Summary

The Symposium on Delamination and Debonding of Materials was held in Pittsburgh, Pennsylvania, on 8–10 November 1983. The Symposium was cosponsored by ASTM Committees D-30 on High Modulus Fibers and Their Composites and E-24 on Fracture Testing. Over one fourth of the speakers were from outside the United States, giving the symposium an international flavor. Twenty-five of the papers presented during the two-and-a-half day conference are included in this volume. This publication is organized into three sections, highlighting each of three subject areas: (1) Stress Analysis, (2) Mechanical Behavior, and (3) Fractography/NDI. The majority of the papers fall in the second section. Most of the papers deal with delamination of composites; five address adhesive debonding.

Stress Analysis

The Stress Analysis section contains five papers. *Kuo and Wang* presented a finite-element method that uses hybrid stress crack-tip elements for analyzing interfacial crack problems under dynamic loadings. The effects of element size, element aspect ratio, and eigenfunction truncation were investigated. *Conti and De Paulis* used an approximate model based on simple polynomial formulations to evaluate the interlaminar stresses that are generated within the interface between two layers near the free edge of angle-ply and cross-ply laminates. Next, *Valisetty and Rehfield* presented a method to estimate the interlaminar stresses using a ply-level sublaminate analysis based upon a homogeneous plate theory. The effect of laminate thickness on interlaminar stresses was studied by *Whitcomb and Raju.* They found that in laminates with delaminations present, the delaminations near the top and bottom surfaces of a thick laminate have much larger total strain-energy-release rates and Mode I components than delaminations deep in the interior. *Mahishi and Adams* discussed the elastoplastic nature of delamination crack growth in composite laminates. A three-dimensional elastoplastic, generally orthotropic finite element method is used to make simple estimations of the local elastic strain energy release rate in the presence of plasticity.

Mechanical Behavior

The Mechanical Behavior section contains fourteen papers. *Anderson et al* evaluated tension tests for adhesives. They found that the debond initiation point changes from the bond edge to the center of the bond area as the adhesive thickness is decreased. They further found that the stress distribution is extremely sensitive to specimen alignment. *Wang et al* used an energy method to describe one-dimensional and two-dimensional delamination growth. *Mohlin et al* presented experimental and theoretical aspects of delamination propagation in graphite/epoxy composite laminate with an unloaded hole subjected to compressive fatigue loading. The fourth paper is by *Johnson and Mall.* They present a fracture mechanics approach based on total strain energy release rate threshold to predict maximum design stresses for no debond initiation or growth. *Gustafson et al* also used the strain energy release rate threshold concept to predict at what stress levels interlaminar flaws will grow in graphite epoxy. Likewise, *Bathias and Laksimi* presented data that demonstrate the importance of determining a delamination threshold to evaluate the damage tolerance of composites. *Hart-Smith* introduced an analysis to illustrate that successful bonded-joint design requires the use of adequately long and thin overlaps to ensure that the development of parasitic peel stresses is suppressed.

Everett and Johnson presented data illustrating the repeatability of adhesive debond growth rates from specimens manufactured and tested by different organizations. *O'Brien* derived an equation to calculate the strain energy release rate associated with local delamination growth from a matrix ply crack. A simple technique for predicting strain concentration in the primary load-bearing plies near the local delamination was also developed. Next, *Whitney and Knight* presented a modified edge delamination specimen in which a crack starter is embedded along the free edges of the laminate at the mid-plane. The purpose of the crack starter is to promote Mode I interlaminar fracture behavior. *Ramkumar and Whitcomb* presented delamination growth rate data from double cantilever beam (Mode I) and from cracked lap shear specimens (Mode I and Mode II). The delamination growth rates are plotted against calculated G_{I} and G_{II} to assess power law relationships. *Aliyu and Daniel* used double cantilever beam (Mode I) specimens to determine the effect of strain rate on delamination fracture toughness of graphite/epoxy. The moisture and temperature effects on mixed-mode delamination fracture of graphite epoxy was examined by *Russell and Street. Mignery et al* found that the introduction of stitching causes little change in interlaminar normal stress, but does reduce the strain energy release rate as the delamination approaches the stitch line.

Fractography/NDI

The Fractography/NDI section contains six papers. *Bradley and Cohen* determined the fracture toughness of graphite/epoxy under pure Mode I and mixed-mode loadings. *In situ* delamination fracture in a scanning electron microscope (SEM) and post-mortem fractography have been used to determine the micromechanisms of fracture which control G_{Ic}. *Johannesson and*

Blikstad used the SEM and radiography to elucidate the relation between state of stress and fracture surface appearance for edge delamination in graphite/epoxy angle-ply laminates under tensile loading. The third paper in this section is by *Harris and Morris*. The authors used radiography and a laminate deply technique to study delamination and damage development in thick notched laminates. *Gustafson and Seldén* also presented a radiographic technique, in addition to acoustic emission, to monitor fatigue damage in composites. They also used SEM for a fractographic investigation of the delaminated surface. *Kenner et al* presented an investigation into the validity of the coin-tapping technique as an NDI tool. Their results indicate that most damage causes an acoustical response beyond the normal audio range. Lastly, *Hillman and Hillman* presented a thermographic inspection technique that may be applied to large carbon epoxy structures to find serious damage.

Summary

It is rare, with today's trend towards large general symposia, to see so many papers assembled on a rather narrow subject. The beauty of this occurrence is that one can observe areas of mutual concurrence, such as the importance of establishing threshold values for debonding or delamination. The application of fracture mechanics appears to be a rational approach for gaining a full understanding of these failure processes. Further, one can see the commonality of test specimens; double cantilever beam, cracked lap shear, and edge delamination specimens are all popular. The stress analysis is predominately finite-element oriented with various degrees of complexity. Effort is being made, however, to find simpler methods to determine these complex stress states.

The next challenge is to take this rapidly expanding knowledge, being extracted from rather simple laboratory coupon specimens, and transfer it to large-scale structures. Historically, the use of fracture mechanics in metals allowed for the transfer to be made with great success. Since much of the work presented in this volume was based on a fracture mechanics foundation, perhaps the successful transfer of this information is imminent. At any rate, it is hoped that this volume will serve as a useful tool and a guiding light in the transfer process.

In closing, I would like to thank my session chairmen—Frank Crossman of Lockheed-California, Jim Whitney of AFWAL, Joe Gallagher of the University of Dayton Research Institute, Hal Brinson of Virginia Tech, and John Masters of American Cyanamid—for a job well done.

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