1 was extended to study the effect of different adherends. For this purpose, cracked-lap-shear specimens of Kevlar/Epoxy bonded with EC 3445 and FM 300 were subjected to constant-amplitude fatigue loading. A peculiar phenomenon of fatigue failure was observed in these cases. This fatigue failure was in the form of the partial cyclic debonding. A possible explanation may be due to the surface condition of Kevlar which is not smooth but contains crests and troughs. Therefore, fatigue failure progressed as partial cyclic debonding (i.e. separation of adhesive on crests) with bonded portion around troughs. A technical paper based on this work is under preparation, and it will be sent for publication in open literature upons it's completion.

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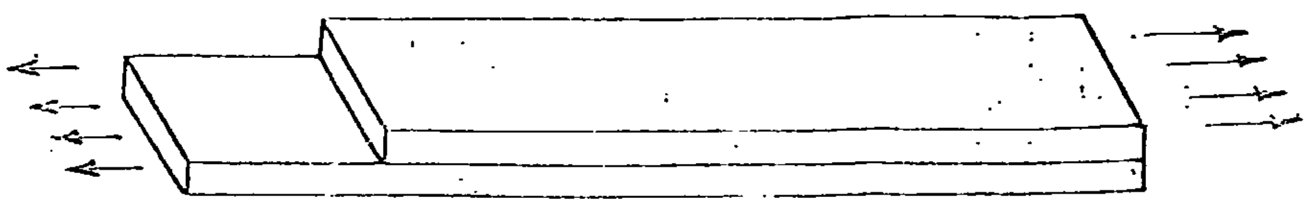
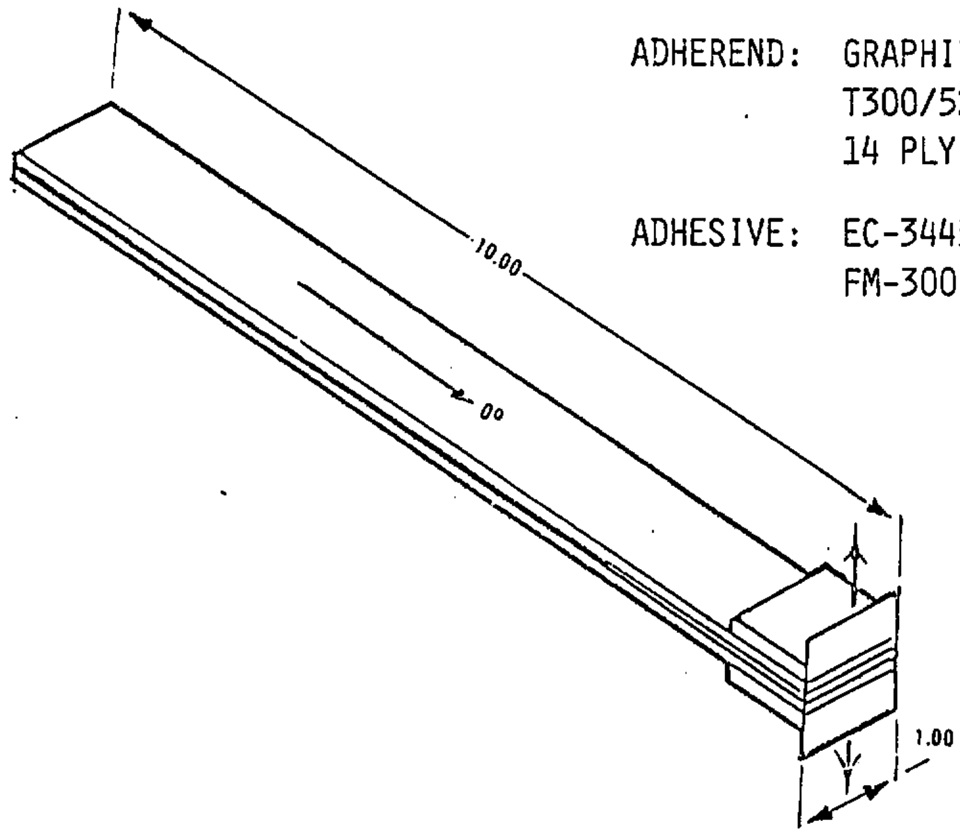


TYPE	TOP PLATE	BOTTOM PLATE
1	8-PLY	16-PLY
2	16-PLY	8-PLY

Figure 1.- Crack-lap-shear specimen.



ADHEREND: GRAPHITE/EPOXY
T300/5208
14 PLY - 0°

ADHESIVE: EC-3445 (0.004 IN)
FM-300 (0.01 IN)

FIGURE 2. DOUBLE-CANTILEVER-BEAM SPECIMEN

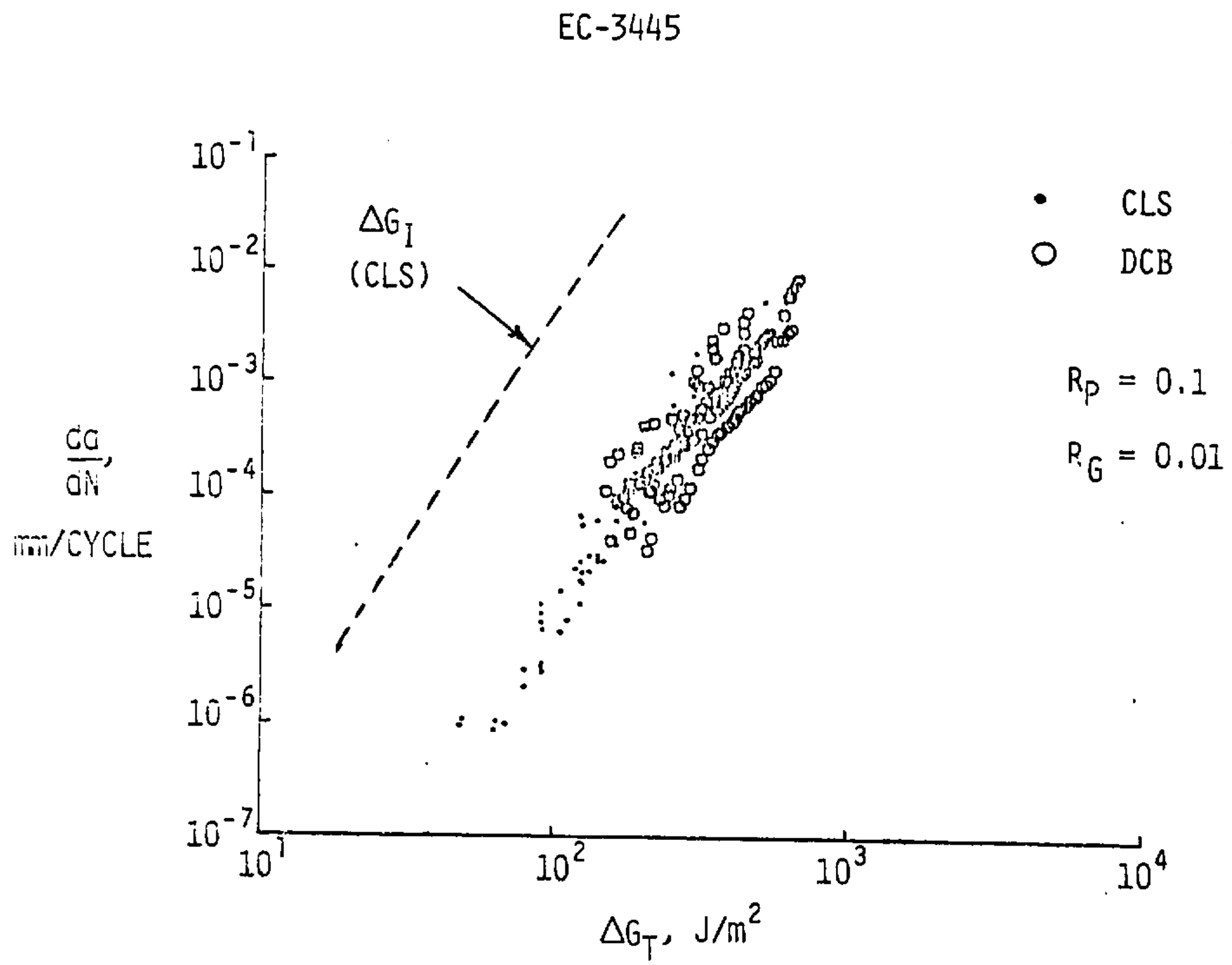


Figure 3.- Relation between strain-energy-release rate and debond growth rate (da/dN) from two specimens.

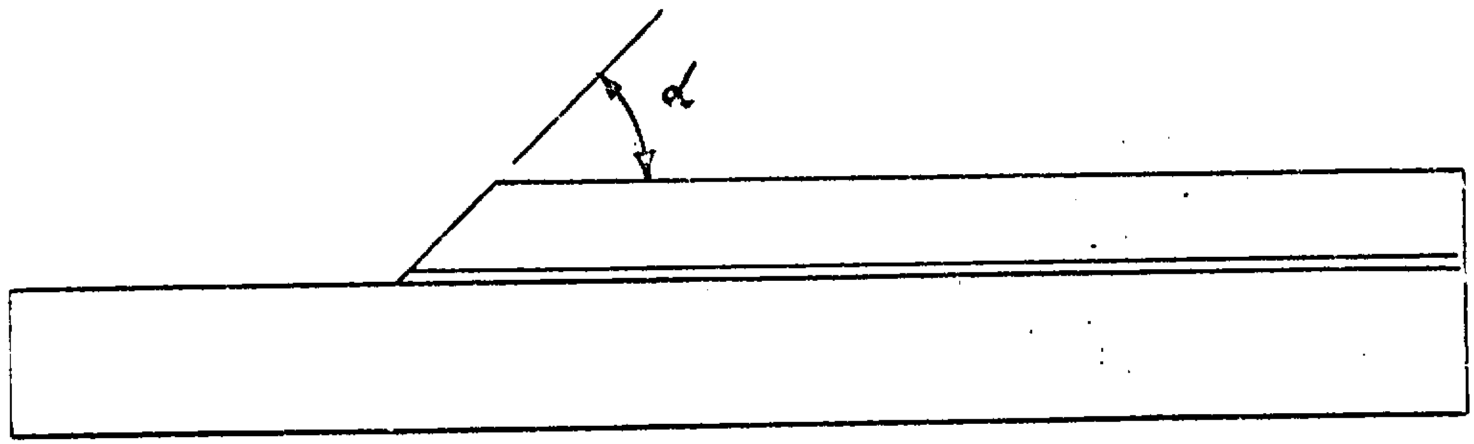


Figure 4.- Tapered crack-lap-shear specimen.