Effects of Defects in Composite Materials

ASTM STP 836

EFFECTS OF DEFECTS IN COMPOSITE MATERIALS

A symposium
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High Modulus Fibers and
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Foreword

The symposium on Effects of Defects in Composite Materials was held in San Francisco, California, 13–14 December 1982. ASTM Committees D-30 on High Modulus Fibers and Their Composites and E-9 on Fatigue sponsored the symposium. Dick J. Wilkins, General Dynamics, presided as symposium chairman.

Related ASTM Publications

Long-Term Behavior of Composites, STP 813 (1983), 04-813000-33

Composite Materials: Quality Assurance and Processing, STP 797 (1983), 04-797000-30

Composite Materials: Testing and Design (6th Conference), STP 787 (1982), 04-787000-33

Damage in Composite Materials, STP 775 (1982), 04-775000-30

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

ASTM Committee on Publications

ASTM Editorial Staff

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Introduction

The objective of the Symposium on Effects of Defects in Composite Materials was to provide a forum for presentations and discussions on the effects of defects on strength, stiffness, stability, and service life. Defects were considered either to originate from the manufacturing process (such as voids, inclusions, and porosity) or to result from service usage including low-energy impact, ballistic damage, ply cracking, and delamination. Contributions were specifically sought on:

1. Observation and measurement of defect location and size.
2. Experimental evidence of consequences of defects.
3. Analytical models for predicting defect behavior.
4. Observations of failure surfaces influenced by defects.

The underlying motivation for selection of this topic for a symposium and publication was an increasing awareness of the importance of defects as they behave as stress concentrators and failure sites in brittle composite materials. The extensive application of such materials in aerospace vehicles and commercial products fostered the need to understand the interrelationships among the manufacturing processes, the inspection techniques, and the in-service performance.

Probably because of various constraints in the industrial community, most of the contributions were from either university or government researchers. Consequently, the viewpoint of the majority of the papers is an attempt to understand and characterize defects, rather than explore their engineering significance.

All but one of the papers is concerned with carbon-epoxy laminates. This amount of emphasis is appropriate because the aerospace industry is so heavily involved with applications of the various commercial forms of carbon-epoxy.

Most of the papers contribute new experimental observations of the effects of various defects. Several papers concentrated on the careful observation and documentation of failure surfaces influenced by defects. The interactions between ply cracks and delaminations have been especially well-documented.

Some intriguing new methods of analysis are proposed by a number of the papers. These new analyses, coupled with the improved understanding provided by the experimental observations, will add to our ability to evaluate the sensitivity of structures to defects.

The contributions provided to this volume by the authors, the reviewers, and the ASTM staff are gratefully acknowledged.

Dick J. Wilkins
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Fracture Toughness and Impact Characteristics of a Hybrid System: Glass-Fiber/Sand/Polyester

REFERENCE: Joneja, S. K. and Newaz, G. M., **"Fracture Toughness and Impact Characteristics of a Hybrid System: Glass-Fiber/Sand/Polyester,"** *Effects of Defects in Composite Materials, ASTM STP 836,* American Society for Testing and Materials, 1984, pp. 3–20.

ABSTRACT: In order to understand the damage mechanism in a glass-fiber/sand/polyester hybrid composite, it is essential to study the effects of inherent flaws or defects on the damage growth in the material. The irregular shape and presence of sharp geometric corners in the sand particles, voids, and improper interfacial bonding are factors that contribute to the weakening of the composite performance. One of the parameters influencing the defect formation is size of sand particles.

In this investigation, the thickness of glass/polyester layer is varied, while the sand/polyester layer is kept at a constant thickness. Laminates are made using different sand particle dimensions in order to investigate their influence on the performance of the hybrid composite. The combined effect of the defects is quantified by measuring the residual backing toughness provided by the glass/polyester layer after the full crack growth in the sand layer. The laminates having fine-sand particles provide better toughness properties in comparison to the coarse-sand laminates.

Impact studies are performed to evaluate the influence of defects on the hybrid composite behavior when subjected to impulsive loading. The load is applied to the glass/polyester face. The effect of thickness of the glass/polyester layer on damage initiation and propagation due to the impacting tup has been studied. It has been found that the thickness of the glass/polyester layer has a predominant influence on damage growth and mode of failure.

KEY WORDS: composite materials, fatigue (materials), fracture mechanics, chopped strand mat, polyester concrete, glass-fiber/sand/polyester hybrid composite, voids, interface, sand particle size, fracture toughness, backing toughness, impact, total energy, initiation energy, ductility index

The relatively low tensile strength and fracture energy of the polyester/sand composite has been the driving force behind the development of glass-fiber-reinforced polyester concrete [*1,2*].[2] Properties of the glass-reinforced polyester

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

sand composite depend on characteristics of the fibers, the resin matrix, and the fiber/matrix interface. For better design of the composite, investigators active in the field are engaged in establishing the relationship between the micro and macro behaviors of the composite. Micromechanical approaches to complex materials such as plain and fiber-reinforced concrete are commonly based on multi- (or two-) phase models. Stroeven [*3*] modeled the hybrid composites based on deterministic as well as probabilistic principles to derive the constitutive relationships. Using this model, he evaluated the stress transfer capability of a cracked region in plain and fiber-reinforced concrete.

Excessive voids and poor interfacial bond adhesion between sand and the matrix are common factors that affect the performance of the material. The irregular shape and size of the sand particles further causes high stress concentration at the interface of the matrix and sand [*4*]. These defects are potential failure initiators. The microscopic defects may combine together to produce degradation of the sand/fiber/polyester hybrid composites. The presence of defects influences critical load for crack initiation and velocity of crack propagation in the material, thus affecting the performance of crack arresting material such as glass fibers.

Equally critical in the design of polyester concrete are the dynamic properties. Many investigators [*5,6*] have observed improvements in the impact resistance of cement when glass fibers or some toughening agents are introduced into the system. However, very little published work is available on impact characteristics of polyester concrete. Basic understanding of the behavior of polyester concrete at high strain rates caused by impact may provide insight for a more rational design analysis of the system under dynamic loads.

In this study, the combined influence of voids, sand particle size, and interfacial bond adhesion on fracture toughness and impact behavior of glass-fiber/sand/polyester hybrid composites has been investigated. The thickness of the glass/polyester backing layer is varied, keeping the layer of sand/polyester concrete at constant thickness to study the effect of backing toughness. Average sand particle dimensions are changed in order to understand their influence on the performance of the hybrid composite. The effect of the thickness of the glass/polyester layer and particle size on damage initiation and propagation during impact has been analyzed.

Material and Specimen Preparation

The material used in this investigation is a composite made of E-glass chopped strand mat, M721 (ARATON®), and polyester resin E-737, both manufactured by Owens-Corning Fiberglas Corporation. The M721 is constructed from chopped fine strands randomly oriented and bonded in mat form by a small quantity of high solubility polyester resin. The mat weighs 0.457 kg/m^2 (4.48 N/m^2). The E-737 is an unpromoted isophthalic polyester resin having 3.8 to 4.5% ultimate elongation. For fabrication of the hybrid laminates, a mold made of high-density polypropylene was used. First, the resin was spread on the surface of the mold for uniform wetting and then five layers of the mat were placed one by one, pouring resin on the top of each layer. A roller was employed to squeeze out and enhance the impregnation of the resin. A mixture of 85/15 sand/polyester resin by weight was prepared and poured on the top of the mat polyester layers in the mold to make 12.7-mm-thick laminates. Figure 1 shows a schematic of the laminate in the mold. Sand with two different particle sizes, 100 and 700 μm, were used to make the laminates. The laminates were cured under uniform pressure of 9.65 KN/m^2 at 22°C for 18 h and postcured at 93°C for 2h.

For fracture toughness tests, single-edge notch beam (SENB) specimens were prepared with three different thicknesses of backing layers, namely, 3.2, 1.6, and 0.8 mm. A notch of 2.5 mm was machined at the center, across the width of the specimen in the sand/polyester layer. A diagram of a finished specimen is shown in Fig. 2*a*. For the impact study, rectangular cross-section specimens of 12.7-mm width and 127.0-mm length with varying thickness of glass fiber mat polyester layer and constant layer of 9.4-mm sand/polyester were prepared (Fig. 2*b*). Most of the impact study was performed with samples having the larger sand particle size (700 μm). A limited number of samples with finer sand particles were also subjected to impact.

Experimental Procedure

Fracture Toughness

The microscopic examination of the material revealed that the defects are distributed and oriented randomly all over in the sand/polyester layer. Due to this, many of the defects are not wholly contained in the plane perpendicular to the maximum tensile stress, therefore, not all defects are stressed in a typical tensile mode, K_I. However, an overall fracture toughness is obtained using notched bend tests. The specimens have been loaded at the rate of 1.27 mm/min on an Instron unit. The critical load is obtained from a load-deflection curve.

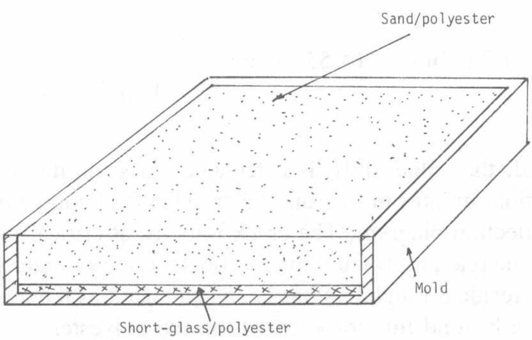

FIG. 1—*Schematic of short glass-fiber/sand/polyester laminate in mold.*

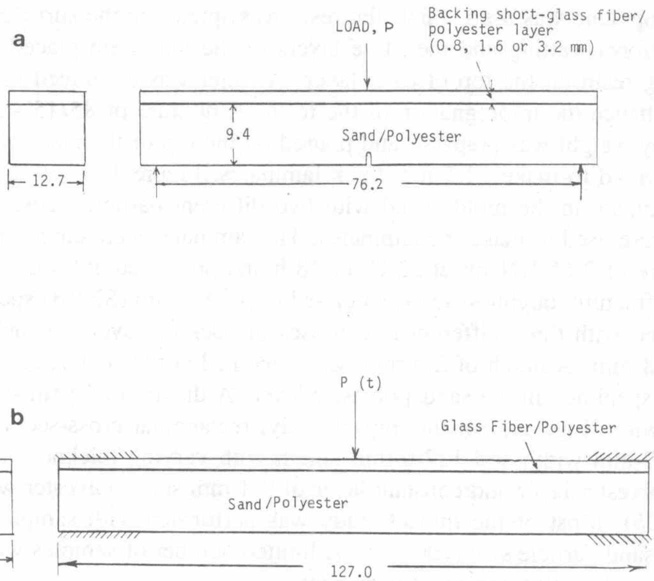

FIG. 2—(a) *Single-edge notched beam specimen for fracture toughness test, and* (b) *specimen for the impact test* (*all dimensions are in millimetres*).

The fracture toughness is calculated using the following form of the Griffith relationship [7].

$$K_{Ic} = \frac{6M_c a^{1/2}}{b\,w^2}\,Y \tag{1}$$

where M_c is the applied critical bending moment; a, b, and w are notch depth, width, and thickness of the specimen, respectively; and Y is a dimensionless parameter that depends on the ratio, a/w, and is given by

$$Y = 1.93 - 3.07\,(a/w) + 14.53\,(a/w)^2 - 25.11\,(a/w)^3 + 25.80\,(a/w)^4 \tag{2}$$

In the hybrid, the value of M_c is calculated based on the load, P_c, at which crack propagation initiates in the sand layer. This load corresponds to first peak in the load-deflection diagram. The crack initiates at critical load and grows in the polyester concrete and finally hits the fiber-glass-polyester layer that arrests the crack. The residual toughness has been calculated as the area under the load deflection curve beyond full crack growth in the polyester concrete (Fig. 3).

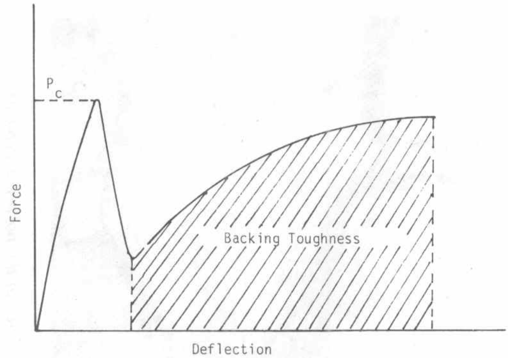

FIG. 3—*A typical load-deflection curve for the hybrid.*

Impact

The Rheometrics High Rate Impact Tester is used to study the impact response of glass-fiber/sand/polyester laminates. The specimens were mounted against a 76.2 mm opening, keeping both ends fixed. A hemispherical tup of 12.7-mm radius was used to impact the specimens on the backing side made of glass-fiber-polyester layer. The impact speeds of 22, 88, and 220 cm/s were selected to determine the influence of velocity of impact on the behavior of the composite. Plots of load-deflection and energy were obtained for different thicknesses of the backing layers.

Some specimens were also subjected to a bumping type impact. The ram displacement was controlled in order to simulate a bumping type impact. The depth of penetration was accomplished by using the "Return Point Select" mode on the Rheometrics High Rate Impact Tester, thus allowing for only partial sample deformation or surface fracture. To do this, the desired penetration depth is entered into the computer memory, then when the ram advances to the pre-selected penetration depth, a "data-stop" sensor is activated. The ram decelerates and returns to its initial position. An overshoot will occur due to the momentum of the ram and deceleration time. The ram velocity was set at 22 cm/s. The actual depth of penetration as well as the amount of surface fracture propagation will reflect the impact resistant characteristics of the material.

Results and Discussion

The optical and scanning electron microscope (SEM) photomicrographs of the composites reveal that the number of voids per square inch in the fine-sand/polyester layer is higher than in the coarse-sand/polyester concrete (Fig. 4*a*). However, the average ratio of the major lengths across the biggest void in the coarse sand and the biggest void in the fine sand is approximately seven to eight (Fig. 4*b*). This may be attributed to the difference in total surface areas of fine-

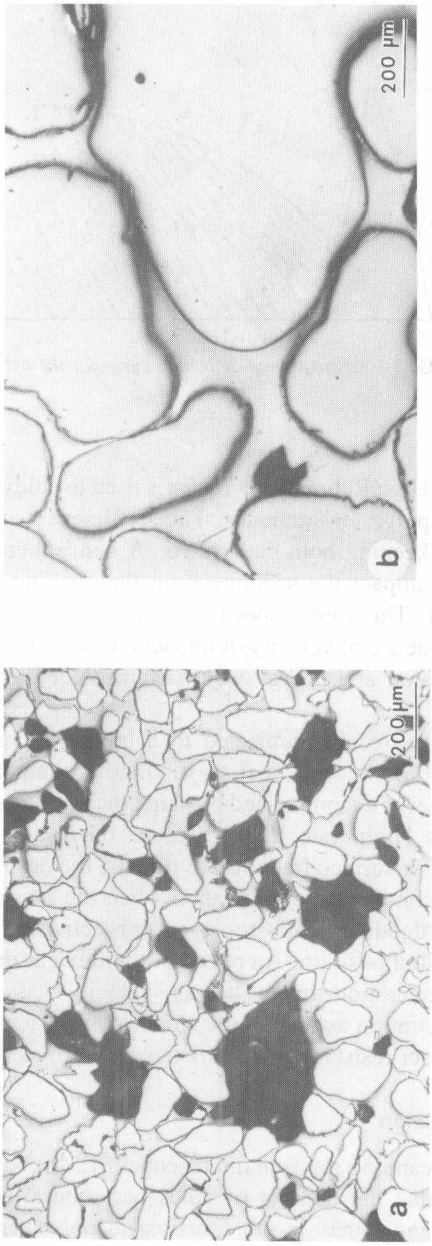

FIG. 4—*Photomicrographs showing voids and packing of (a) fine-sand and (b) coarse-sand particles in the polyester cements.*