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PROBABILISTIC ASPECTS OF EVALUATION OF FIBRE-MATRIX ADHESION FROM PULL-OUT FIBRE LENGTHS ON FRACTURE SURFACES OF SHORT FIBRE COMPOSITES.

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ABSTRACT

A new method of evaluation of fibre-matrix adhesion in short fibre composites is proposed. The method is based on a comparison of experimental and model probability distribution functions of fibre pull-out length. The real pull-out lengths are measured on scanning electron micrographs of composite fracture surfaces. Two models for prediction of pull-out lengths are based on a known fibre length distribution in injection-moulded composites.

Keywords: short fibre composite, fibre-matrix adhesion, probability distribution function, fibre pull-out length.

INTRODUCTION

It is well known that the level of adhesion between fibres and matrix affects the ultimate thermomechanical properties of a composite. The usual experimental methods for estimation of adhesion are the fibre pull-out method and the fragmentation test, both relied on the use of single and long fibre. The most common techniques have been reviewed by Herrera-Franco and Drzal (1992). An indirect measure of the strength of an interfacial bond in laminates with continuous aligned fibres can be obtained from the fracture surface. When unidirectional composite is tested in longitudinal tension, an extensive fibre pull-out appears in case of weak interfacial adhesion. Calculation of the interfacial shear strength in composite with elastic fibre and plastic matrix have been carried out in the literature by Kelly-- Tyson (1965), expression based on the assumption of the maximum fibre pull-out length on fracture area being equal to half the critical fibre length. Random orientation and various length distribution of short fibres in injection molded composites are a fundamental obstacle to using this simple method. No satisfactory method of measuring of the bond level in short fibre composite with higher fibre volume fraction has been described so far.

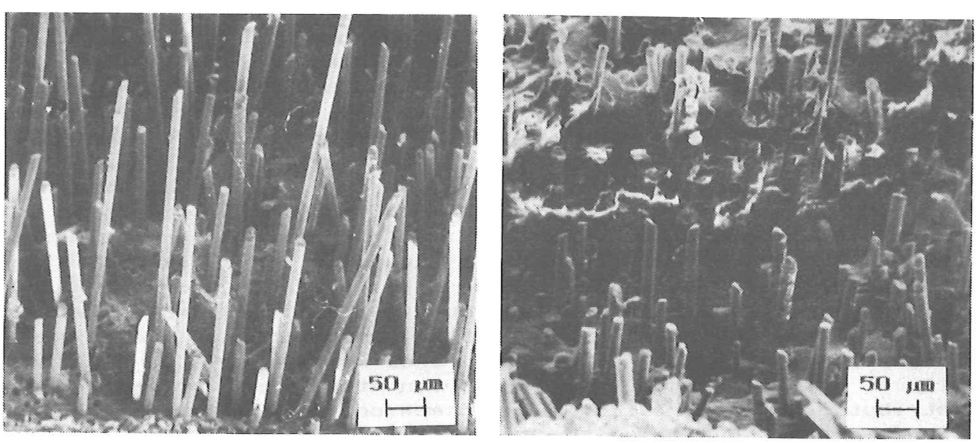
MATERIALS AND EXPERIMENTAL METHODS

The principal materials used in our investigation are listed in Table 1. Injection-moulded specimens for a Charpy impact tester were made from commercially available polymers and glass fibres.

Table 1. List of composite materials with 30 wt.% glass fibres.

Matrix	Designation
Polypropylene (homopolymer)	Taboren 30GF
Polypropylene (homopolymer)	Mosten 30GF (Union Carbide agent)
Polypropylene (modified PP)	Propathene HW60GR30 (ICI commercial product)
Polyamid 6 (Spolana)	Spolamid 30GF
Polyamid 6 (Rhône-Poulenc)	Technyl 30GF

Microstructural parameters of the composite such as fibre diameter and orientation distribution were determined by a measurement on optical micrographs of polished sections cut from the specimens. The fibre length distribution F was evaluated by a direct measurement of the length of each fibre after separation of fibres from under-surface layers of the composite after burning off the matrix.
Very sharp and shallow notches were made in a width direction of the centre span of Charpy specimens (cross-section 4x10 mm, 55 mm long) as initiators of brittle crack. The fracture surfaces were examined with a scanning electron microscope (SEM). Fibre pull-out length distribution F_e was determined from micrographs of the under-surface regions with unidirectionally aligned fibres near the notch tip (see Fig.1). Inclination angle 45° was taken into account in the true pull-out length calculation.



(a) (b)

Fig.1. Scanning electron micrographs of fractured specimens of injection moulded glass fibre reinforced plastics:
(a) polypropylene matrix, b) polyamide matrix
(tilt angle is 45°)

THEORETICAL MODELS

Our theoretical model of spatial distribution of parallel fibres in the matrix assumes Boolean segment process, i.e. centres of segments form a Poisson point process. The fibre lengths L are well described by a Weibull distribution

$$F(L) = 1 - \exp\left[-\left(\frac{L}{\theta}\right)^{\beta}\right], \quad L \geq 0 \qquad (1)$$

Let us now consider the situation when a brittle transverse crack of the matrix propagates across the composite and no fibre failure occurs. The result is represented by model A based on the assumption that fibres are only pulled out on their shorter side (see Fig.2, model A). Then the theoretical distribution function G of the pull-out length of fibres l is

$$G(l) = F(2l) + 2l \int_{2l}^{\infty} \frac{F(L)}{L}\, dL, \quad l \geq 0 \qquad (2)$$

where the integral part defines the incomplete gamma function. However, for commercially available compounds with low fibre length and a strong fibre-matrix bond the model has to be modified to include:

- partial sliding fibres in matrix at their longer part
- tension failure of fibres

We propose a model B for partial slide l_v of the fibre length l_p (see Fig.2, model B)

$$l_v = l_p \exp[-(L-l_p)/c], \quad c > 0 \qquad (3)$$

where l_p is pull-out length in model A. (3) gives the protruding length of fibre l_t

$$l_t = l_p + l_v = l_p\,(1 + \exp[-(L-l_p)/c]) \qquad (4)$$

Because there is a positive failure probability P of the longest fibre bridging the brittle crack of matrix (see Fig.2), we assume (for unknown critical length of fibres) that all fibres longer than the quantile $L_{0,95}$ of original length L have a failure probability P = 1. There exists a constant K such that P = 0 for $L \leq K$ and $P = (L-K)/(L_{0,95}-K)$ for $K \leq L \leq L_{0,95}$. The random position B of fibre failure is modelled by a fixed distribution function H:

$$H(x) = \frac{x^2}{L\, l_p}, \qquad x \in \langle 0, l_p) \qquad (5)$$

$$H(x) = 1 - \frac{(L-x)^2}{L(L-l_p)}, \qquad x \in \langle l_p, L\rangle \qquad (5)$$

with mode l_p corresponding to maximal stress location. Assuming not more then one failure of the fibre we obtain the total length of protruding

$$l_t = (l_p - B)(1 + \exp[-(l - l_p)/c]) , \quad B < l_p$$
$$= (B - l_p)(1 + \exp[-l_p/c]) , \quad l_p \le B < 2l_p \quad (6)$$
$$= l_p (1 + \exp[-(B - l_p)/c]) , \quad B \le 2l_p$$

The formula for the distribution function of l_t given by (4) and (6) is analytically insolvable. However, a Monte-Carlo algorithm using (1) - (6) enables to obtain the value of l_t. Thus for given c, K and parameters Θ, β of the random length L in (1), an empirical distribution function F_s of l_t is obtained by computer simulation. The desired optimal values c, K are solutions of the problem:

$$\min_{c,\,K} Q, \text{ where } Q = \max_{l} |F_e(l) - F_s(l)| \quad (7)$$

F_e being the experimental distribution function of pull-out length in the specimen.

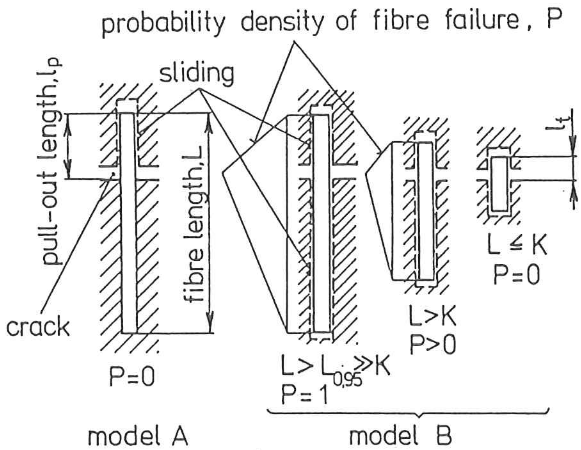
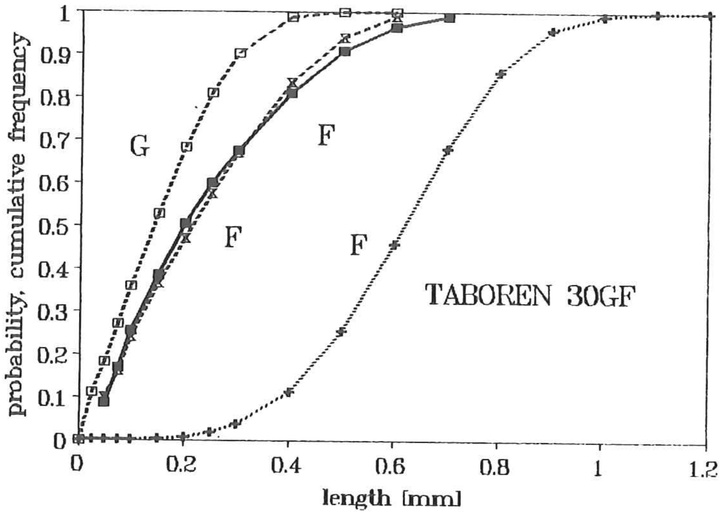


Fig.2. Schematical diagram of short fibre composite fracture ahead of a notch. Model A - without fibre failure and one-side sliding of fibre, model B - with fibre failure and two-side sliding.

RESULTS AND DISCUSSION

The curves of theoretical probability distribution function G (model A) and experimental distribution function (cumulative frequency) F_e of pull-out lengths, original length distribution F, and computer simulated distribution F_s (model B) for two composite materials, Taboren 30GF and Spolamid 30GF, are shown in Fig.3.



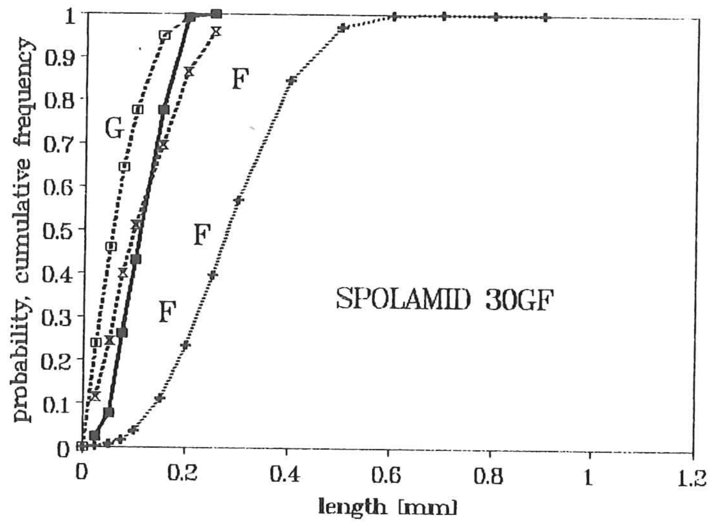


Fig.3. Probability distribution of length F, experimental pull-out length F_e, theoretical pull-out length G (model A) and computer simulated distribution F_s (model B).

When either the distribution function G is on the right side of the experimentally determined function F_e or there is an intersectioning of G and F_e and a maximum fibre pull-out length

l_{max} of the distribution F_e is smaller $L_{0,95}/2$ (the theoretical maximum pull-out length), a significant fibre failure occured during crack propagation. The fibre-matrix bond strength can be calculated from a critical fibre length $l_c = 2l_{max}$ by the Kelly-Tyson expression.

The polypropylene composite (Fig.3 above) exhibits fibre length $L_{0,95}$ = 0,887 mm and maximum pull-out length l_{max} = 0,55 mm. The critical length l_c can not be evaluated. However, there is intersectioning of the distribution G and F_e for a polyamide composite and maximum experimental pull-out length of fibre l_{max} = 0,18 mm is lower the theoretical maximum pull-out length $L_{0,95}/2$ = 0,235 mm ($L_{0,95}$ = 0,47 mm), see Fig.3 below. This is a confirmation of the failure of the longest fibres. Therefore, the critical length of fibre can be obtained as $l_c = 2l_{max}$ = 0,36 mm. The other l_c have been treated identically (see column l_c in Table 2).

Results of the computer simulation are shown in Table 2.

Table 2. Variation in model parameters with composite type.

short fibre composite (abbr.)	parameters						
	θ	β	$L_{0,95}$ mm	K	c	$\frac{K}{L_{0,95}}$	l_c mm
MOSTEN	0,578	2,31	0,93	0,315	0,15	0,339	0,8
TABOREN	0,676	4,05	0,887	0,865	0,78	0,975	
PROPATHENE	0,663	3,467	0,909	0,595	0,09	0,654	0,62
SPOLAMID	0,319	2,806	0,47	0,405	0,56	0,861	0,36
TECHNYL	0,295	2,412	0,465	0,334	0,46	0,718	0,32

It may be concluded that pull-out of fibres becomes negligible for lower value of parameter c and no major fibre fracture occured during crack propagation for values of normalized parameter $K/L_{0,95}$ near to 1. F_B gives a better fit of the F_e for material in which prevailing pull-out fibres occurs, it follows that the model B is appropriate. It is the objective of further study to obtain a better fit for materials with extensive failure of fibres. This can be solved by increasing the number of parameters in a model of probability and location of fibre failure.

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