On the efficiency of interleaves in carbon fibre/epoxy composite laminates by the fractal approach

Q. YUAN, J. KARGER-KOCSIS*
Institut für Verbundwerkstoffe GmbH, Universität Kaiserslautern, Pf. 3049, D-67653 Kaiserslautern, Germany

It is well documented in the literature how vulnerable laminates composed of unidirectional (UD) carbon fibre/epoxy (CF/EP) prepregs are to transverse single or multiple bounce low energy impacts [1–3]. Interleaving, i.e. incorporation of a non-reinforced thin adhesive layer between the prepregs, has been found to be effective to suppress the delamination caused by transverse static or dynamic loading. The adhesive layer (A) or interleaf in CF/EP composites is generally a modified EP resin, in some cases coated on a textile carrier fabric.

The efficiency of the interleaving can be evaluated in different ways. The techniques used are related to one or more of the following: determination of the onset of property degradation, evaluation of the residual mechanical properties after low-energy impact, and direct assessment of the delamination damage by (quasi) non-destructive methods. All of these tests are time-consuming and, in addition, they require skilled personnel. The aim of the study reported here was to find a simple and reliable way of ranking different interleaves in CF/EP laminates.

In a damage cone developed due to low-energy transverse impact across the thickness of a laminate the following individual failure events can be resolved: delamination and matrix cracking. From the viewpoint of the latter, shear and transverse type matrix cracking can be distinguished (Fig. 1). It was reported earlier that interleaving suppresses the delamination caused by transverse loading, and thus the cone of damage becomes narrower [4, 5]. At the same time, however, the crack density in the EP matrix seems to be increased. Supposing that the adherence of the interleaf to the neighbouring prepreg layers is the key factor of delamination suppression, and interleaving encourages the formation of less harmful matrix cracking, the fracture surface of the interleaf should indicate (at least implicitly) the efficiency of the interleaf.

In order to check the above working hypothesis, cross-ply CF/EP laminates were produced in the usual autoclave bagging process using Celion CF G30–500/Rigidite 5212 prepregs (BASF, Germany) [5]. The stacking sequence of the laminates was $[0_5/90_5/0_5]$. In the laminates three different interleaves were positioned between all crossing plies: modified EP resin on a non-woven polyester fabric (A1-Strukturkleber, BASF); modified EP (A2-FM300; American Cyanamid, USA) and polyethersulphone film (A3-PES; Litrex S, PCD, Austria). High-speed three-point bending impact was used at $v = 3.7\ \mathrm{m\,s^{-1}}$ to break the Charpy specimens cut from the laminates by means of an AFS-MK4 fractoscope (Ceast, Italy). The dimension of the Charpy specimens were 120 mm length × 6 mm width × ~4 mm thickness. Specimens for fractographic analysis and for determination of the surface roughness were taken from delamination sites along the interleaf in the laminates of $[0_5/A/90_5/A/0_5]$ lay-up, where A designates the interleaves (Fig. 2). The delamination site selected was near to the fracture surface induced by high-speed impact. The surface roughness was measured by a non-contact laser profilometer (UBM Messtechnik, Germany). A delamination area of area 1 mm × 1 mm was scanned with a resolution of 200 points $\mathrm{mm^{-1}}$ and converted into a three-dimensional roughness con-

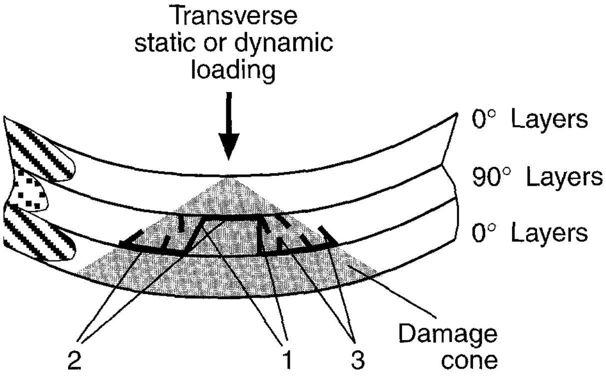

Figure 1 Damage cone and failure mechanisms involved in a cross-ply CF/EP laminate due to transverse loading. 1, Critical shear or transverse matrix crack; 2, delamination; 3, matrix microcracking.

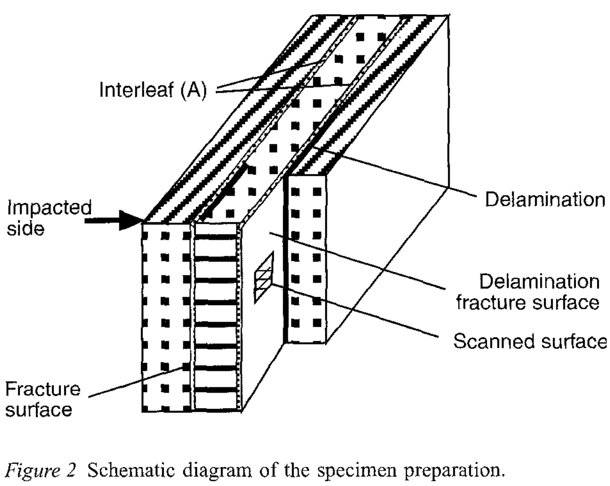

Figure 2 Schematic diagram of the specimen preparation.

*Author to whom all correspondence should be addressed.

0261-8028

tour plot by the UBM software. Mean surface roughness data were derived from at least five scans taken from different areas of the delamination. The topology of the delaminated surface was studied in a scanning electron microscope (SEM: Jeol 5400) after gold coating.

A comparison of the SEM images taken from the delamination sites of the non-interleaved and interleaved composites shows the difference in the surface roughness (Fig. 3). The roughness seems to increase according to: A3 < non-interleaved < A2 < A1. It should be emphasized that this qualitative ranking agrees with that of the resistance to low-energy transverse impact [6]. This fact supports our working hypothesis, outlined earlier.

Further attempts were made to quantify the topology of the delamination surface. Fig. 4 shows the surface height roughness profile in three-dimensional representation for the delamination sites of the composites. Fig. 4 confirms that the aforementioned roughness ranking holds. The surface height roughness was characterized by the following parameters [7]: ten-point height (R_z), central line average (R_a), root mean square roughness (R_q) and mean value of the maximum peak-to-valley height (R_{tm}), which are listed in Table I. The data in Table I demonstrate very clearly that the roughness ranking concluded from the SEM images (Fig. 3) is also correct on a quantitative base.

An alternative quantitative approach for characterization of the delamination surface relied on determination of the fractal dimension (D), proposed by Mandelbrot [8]. The suitability of this approach was also demonstrated for the materials' surface roughness [9, 10]. In our case D was calculated by the method of Gagnepain and Roques-Carmes [9]. This method, based on the original reticular cell counting (RCC) approach, is introduced briefly below. An initial square area of the delamination (in this case 1 mm × 1 mm) was divided into subsquares in n steps following the rule 2^{2n} (i.e. 1, 4, 16, 64 etc). After n iterations this yielded $N = 2^{2n}$ subsquares with a side length of $\lambda = 2^{-n}$. The fractal dimension (D) is defined by:

$$N = \lambda^{-D} = 2^{nD} \tag{1}$$

After n iteration steps the surface area of the squares (S) becomes:

$$S = N \cdot 2^{-2n} \tag{2}$$

Substitution of N from Equation 1 into Equation 2 yields:

$$S = 2^{nD} \cdot 2^{-2n} = 2^{nD-2n} \tag{3}$$

which can be converted for D:

$$D = 2 + \frac{\log S}{n \log 2} \tag{4}$$

Considering the fact that $N = 2^{2n}$, Equation 4 can be rewritten as:

$$D = 2 + \frac{2 \log S_s}{\log N} \tag{5}$$

which allows us to determine D from the slope of the log–log plot of S_s against N, where S_s denotes the topological (i.e. rough) surface (Fig. 5).

The fractal dimension D follows, of course, the same trend as the various roughness parameters (Table I). According to our impact fatigue tests using instrumented Charpy [6] and falling weight [5] set-

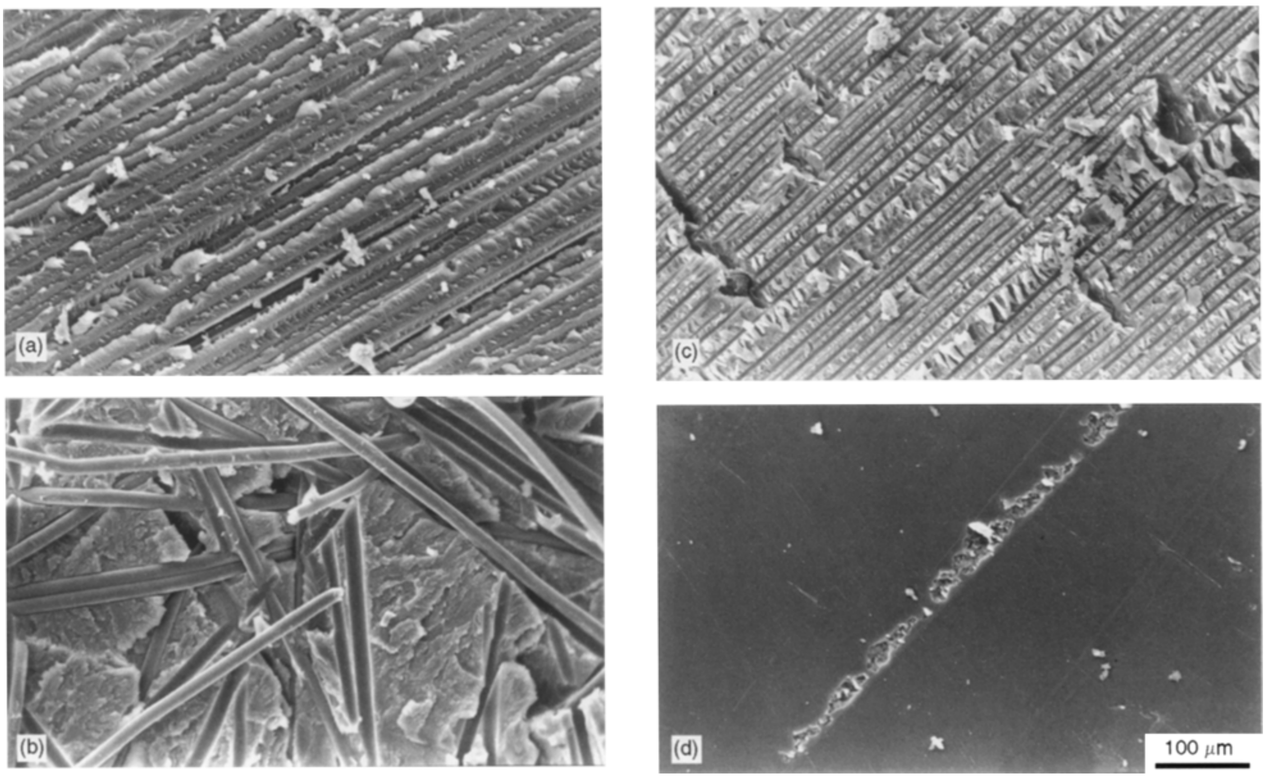

Figure 3 SEM micrographs taken from the delamination surface in cross-ply CF/EP laminates (a) without and (b–d) with interleaves: (b) A1, (c) A2 and (d) A3. Note: (b) shows that delamination occurred across the interleaf (cohesive failure) making visible the PET fibres of the carrier fabric.

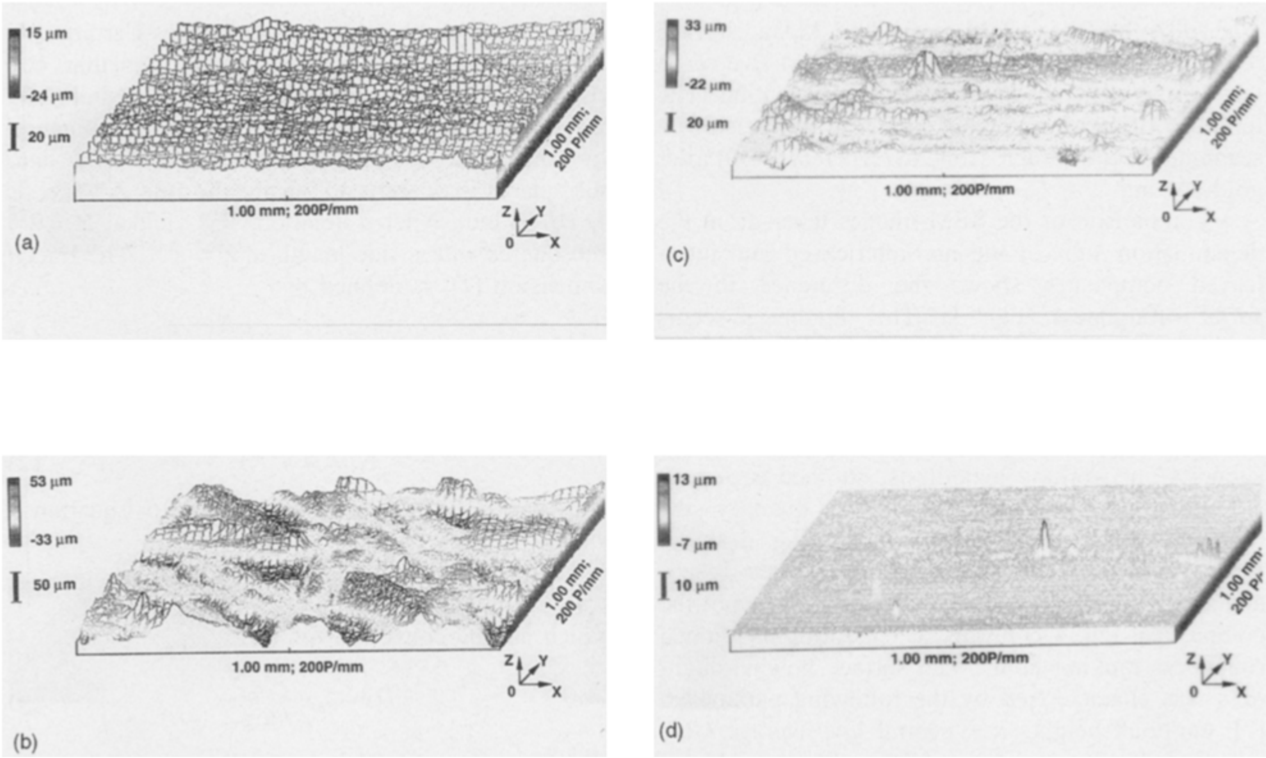

Figure 4 Three-dimensional contour plots of the roughness of the delamination surface in cross-ply CF/EP laminates (a) without and (b–d) with interleaves: (b) A1, (c) A2 and (d) A3.

TABLE I Surface height roughness values and fractal dimension (D) of the delamination site in CF/EP composite laminates without and with interleaves. The data represent mean values of at least five scans taken from various sites on the delamination surface

Composite	R_z (µm)	R_a (µm)	R_q (µm)	R_{tm} (µm)	D
CF/EP	35.1	4.0	5.2	38.4	2.107
CF/EP-A1	101.7	15.8	19.2	112.7	2.247
CF/EP-A2	50.8	4.5	5.9	66.5	2.124
CF/EP-A3	10.8	0.3	0.5	16.5	2.006

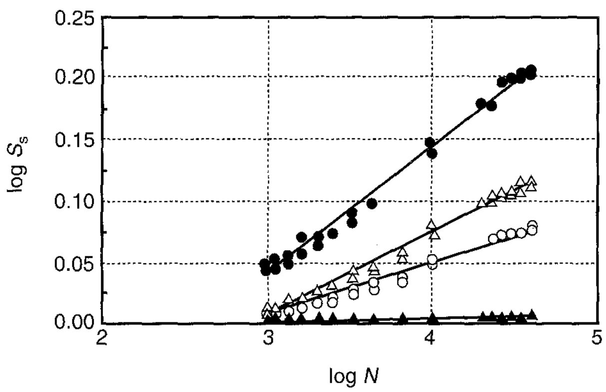

Figure 5 Log–log plot of the delamination surface (S_s) as a function of the number of subsquares selected (N). (○), CF/EP; (●), CF/EP-A1; (△), CF/EP-A2; (▲), CF/EP-A3.

up, for the efficiency of the interleaves the following ranking was deduced: A3 < non-interleaved < A2 < A1. This is in full harmony with the course of the D values (Table I). It can therefore be stated that the fractal approach on the topology of the delamination surface hints at the efficiency of the interleaf used. A basic requirement is, however, that the delamination site investigated should be characteristic and thus representative for the failure mode in the composite. The proposed method can be used for screening purposes for potential adhesive interlayers that might be incorporated in unidirectional fibre-reinforced composites with improved resistance to transverse loading.

Acknowledgement
Thanks are due to the DAAD for granting a PhD fellowship to Q. Yuan at the IVW in Kaiserslautern.

References
1. P. A. LAGACE, J. E. WILLIAMSON, P. H. W. TSANG, E. WOLF and S. THOMAS, *J. Reinf. Plast. Compos.* **12** (1993) 584.
2. H. Y. CHOI, H.-Y. T. WU and F.-K. CHANG, *J. Compos. Mater.* **25** (1991) 1012.
3. H. WANG and T. VU-KHANH, *ibid.* **29** (1995) 156.
4. C. T. SUN and S. RECHAK, in "Composite materials: testing and design", edited by J. D. Whitcomb, ASTM STP 972 (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1988) p. 97.
5. Q. YUAN and J. KARGER-KOCSIS, *Polym. Polym. Compos.* **3** (1995) 171.
6. Q. YUAN, K. FRIEDRICH and J. KARGER-KOCSIS, *Appl. Compos. Mater.* **2** (1995) 119.
7. G. W. STACHOWIAK and A. W. BATCHELOR, in

"Engineering tribology" (Elsevier, Amsterdam, 1993) p. 534.
8. B. B. MANDELBROT, "The fractal geometry of nature" (Freeman, San Francisco, California, 1983).
9. J. J. GAGNEPAIN and C. ROQUES-CARMES, *Wear* **109** (1986) 119.
10. T. R. THOMAS and A. P. THOMAS, *Surf. Topography* **1** (1988) 143.

Received 2 October
and accepted 6 December 1995