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Contract U.S. AIR FORCE/ARMINES-
Centre des Matériaux

THE DEPENDANCE OF DAMAGE ACCUMULATION IN
CARBON FIBRE REINFORCED EPOXY COMPOSITES
ON MATRIX PROPERTIES

86 4   02

AD A 166 577

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS N/A		
2a SECURITY CLASSIFICATION AUTHORITY UNCLASSIFIED	3 DISTRIBUTION/AVAILABILITY OF REPORT		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	A		
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-85-0397		

6a. NAME OF PERFORMING ORGANIZATION Ecole Nationale Superieure des	6b OFFICE SYMBOL (If applicable) N/A	7a NAME OF MONITORING ORGANIZATION EOARD
6c ADDRESS (City, State, and ZIP Code) Mines de Paris, B.P. 87 F-91003 Evry Cedex France		7b ADDRESS (City, State, and ZIP Code) Box 14 FPO NY 09510
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFWAL	8b OFFICE SYMBOL (If applicable) MLBM	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB, OH 45433	10 SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO. 61102F	PROJECT NO. 2301	TASK NO. D1	WORK UNIT ACCESSION NO. 185

11. TITLE (Include Security Classification)
THE DEPENDANCE OF DAMAGE ACCUMULATION IN CARBON FIBRE REINFORCED EPOXY COMPOSITES ON MATRIX PROPERTIES (UNCLASSIFIED)

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT FINAL SCIENTIFIC	13b. TIME COVERED FROM 30Sep84 TO 29Sep85	14. DATE OF REPORT (Year, Month, Day) DECEMBER 1985	15. PAGE COUNT 44

16 SUPPLEMENTARY NOTATION

17. COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Composites, Damage accumulation, Durability, Matrix propertie

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Two types of fibre reinforced resin specimens have been tested, each having the same type of fibre but with very different resin systems. In this way the effect of matrix properties on carbon fibre reinforced resin systems has been studied. Steady loads on unidirectional specimens have confirmed that far from being the unresponsive purely elastic bodies that most measuring techniques suggest the acoustic emission technique reveals the continuous accumulation of internal damage. The acoustic emission behaviour is characterized by curves of $\ln(dt/dN)$ as a function of total accumulated emissions which typically shows two asymptotic slopes, one at the origin, the other at infinity. An analytical expression has been proposed to describe this behaviour involving four parameters. The rate of damage accumulation has been shown to be greatly influenced by the properties of the matrix, with an increased rate observed with a resin containing a high percentage of plasticizer. The histograms of the

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☑ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete.

amplitude distributions reveal a peak at 25 db at low stresses which is seen to be displaced towards 40 db at higher applied loads. It is concluded that the peak at 40 db is due to fibre failure whereas the lower peak may be due to microcracking of the matrix. The study has revealed that period of overloading are equivalent to accelerated mechanical aging at lower loads.

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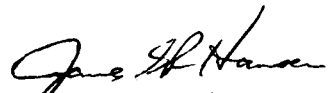REPLY TO
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26 March 1986

SUBJECT: EOARD-TR-86-04, Final Scientific Report, "The Dependance of Damage Accumulation in Carbon Fibre Reinforced Epoxy Composites on Matrix Properties

TO: DTIC/Air Force Liaison Representative
Cameron Station
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    Structural Materials

2 Atchs
1. EOARD-TR-86-04 (2 cys)
2. DD Form 50

cc: EOARD/CMX
    EOARD/CI

CONTRACT U.S. AIR FORCE/A.R.M.I.N.E.S. - Centre des Matériaux

N° A.F.O.S.R. 84-0397

Final Report

December 1985

THE DEPENDANCE OF DAMAGE ACCUMULATION IN CARBON

FIBRE REINFORCED EPOXY COMPOSITES ON MATRIX PROPERTIES

A.R. BUNSELL - B. PONSOT

S U M M A R Y

I. INTRODUCTION

The object of this study was to reveal the importance
of the properties of the matrix in determining the rate of da-
mage accumulation in carbon fibre reinforced epoxy resin. The
specimens tested were in the form of flat plates which were sub-
jected to mechanical loading. It is thought that a better under-
standing of the processes involved in damage accumulation will
improve predictions of long term behaviour of composite struc-
tures.

In the case of unidirectional carbon-epoxy loaded paral-
lel to the fibres it is known that the overall behaviour is
elastic [1]. At the microscopic level however it has been shown
that this is not the case and fibre failure under steady loads
can be detected by the acoustic emission technique [2].

The role of the matrix in a composite is to ensure the
structural integrity of the material. Reinforcement is assured
by the fibres which can continue to contribute to the load
bearing capacity of the composite, even if broken, due to load
transfer by shearing of the matrix around the break which in
this way is isolated. The length over which the matrix is shea-
red around a fibre break depends on the rigidity of the matrix
and time dependent effects can be proposed if the matrix is
viscoelastic.

In order to study the effects of matrix properties pla-
te specimens were made with three types of resins having very
different mechanical properties. These specimens were tested
under various loading conditions and the internal damage which
accumulated was monitored by acoustic emission and compared to
a previously developed failure model [3].

II. FAILURE MODEL

No classical model based on fracture mechanics is able to predict failure in unidirectional carbon fibre epoxy specimens loaded parallel to the fibres. This is equally true for many filament wound structures in which the fibres are positioned to carry most of the applied stresses. Fracture mechanics assures that the material behaves as a continium and fails by the propagation of two fracture surfaces. The composites considered in this study fails by the accumulation of internal damage which, in the absence of stress raisers, occurs throughout the body of the structure. Carbon fibre epoxy resin is usually considered as being perfectly elastic when loaded in the direction of the fibres however delayed failure of even unidirectional cfrp has been reported indicating non elastic behaviour and the time dependent accumulation of damage [4,5]. The viscoelastic properties of the matrix must be considered as being at the origin of this time dependent behaviour as it is known that carbon fibres are purely elastic at room temperature.

Rosen's model of failure of a unidirectional composite material is based on the weakest link idea and the failure scenario described below is based on a similar approach but taking into account the viscoelastic nature of the matrix [6]. The failure of a fibre in a bundle of fibres subjected to a steady load increases the load on all the other remaining intact fibres in the bundle. In the absence of a matrix the over load experienced by the intact fibre occurs at every point over their whole length. Subsequent failure of fibres will as a consequence be unrelated to the point of failure of the broken fibre and only due to the distribution of weakening defects on the fibres. If instead of a fibre bundle a unidirectional composite is considered the effect of the fibre break is restricted to a small section of the composite due to load transfer through the matrix at the broken ends of the fibre. The zone

over which the increase in load is experienced by fibres neigh-
bouring a fibre break depends on the shear properties of the
matrix, the quality of the interface and the Young's modulus
of the fibre. If the properties of the matrix are time
dependent this zone can increase in length along the fibre due
to relaxation of the matrix and so its effect on neighbouring
fibres will vary. This behaviour has been evoked by Rotem and
Lifschitz to explain delayed failure in composites [7].

It has been observed that when unidirectional cfrp
specimen is subjected to a constant load in the fibre direction
the emission rate decreases with time. It is reasonable to
assume that the emissions are directly related to internal da-
mage accumulation and that in this case the principal source
of emissions are fibre breaks. Laroche and Bunsell [2], studying
a rigid matrix cfrp in which the resin was the CIBA GEIGY 914 C
epoxy resin, showed that the rate of emissions obeyed a law of
the form :

$$\frac{dN}{dt} = \frac{A}{t + \tau} \tag{1}$$

where t is time

$\quad$ τ a time constant

$\quad$ A a function of the applied stress

Developing this relation we obtain :

$$\log \frac{dt}{dN} = \frac{N}{A} + \log \frac{\tau}{A} \tag{2}$$

so that the gradient of a plot of $\log \frac{dt}{dN}$ against $f(N)$ gives $\frac{1}{A}$.

A more general relationship was later proposed by
Valentin and Bunsell [3] such that :

$$\frac{dN}{dt} = \frac{A}{(t + \tau)} \tag{3}$$

where n is a dimensionless parameter.

It was observed that for cfrp with a rigid matrix, n = 0,99 and the value of n represented the variation from linearity with the curve being more closely described by

$$\log \frac{dt}{dN} = \log \frac{\tau^n}{A} + \frac{n}{1-N} \log[1 + \frac{N\ (1-n)}{A\ \tau^{(1-n)}}]\qquad(4)$$

Equation (4) has been successfully applied to the emission recorded from unidirectional plates subjected to steady loads. Long term tests reveal however that the curve tends to an asymptote. The curve therefore presents two asymptotes, one at the origin with a gradient C1 and at infinity of gradient C2. The asymptote at infinity is of particular importance as it is its stage which describes damage accumulation during long term steady loading and which can indicate time to failure. The acoustic emission behaviour tends to the second asymptote very quickly in the case of rigid matrices, loaded parallel to the fibres as described previously [2 , 3]. The use of more flexible resins emphasizes the initial behaviour.

As a first approach it has been assumed that the acoustic emission behaviour results from two distinct mechanisms resulting in different emission rates but governed by the same type of law such that :

$$\frac{dN}{dt} = \frac{A_1}{t + \tau_1} + \frac{A_2}{t + \tau_2}\qquad(5)$$

with $A_2 \gg A_1$ and $\tau_2 \gg \tau_1$

This expression was proposed by Valentin [8] in order to describe the acoustic emission behaviour of crossplied cfrp specimens with $(\pm45°)_s$ and $(\pm30°)_s$ lay ups. A second approach is to modify the initial expression by adding a term which become negligable as the number of emissions increases.

Thus, the initial expression proposed by Laroche and
Bunsell [2]

$$N = A \log \frac{t + \tau}{\tau}$$

becomes :

$$N = a \log \left(\frac{t + c}{b}\right) + g(N) \qquad (6)$$

where a, b, c are constants

t the time

g(N) tends to zero as N tends to N_{max}

N = 0 when t = 0

So that :

$$a \log \frac{c}{b} + g(0) = 0$$

and

$$C = b \exp\left(-\frac{g(0)}{a}\right)$$

If we write :

a = 1/K1.

b = K2.

C = K2 exp [− K1 g(0)]

we have :

$$N = \frac{1}{K1} \log \left(\frac{t + K2 \exp(-K1.g(0))}{K2}\right) + g(N)$$

Putting :

N = 0 and t = 0

we obtain :

$$\frac{t + K2. \exp\left[- K1. \; g(0)\right]}{K2} = \exp \quad \left[K1 \; (N - g(N))\right]$$

so that :

$$t = K2 \; \left[\exp \left[K1 \; (N - g(N))\right] - \exp \; (- K1. \; g(0))\right] \qquad (7)$$

and :

$$\frac{dt}{dN} = K1. \; K2 \; (1 - \frac{dg}{dN} \; (N)) \; \exp \left[K1 \; (N - g(N))\right]$$

therefore :

$$\log \frac{dt}{dN} = \log \; (K1 \; K2) + \log \; (1 - \frac{dg}{dN}(N)) + K1 \; (N - g(N)) \qquad (8)$$

with $g(N) \longrightarrow 0$

when $N \longrightarrow N_{max}$

If we put $\qquad \frac{dg}{dN} \; (N) \longrightarrow 0$

when $N \longrightarrow N_{max}$

equation (8) gives a straight line for $\log \frac{dt}{dN}$ as a function of N when N becomes large.

We have therefore a general expression which includes two constants K1 and K2 and a function of N which has still to be defined. The experimental curve obtained by recording $\log \frac{dt}{dN}$ as a function of N can be described by four constants C1, C2, C3, C4 as shown in Figure 1 where :

C1 is the gradient at the origin

C2 is the gradient at infinity

C3 is the ordinate of the second asymptote at N = 0

C4 is the ordinate of the curve at N = 0
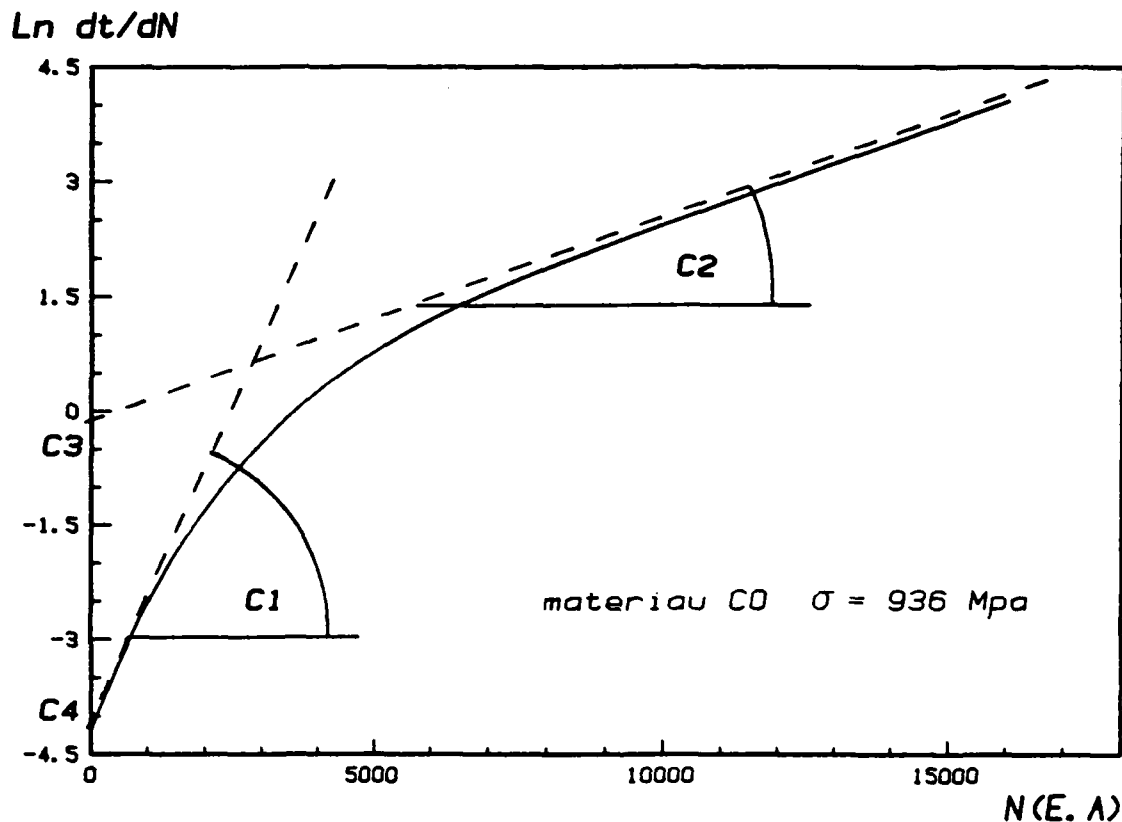

Figure 1 : Experimental curve giving the four constants C1, C2, C3, C4.

It is therefore necessary to calculate the constants Ki as a function of the constants Ci.

The gradient of the curve at the origin C1 is :

$$\frac{d\ (\log \frac{dt}{dN})}{dN} = K1 - K1\ \frac{dg}{dN}\ (N) + \frac{-\frac{dg^2}{dN^2}\ (N)}{1 - \frac{dg}{dN}\ (N)} \tag{9}$$

$$C1 = \lim \frac{d\ (\log \frac{dt}{dN})}{dN}\ (N)$$

$$N \longrightarrow 0$$

The gradient at infinity C2 :

$$C2 = \lim \frac{d\ (\log \frac{dt}{dN})}{dN}\ (N) \tag{10}$$

$$N \longrightarrow N_{max}$$

If we put $\frac{dg^2}{dN^2}\ (N) \longrightarrow 0$ when $N \longrightarrow N_{max}$ we see that $C2 = K1$

as under these conditions $\frac{dg}{dN}\ (N)$ tends to 0

The ordinate of the asymptote at N=0 giving C3 is described by an equation of the form :

$$H(N) = \log K1K2 + K1.\ N$$

putting $N = 0$ $H(0) = \log K1K2$

so that $C3 = \log K1K2$ $\tag{11}$

The ordinate for the curve when N = 0 gives C4 so that :

$$C4 = \log K1\ K2 + \log (1 - \frac{dg}{dN}(0)) - K1.\ g(0) \qquad (12)$$

The following conditions are therefore necessary as N tends to N_{max}

$$g(N),\ \frac{dg}{dN}(N),\ \frac{d^2g}{dN^2}(N) \longrightarrow 0$$

Putting $\qquad g(N)$ in the form $g(N) = \exp [- K3N + K4]$

with $\qquad K3 > 0$ we see from equation (8) that :

$$\log \frac{dt}{dN} = \log K1\ K2 + \log (1 + K3\ e^{-K3N+K4}) + K1\ (N - e^{-K3N + K4}) \qquad (13)$$

with the following conditions for the constants :

(a) $C1 = K1\ (1 + K3\ e^{K4}) - \dfrac{K3^2\ e^{K4}}{1 + K3\ e^{K4}}$

(b) $C2 = K1$

(c) $C3 = \log K1\ K2$

(d) $C4 = \log K1\ K2 + \log (1 + K3\ e^{K4}) - K1\ e^{K4}$

If

(e) $K5 = 1 + K3\, e^{K4}$ with $K5 > 1$ as $K3 > 0$.

such that $e^{K4} = \dfrac{K5 - 1}{K3}$

(a) $-K3 = (C1 - C2K5)\, \dfrac{K5}{K5 - 1}$

(d) $C3 - C4 + \log K5 + \dfrac{C2\,(K5 - 1)^2}{(C1 - C2\,K5)\,K5} = 0$

we have $C3 - C4 > 0$ $C3 > C4$

$\log K5 > 0$ $K5 > 1$

$C2 > 0$

which gives : $C1 - C2K5 < 0$ ou $K5 > \dfrac{C1}{C2}$

As the gradient at the origin is always greater than the gradient at infinity we have $C1 > C2$ which verifies the relation :

$$K5 > \frac{C1}{C2} > 1.$$

We therefore have a non linear relationship for $K5$ (d) which can be solved by a numerical method so allowing $K3$ and $K4$ to be calculated

(a) $K3 = (C2K5 - C1)\, \dfrac{K5}{(K5 - 1)}$

(e) $K4 = \log \left(\dfrac{K5 - 1}{K3}\right)$

It is only necessary to adjust the values of the four constants K1, K2, K3, K4 as a function of the experimental points as explaining in Annex 1. In this way an expression for the diagram of $\log \frac{dt}{dN}$ as a function of $f(N)$ is obtained

$$\log \frac{dt}{dN} = \log K1K2 + \log (1 + K3 \ e^{-K3N \ + \ K4}) + K1 \ (N - e^{-K3N+K4}) \quad (13)$$

An example of this calculation is given in Figure 2 and it can be seen how the experimental values fit the calculated curve very closely.
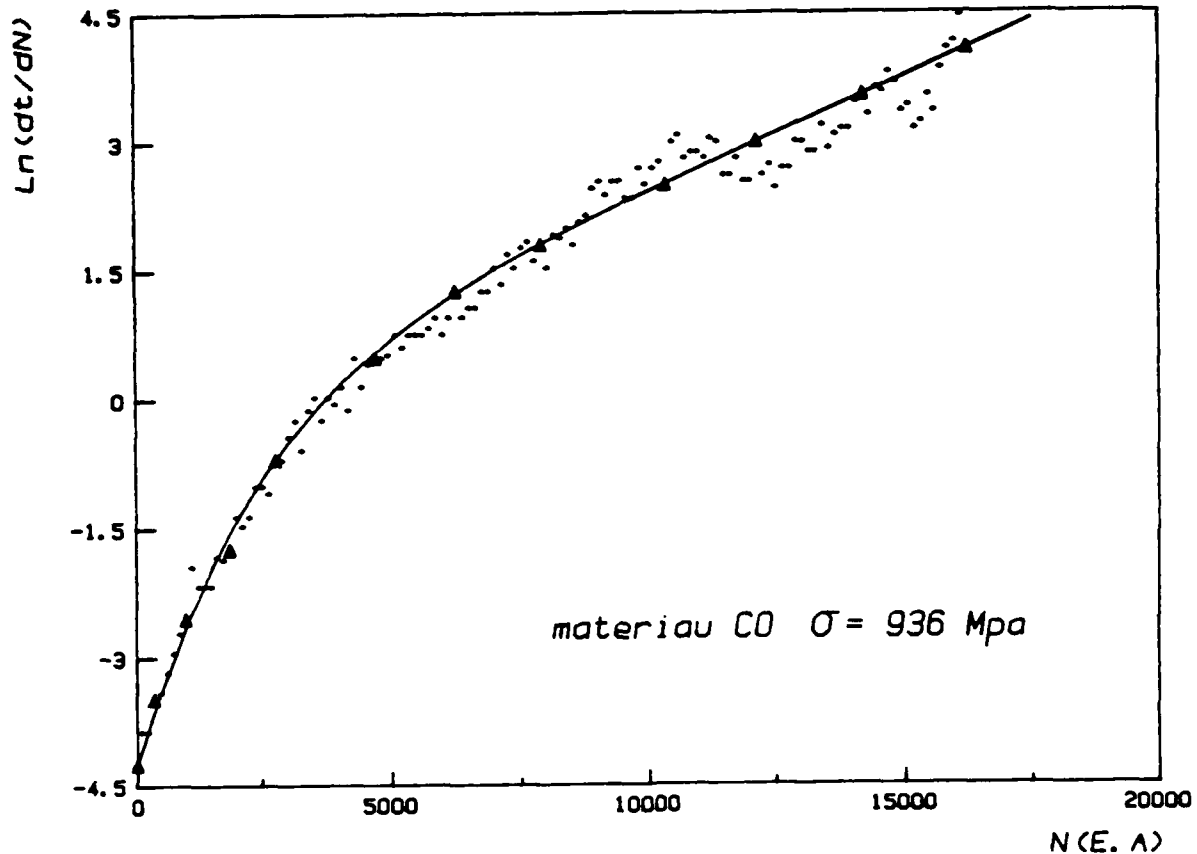

Figure 2 : Exemple of a calculated curve fitting experimental values

III. EXPERIMENTAL METHODS .

III-1. Matrix systems

In order to test composites reinforced with the same type of carbon fibres (T300) but with matrix materials with very different behaviours it was necessary to make our own specimens from unimpregnated tow and different types of resins. The resin systems were chosen as they gave very different properties, particularly in elongation and creep behaviour but should not be considered as possible systems for composite structures.

Two such systems were made using different ratios of the CIBA GEIGY resins CY 208 a plasticizer and CY 205 as shown in Table (1). The two systems gave resins with very different properties.

	CY 208	CY 205	Fibres
Composite CO	70 %	30 %	T 300-B
Composite C1	30 %	70 %	T 300-B

Table (1) : Formulation of the resin systems studied

III-2. Composite fabrication

Unidirectional plates were made by filament-winding on a machine developed for this study and shown in Figure 3. The fibre tow passed into a heated bath containing the resin system and was impregnated by the resin. After leaving the bath, excess resin was removed from the tow as it passed over a free turning
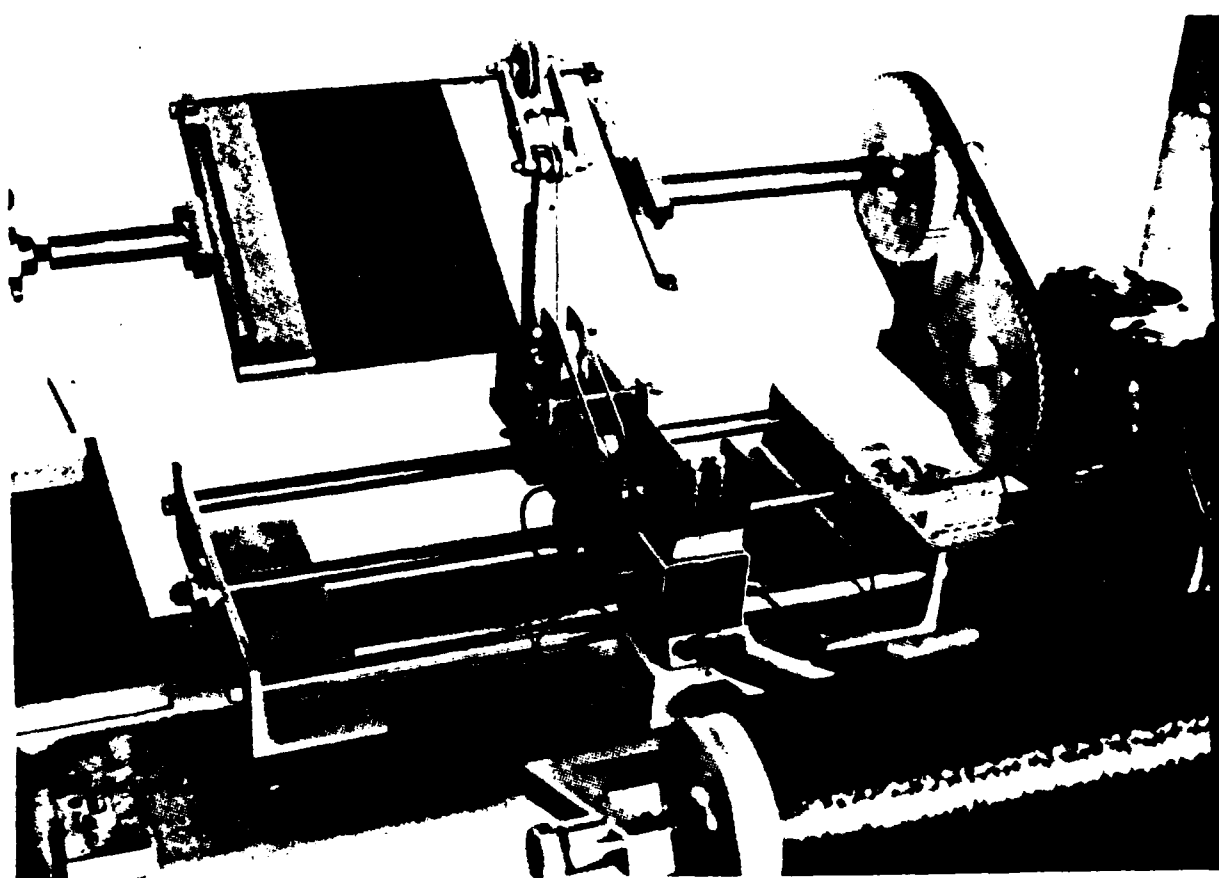
Figure 3 : Impregnation and filament winding apparatus

drum. The tow was then wound onto a mandrel in the form of a
flat plate. Curing of the system took place after filament
winding was complete and involved hot pressing the material
using two flat plates which were placed against the mandrel.

III-3 . Specimens

Unidirectional specimens were cut from the plates
which had been made as described above. The specimens were
17 mm Wide and 0.7 mm thick. Steel tabs were glued to each end
of the specimens to protect them in the grips of the tensile
machine. The tabs and specimens were drilled so that the load
was transferred via a circular pin. The gauge length of the
specimens was 100 mm.The fibre volume fraction was measured to
be of around 53 %.

Pure resin specimens were cut from plates made with
the proportions shown in table (1). These specimens were 15 mm
wide by 4 mm thick with a gauge length of 30 mm. It was neces-
sary to develop a strain measurement technique capable of mea-
suring strain of 60-70 %. The gauges consisted of two induction
displacement transducers giving a total displacement of 70 mm.
To avoid problems of flexing the average of the two signals
was used.

III-4 . Acoustic Emission Monitoring

All tests were monitored with a Dunegan-Endevco 3000
series acoustic emission apparatus. A piezo electric transdu-
cer, type D140B was used with a resonance frequency at about
200 KHz. The transducer was fixed to the centre of the speci-
men and acoustic coupling ensured by silicone grease.
Amplification of the signal was of 95 db (40 db from
the preamplifier and 55 db from the main amplifier).
The counting system used a threshold level of 25 db, the db measure-
ments were given in reference to a signal of 1 uV at the trans-
ducer. The signal was then analyzed as the number of accumula-

ted pulses, or by the use of an enveloppe generator as the number of events by introducing a dead time period after the recording of each signal. The dead time was chosen to be 100 µs. In addition a logarithmic time base with a reset to zero after a fixed number of events ΔN was also used. In this way it was possible to plot directly the curve of ln dt/dN as a function of N.

IV. EXPERIMENTAL RESULTS

IV-1 . Pure resin specimens

The aim of these tests was to reveal the differences of behaviour between the two types of resins used. Table (2) gives the properties measured with each type of resin.

Resin	σ_R (MPa)	ε_R (%)	σ_Y (MPa)	ε_Y (%)	E (MPa)
R 0	40	4	13	0,6	2200
R 1	50	1	25	0,6	4000

Table (2) : Properties of the two resin systems employed

Tensile tests were conducted at a strain rate of 8 mm/mn. There was considerable scatter in the results of strength and failure strain, most probably due to internal defects produced during manufacture. It was decided to characterize the material as a function of the pseudo-yield stress σy beyond which the behaviour was no longer linear, see Figure 4.
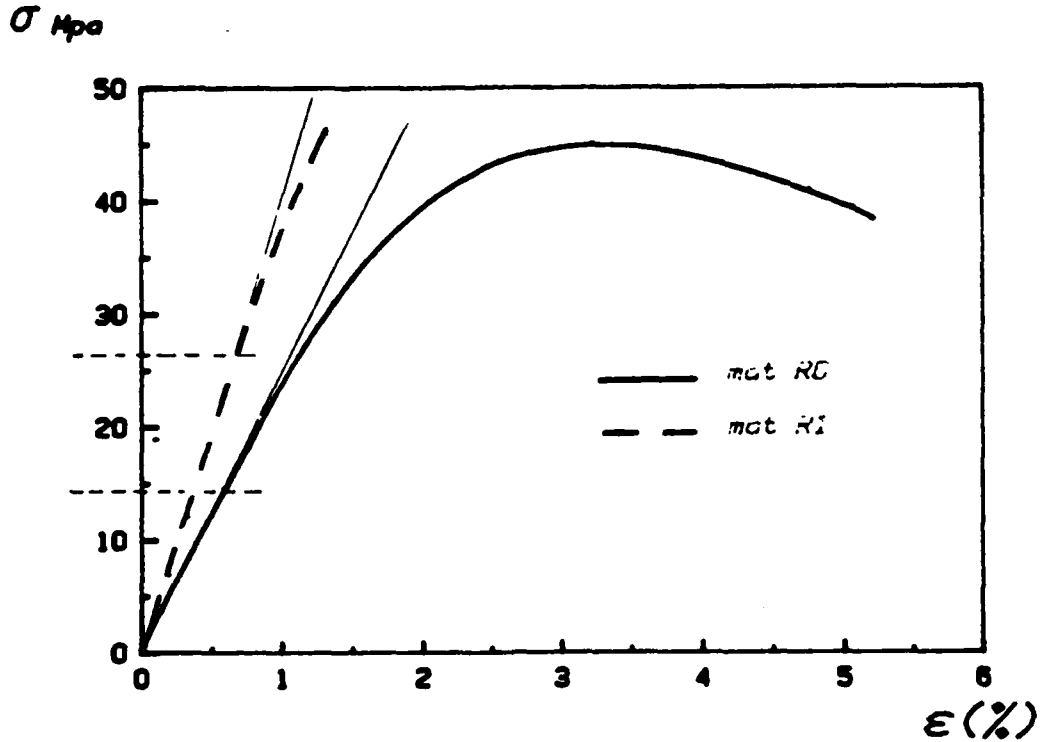
Figure 4 : Stress-strain curves of the two resin systems

Creep tests were conducted with reference to the pseudo
yield stress and were conducted on a Mayes creep machine.
The RO resin deformed greatly with breaking strains often
being of about 60 %. It was assumed as a first approximation
that the volume of the specimen remained constant so that :

$$\sigma(t) = \sigma(0) \times [1 + \varepsilon(t)]$$

In order to compare the behaviour of the two materials
we could also study the evolution of the modulus $E(t)$ or its
compliance

$$D(t) = 1/E(t)$$

so that $E(t) = \dfrac{\sigma(t)}{\varepsilon(t)} = \dfrac{\sigma(0) \cdot [1 + \varepsilon(t)]}{\varepsilon(t)}$

$$D(t) = \frac{\varepsilon(t)}{\sigma(0) \cdot [1 + \varepsilon(t)]}$$

The results of several tests are shown in Figure 5. Two distinct regions can be seen which show clearly the differences in behaviour between the two resin systems. The composites made with the system RO were therefore expected to reveal a greater effect of the time dependent properties of the matrix than the composites made with the R1 system. Lifschitz and Rotem [7] have shown that the stress along a broken fibre varies as a function of time such that:

$$\sigma(x,t) = \sigma o \cdot [1 - \exp\{-(J(t) \cdot A)^{-\frac{1}{2}} \cdot x\}]$$

when $J(t)$ is the shear compliance

t   is the time

x   is the distance from the point of failure

σo is the stress in the fibre far from the failure

and $A = Ef \cdot rf \cdot (rm - rf)/2$

where Ef is the fibre Young's modulus

rm is the radius of the cylinder of matrix around the fibre

rf is the radius of the fibre

We have studied the tensile compliance of these materials however it is to be noted that if $D_{Ro}(t) > D_{R1}(t)$ then $J_{Ro}(t) < J_{R1}(t)$ so that at the same distance x_1 from the failure and after the same interval of time t_1 we have :

$$\sigma_{CO}(x_1, t_1) < \sigma_{C1}(x_1, t_1)$$

It is therefore necessary to have a greater load transfer length with the resin system RO and neighbouring fibres are therefore subjected to a higher load over a greater length than with the R1 system.
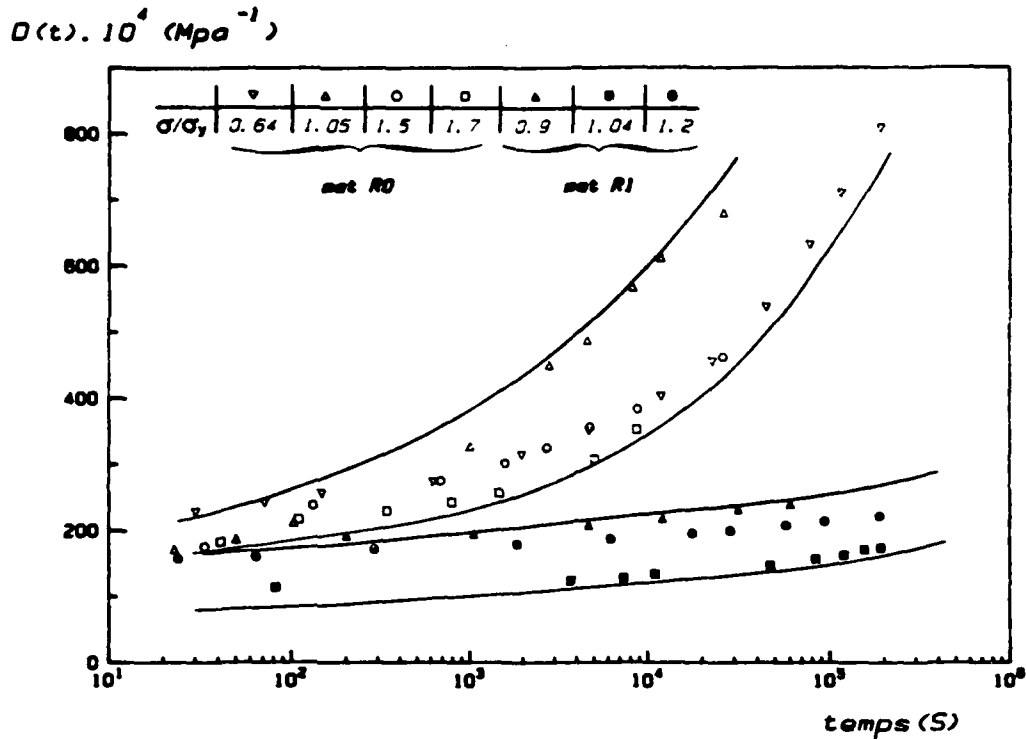
$D(t). 10^4 (Mpa^{-1})$

Figure 5 : Tensile compliance of the R0 and R1 resin systems

IV-2 . <u>Composite specimens</u>

- Tensile test :

In order to characterize the materials tensile tests were conducted on the two types of composites C0 and C1. Tests were conducted at a rate of 0,05 cm/mm. Table (3) gives the results

Composite	$\overline{\sigma}_R$ (MPa)	Mean deviation (MPa)
C0	1260	148
C1	1143	68

Table (3) : Mean results of tensile tests on the two composite systems

The average fibre volume fraction was 53 %. Figure 6 shows the acoustic emission recorded during a tensile test on the CO material.
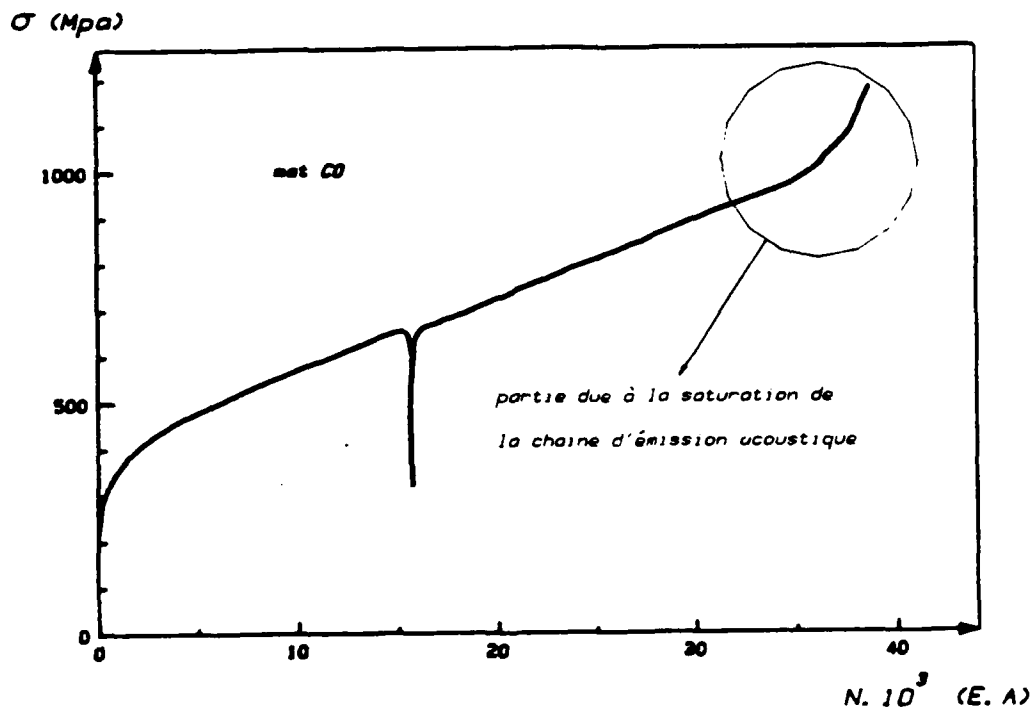

Figure 6 : Acoustic emission recorded during a tensile test on the composite CO

It was found that the Käiser effect was more closely obeyed at the lower stress levels and that the more rigid composite material Cl showed closer adherence to the Kaiser effect than did the CO material. Both materials began emitting at lower stresses than is reported for the more rigid T300-914 systems previously studied [8].

- Creep tests :

Creep tests at different load levels having stress ratios σ/σ_R from 0,4 to .1 were conducted. Below $\sigma = 0,4 \ \sigma_R$ negligeble acoustic activity was recorded within reasonable time periods.

Table (4) gives typical results from a number of studies. The results for each specimen tested show the number of events recorded for each period of steady loading and the length of loading. In addition time necessary for composite C0 to accumulate the same number of events as recorded for the composite Cl was calculated from the equation

$$t = K2 \left[\exp(K1(N - \exp(-K3N + K4))) - \exp(-K1 \exp K4) \right]$$

where: t is in seconds

K1, K2, K3, K4 experimentally ajusted constants

N is the number of accumulated events at that load level

In all cases the time necessary to accumulate a given number of emissions was shorter for the C0 material than for the Cl material which reveals the greater speed of damage accumulation for the former composite. Figure 7 give examples of the stabilisation of the acoustic emission activity of the C0 unidirectional specimens.
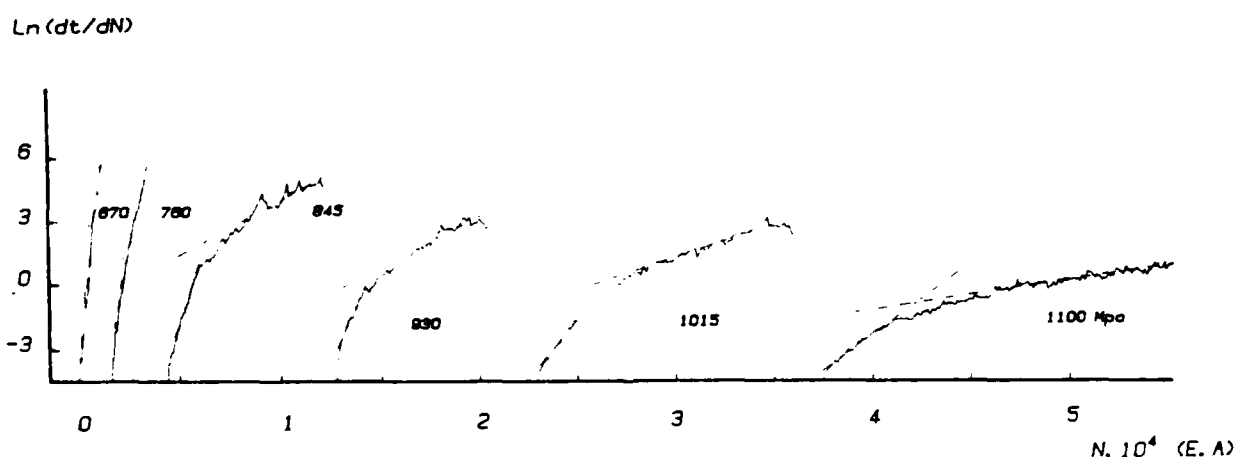

Figure 7 : Stabilisation of acoustic emission activity from unidirectional C0 specimens

It can be seen that damage accelerated at the higher

| σ/σ_R	N(E.A.)	t(s)	N	t	N	t	N	t	N	t	N	t
0,41 - 0,45		-	2480 1040	$3.2\ 10^5$ $8.45\ 10^3$	1600	$3.84\ 10^7$	1040	$2.23\ 10^4$		-		-
0,46 - 0,50	1600 1760	$1.21\ 10^4$ $1.878\ 10^4$		-		-		-		-	1760	$1.15\ 10^5$
0,51 - 0,55	4000 3120	$2.7\ 10^4$ $9.2\ 10^3$	7200 3120	$6.5\ 10^5$ 6.5 20	2000 3120	$4.41\ 10^5$ $9.1\ 10^5$					3120	$2.89\ 10^5$
0,56 - 0,60	13360 1360	$1.12\ 10^5$ 127	9200 1360	$2.7\ 10^5$ 312	9760 1360	$1.15\ 10^6$ 526	1360	$3.32\ 10^4$			4320	$1.99\ 10^5$
0,61 - 0,65	24000 2720 2240 4320	$9.0\ 10^4$ 739 448 $2.54\ 10^3$	16960 2720 2240 4320	$2.6\ 10^5$ 483 275 $2.07\ 10^3$	15695 2720 2240 4320	$3.6\ 10^5$ $1.68\ 10^3$ 893 $7.92\ 10^3$	2720	$6.18\ 10^4$	2240	$5.06\ 10^4$		
0,66 - 0,70		-	18480 5200 6560	$5.38\ 10^4$ 960 $1.899\ 10^3$	20800 5200 6560	$1.83\ 10^5$ $2.97\ 10^3$ $6.71\ 10^3$		-	5200	$3.54\ 10^5$	6560	$7.33\ 10^4$
0,71 - 0,75	20800 2800 12000	$4.99\ 10^4$ 150 $8.18\ 10^3$		-	30880 2800 12000	$7.43\ 10^4$ 115 $5.34\ 10^2$	2800	$3.87\ 10^4$		-	12000	$2.14\ 10^5$
0,76 - 0,80		-		-		-	8460	$5.46\ 10^4$	5920	$9.33\ 10^4$		-

Mat Ø

Mat 1

Table (4) : Results of creep tests on a number of plate specimens

loads. Figures 8 and 9 show similar curves for both the CO and
Cl specimens but all curves are drawn through the origin.

Figure 10 shows the evolution of the two composites at
the same stress level. It can be seen that the CO accumulates
damage at all stress levels faster than the Cl specimens.
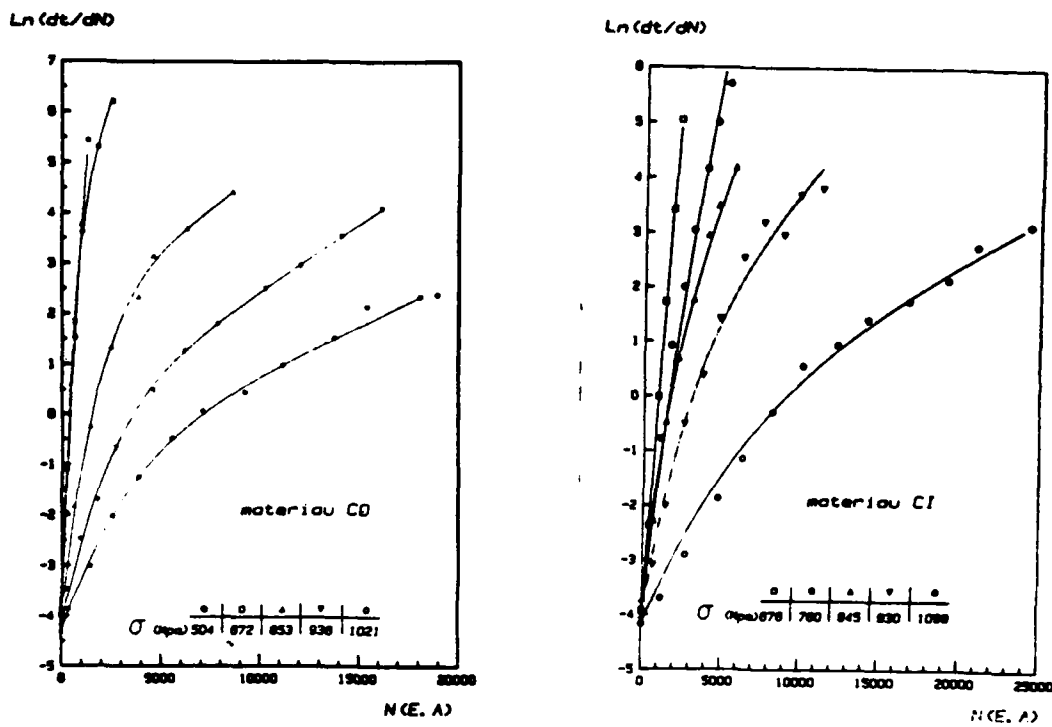
Figures 8 and 9 : Stabilisation af acoustic emission for the
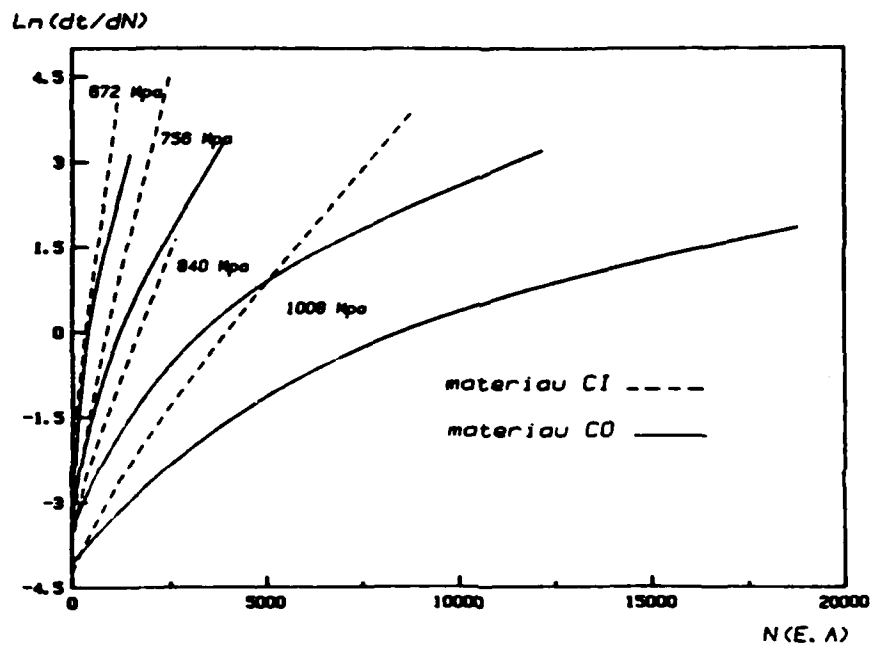composite CO and the composite Cl

Figure 10 : Evolution of the composites CO and Cl at the
same stress level

It has not been possible to correlate the variation
of the parameters Kl with physical processes. Figure 11 shows
the variation of Log Kl as a function of applied stress. The
value of Log Kl can be seen to decrease linearly as a function
of increasing stress for both types of composite tested. The
values of Kl for the CO composites were always superior to
those for the Cl composite, again revealing a more rapid accu-
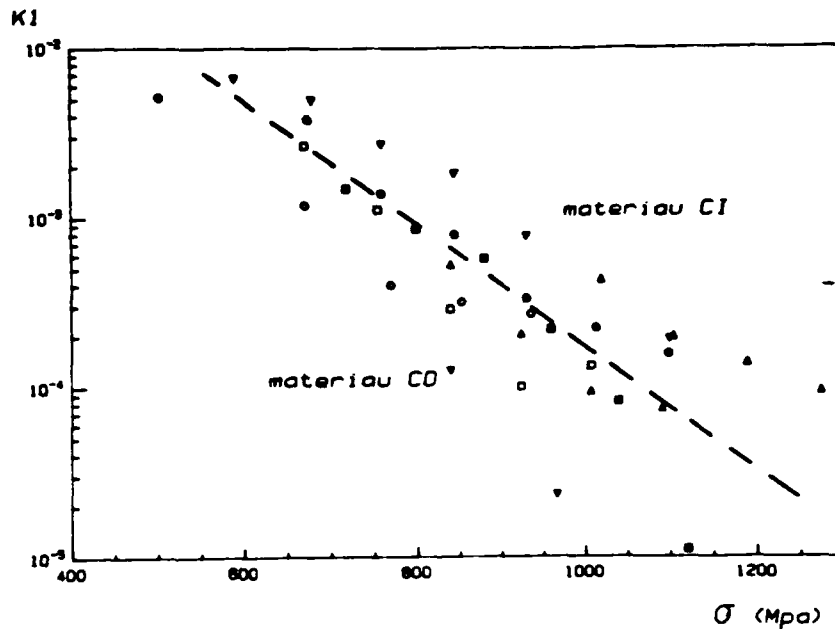mulation of damage for the CO specimens.

Figure 11 : Variation of Kl as a function of applied stress

- Loading sequence effects

Several specimens were held at different load levels
and the loads increased or decreased during certain periods.
An increase in load provoked an acceleration of emissions and
produced a stabilisation giving a new value of K1. It is
significant to note that returning to the original load level
produced acoustic activity which was practically that which
would have been obtained by extrapolating the original curve
as shown in Figure 12. In this way it can be seen that an
increase in load was equivalent to a physical aging process
as a much longer period would have been necessary at the lo-
wer load to accumulate the emissions recorded at the higher
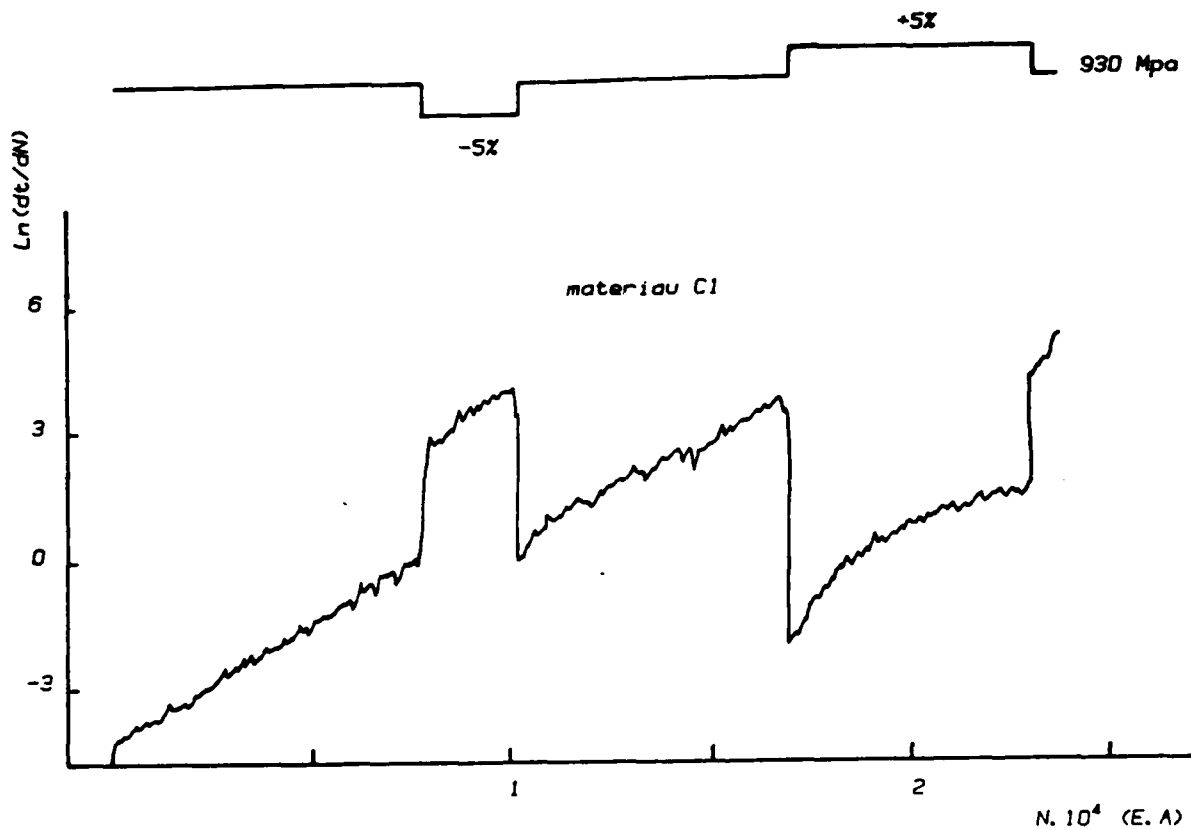level.

Figure 12 : Effect on acoustic emission rate of loading
              sequences

The acoustic emission rate was reduced by a reduction of load and a return to the original load level again produced the extrapolated behaviour.

- Effect of temperature

It has been shown that the viscoelastic properties of the matrix have a considerable effect on damage accumulation. The properties of the matrix can be affected by temperature and so studies were conducted on the composites at different temperatures. The temperature was modified during a period of steady loading on the composite C1. Figure 13 shows the results obtained .

An increase in temperature was found to produce an increase in emission rate. The stabilisation during the period of increased temperature was not regular probably due to the effect of internal stresses and thermal inertia . A return to the initial room temperature produces an extrapolation of the initial part of the curve. The effects of the change of tempe-rature of the environment take sometimes to produce the change in the composite which explains a certain lag in acoustic emis-sion behaviour. In this, an increase in temperature is analo-gous to the aging produced by an overload as explained earlier.

It proved possible to reproduce the results obtained with composite CO at room temperature by testing the composite C1 at a raised temperature, once again emphasizing the impor-tance of the viscoelastic properties of the matrix.

Tests on the composite CO were also conducted at rai-sed temperatures. The properties of the resin Ro were very temperature dependent and it was expected that as the tempera-ture of the test was increased the load transfer length around fibre breaks would increase markedly . With an extremely soft matrix it could be expected that the behaviour of the fibre bundle would encountered. In this case emissions would cease altogether. This was found not to be the case however it was
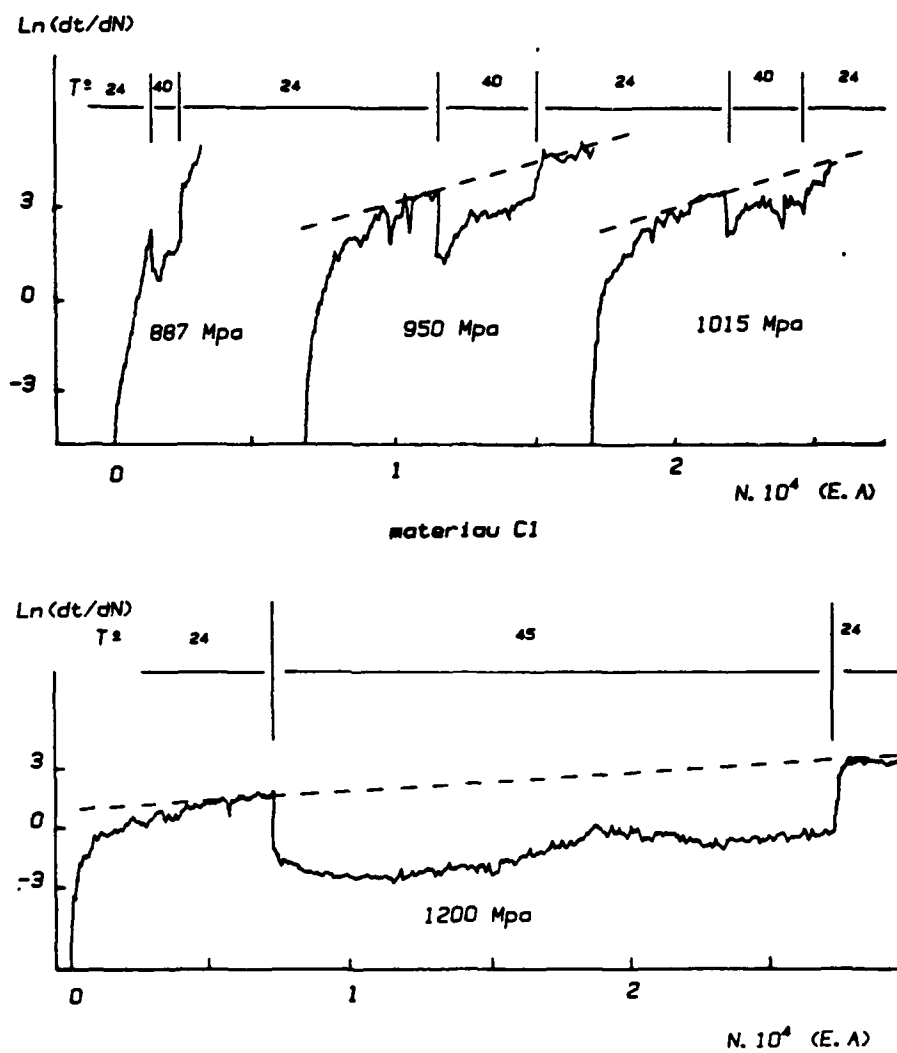
Ln(dt/dN)

materiau C1

Figure 13 : Influence of temperature on the stabilisa-
tion of the acoustic emission during stea-
dy loading

observed that an increase in temperature of only a few degrees
had a considerable effect on acoustic activity. Figure 14 shows
that similar behaviour to that seen with composite C1 was ob-
tained but for smaller increases in temperature. This observa-
tion has implications interpreting certain results obtained
in a laboratory which was not temperature controlled. Figure 15
shows that acoustic activity of a CO specimen showing two peaks
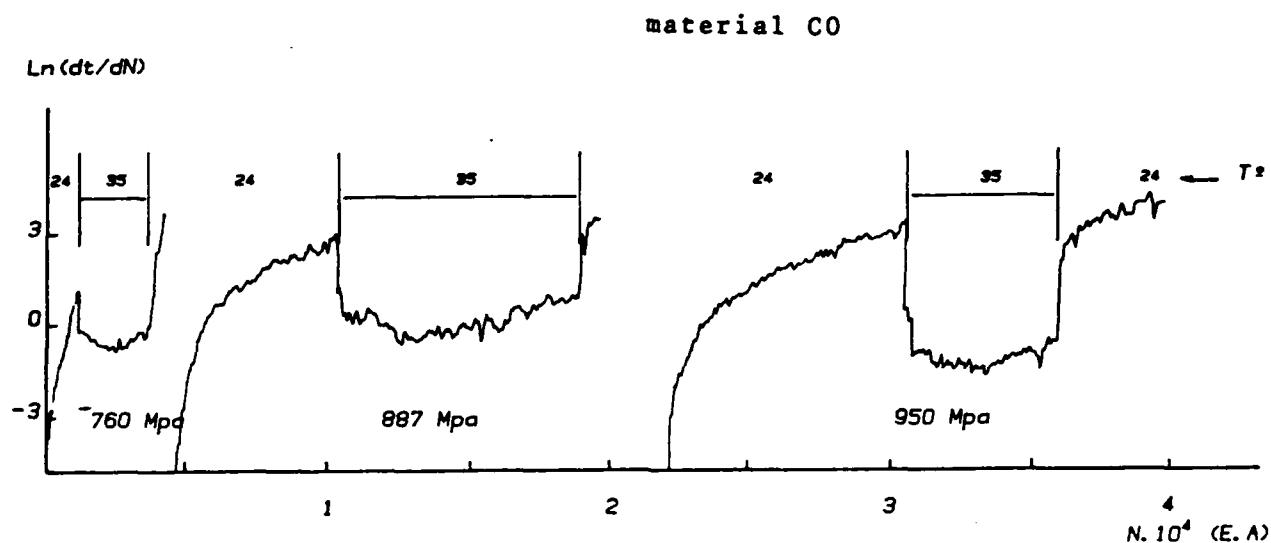at an interval of approximately twenty four hours.

material CO

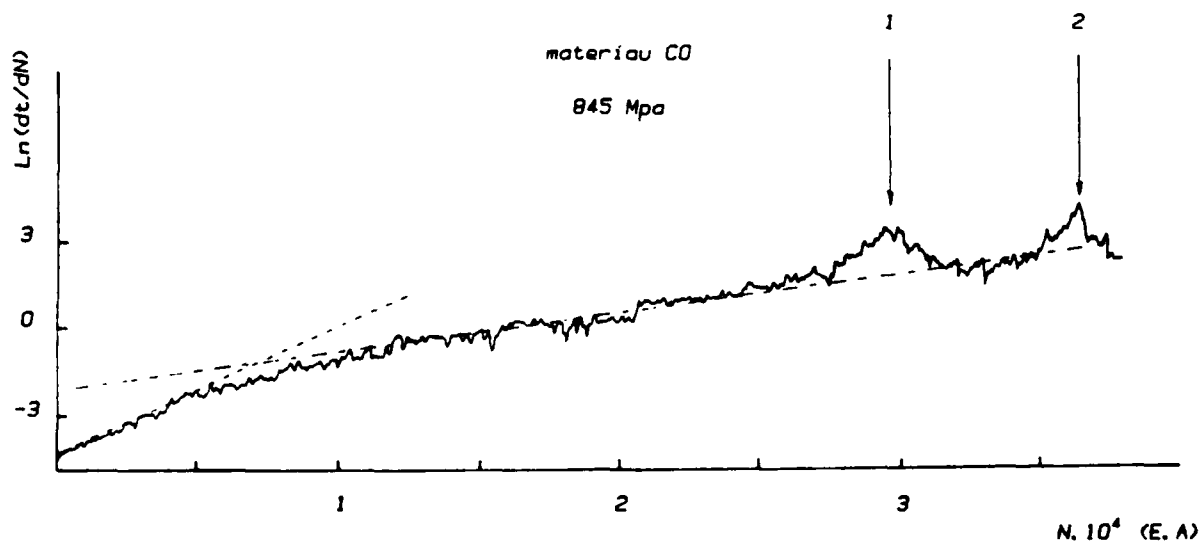Figure 14 : Influence of a temperature change on acoustic emission during
steady loading

Figure 15 : Small changes in temperature in a laboratory between day and
night were the most likely cause of the two peaks recorded

IV-3. <u>Statistical Analysis of the Acoustic Emission</u>

The acoustic activity monitored from a material can be
characterized by several parameters
- number of emissions
- maximum amplitude
- duration
- energy

The acoustic emission chain used in this study allowed
the first three types of analysis to be carried out. The respon-
se of the transducer to a pressure wave is schematically a dam-
ped sine wave with the form [9 ,10]

$$V = Vo \exp(-\eta t)\sin\omega t$$

where η is the damping factor of the transducer

$\omega = 2\pi\upsilon$

Vo = maximum amplitude

t = time

Certain parameters are interrelated, so that the energy
depends on the square of the amplitude and the logarithm of
the amplitude can be related to the number of emissions [10].
This being,we selected the signal amplitude as the characteris-
tic parameter. The module used to record signal amplitude was
the Dunegan-Endevco 921 module fitted to the 3 000 series appa-
ratus immediately after the preamplifier. A threshold level of
25 db was chosen for all studies. The amplitudes were stored
in the 921 amplitude analiser which had 101 memory stores
classified from 0 to 100 db. The capacity of these memory sto-
res was 4 096 events.The analog output giving signals from 0
to 10 volts allowed the distribution function to be traced di-
rectly on a recorder. In order to identify the evolution of
amplitude histograms as a function of load, tensile tests on
the unidirectional specimens were conducted and the load held
steady at different levels. The amplitude histograms were recor-
ded during each period of steady loading.

It was found that for a given hold time the number of

events recorded varied greatly between the first load level and
the last. For these reasons, it was necessary to normalize the
result at each load level by dividing the number of emissions
of each amplitude level by the total number of emissions recor-
ded during the hold period. Figures 16 and 17 show the results
obtained at three load levels. In both cases it can be observed
that the peak observed at 25 db at low stress levels increased
to 40 db at higher stresses.

Several hypotheses can be advanced to explain this
observation. The peak could be due to one type of mechanism
which in the case of fibre failure liberates more energy at
higher stress levels than at lower levels [11]. If two mecha-
nisms are involved, one could dominate at higher stress levels.
This would be the case if microcracking was at the origin of
the 25 db peak and fibre failure the source of the 40 db peak.
This second hypothesis although simplist seems the most plau-
sible as the shape of the histogram changes with the increa-
sing load. There is tittle in the literature to which we can
turn to help interprete these results although Shippen and
Adams [12] attribute high amplitude peaks to fibre failure and
low amplitude peaks to microcracking of the matrix. Finally it
should not be forgotten that all of the fibres must be broken
at least once in order to break the specimen and fibre failure
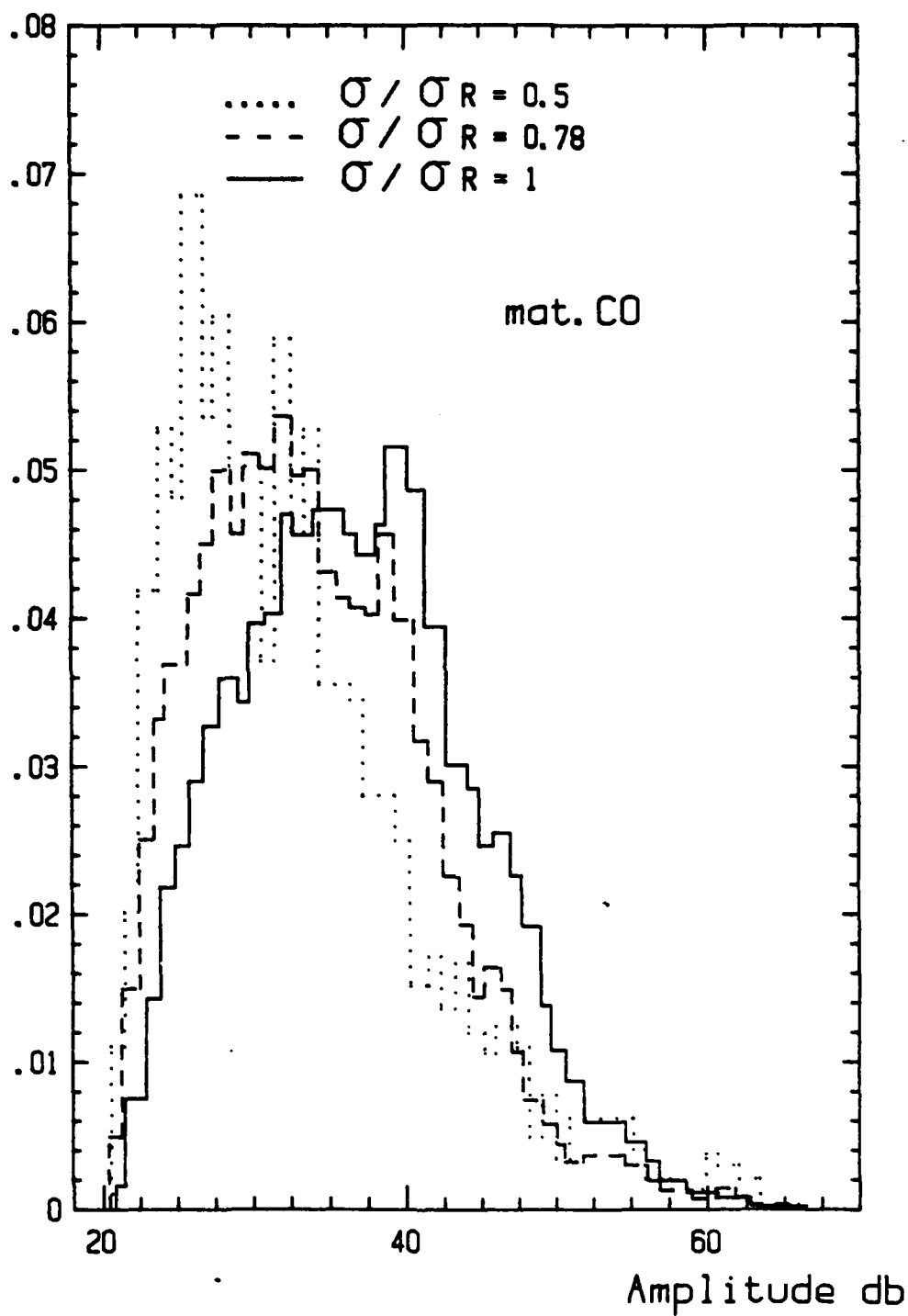must predominate near the final failure stage.

N/Nt

Figure 16 : Histograms of the amplitude distribution obtained
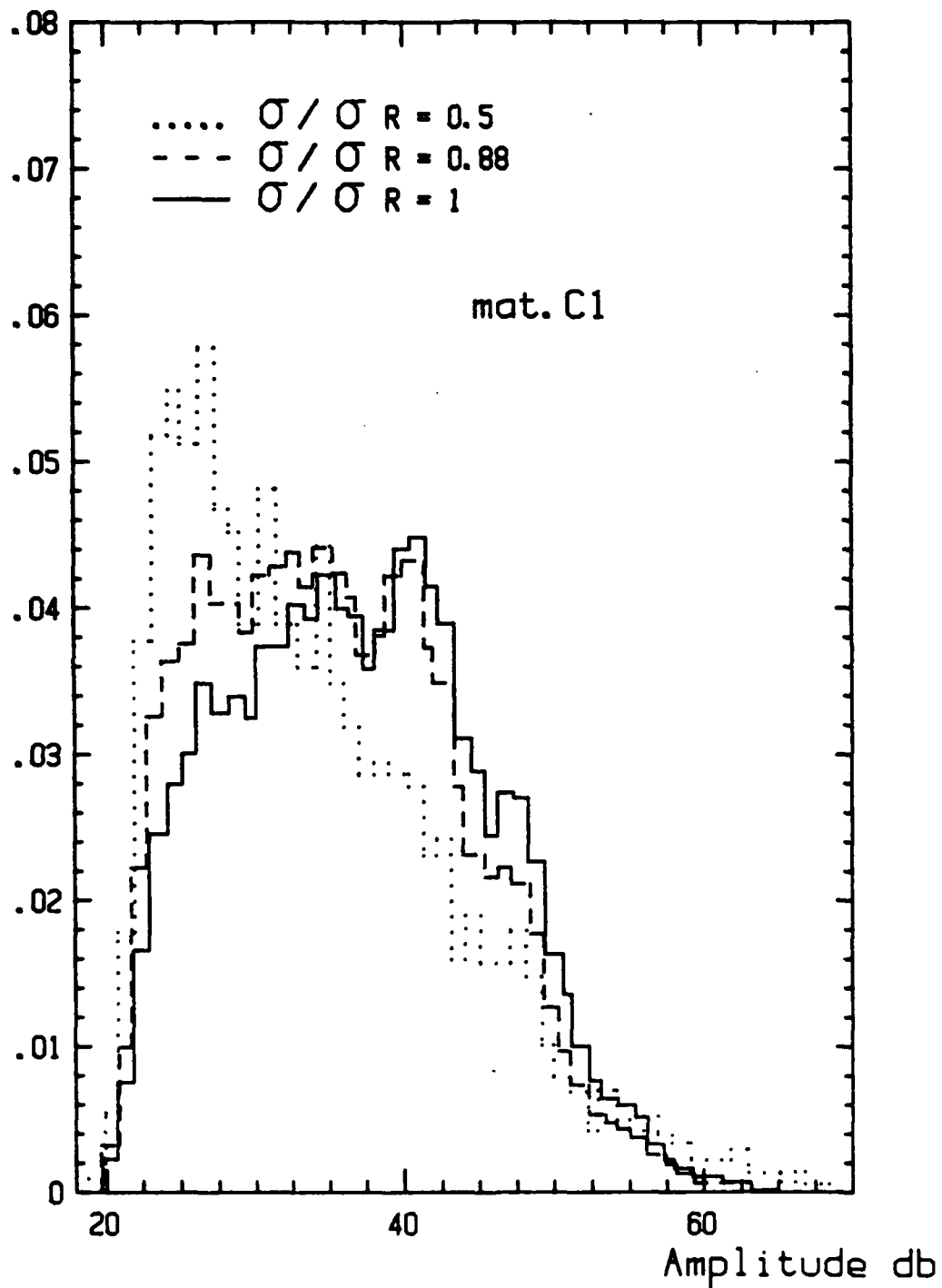with the CO specimen

N/Nt

Figure 17 : Histograms of the amplitude distribution obtained
with the Cl specimen

V. CONCLUSION

Two types of fibre reinforced resin specimens have
been tested, each having the same type of fibre but with very
different resin systems. In this way the effect of matrix pro-
perties on carbon fibre reinforced resin systems has been stu-
died.

Steady loads on unidirectional specimens have confirmed
that far from being the unresponsive purely elastic bodies
that most measuring techniques suggest the acoustic emission
technique reveals the continuous accumulation of internal
damage. The acoustic emission behaviour is characterized by
curves of $\ln(dt/dN)$ as a function of total accumulated emis-
sions which typically shows two asymptotic slopes, one at the
origin, the other at infinity.

An analytical expression has been proposed to describe
this behaviour involving four parameters.

The rate of damage accumulation has been shown to be
greatly influenced by the properties of the matrix, with an
increased rate observed with a resin containing a high percen-
tage of plasticizer.

The histograms of the amplitude distributions reveal
a peak at 25 db at low stresses which is seen to be displaced
towards 40 db at higher applied loads. It is concluded that
the peak at 40 db is due to fibre failure whereas the lower
peak may be due to microcraking of the matrix.

The study has revealed that period of overloading
are equivalent to accelerated mechanical aging at lower loads.
This is also true of temperature rises during steady loading
which induces a more rapid rate of damage . This effect of
accelerated aging could be turned to use in determining the
long term behaviour of structures under load.

The acoustic emission technique is an indirect method
of obtaining information concerning the damage of composite.

The signals arriving at the transducer do so from all over the material and are most probably considerably modified. Despite these difficulties the approach developed in this study offers a quantitative method of analysis of damage accumulation in carbon fibre reinforced resin composites.

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J. of Reinforced Plastics and Composites, vol 7,
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ANNEX

```
]LIST

1  E = 1E4:EA = 1E4
2  W = 0
3  D$ =  CHR$ (4)
4  I = 0
6  U = 0:DI = 5:ZO = 0
7   PRINT
9  DI = 5:VI = 25
11  PRINT
13  INPUT "C1=";C1: INPUT "C2=";C2: INPUT "C3=";C3: INPUT "C4=";C4
14  PRINT D$;"PR#1": PRINT "VALEURS INITIALES"
15  PRINT "C1=";C1;"    C2=";C2: PRINT : PRINT "C3=";C3;"    C4=";C4: PRINT
16  PRINT D$;"PR#0"
17  DEF  FN R(X) = C3 +  LOG (X) + ((C2 * X ^ 2 - 2 * C2 * X + C2) / ( - C2 * X
  ^ 2 + C1 * X)) - C4
19  DEF  FN F(X) =  LOG (K1 * K2) +  LOG (1 + K3 *  EXP ( - K3 * X + K4)) + K1 *
  (X -  EXP ( - K3 * X + K4))
20  DIM D(3): PRINT "VOULEZ-VOUS CHANGER LES PARAMETRES DE RECHERCHE (ACTUELS: +
  OU - 5% ET 25 PAS)": INPUT A$
21  IF A$ = "N" THEN  GOTO 25
22  PRINT "ENTREZ L'INTERVALLE DE RECHERCHE:": INPUT DI: PRINT "LE NOMBRE DE PAS
  :": INPUT VI
25  GOTO 600
30  GOTO 3700
72  A = C1 / C2 + C1 / C2 * 1E - 3:B = C1 / C2 + 100
152  A1 =  SGN ( FN R(A))
162  B1 =  SGN ( FN R(B))
172  IF A1 * B1 = 0 THEN 360
182  IF A1 * B1 < 0 THEN 280
192  FOR I = 1 TO 1000
222  X = A +  RND (2) * (B - A)
212  X1 =  SGN ( FN R(X))
222  IF X1 = 0 THEN 400
232  IF A1 * X1 < 0 THEN 270
242  NEXT I
272  B = X
282  D(2 + A1) = A
292  D(2 - A1) = B
300  Y = (D(1) + D(3)) / 2
310  Y1 =  SGN ( FN R(Y))
320  IF Y1 = 0 THEN 400
332  D(2 + Y1) = Y
342  IF  ABS (D(1) - D(3)) /  ABS (D(1) +  ABS (D(3))) < 5E - 5 THEN 400
352  GOTO 300
360  IF A1 = 0 THEN 390
372  Y = B1
382  GOTO 400
392  Y = A1
400  IF ZO = 1 THEN  GOTO 420
410  A = Y - (Y * 5 / 100):B = Y + (Y * 5 / 100):ZO = 1
420  GOTO 150
422  IF ZO = 1 THEN  GOTO 440
410  A = Y - (Y * 5 / 100):B = Y + (Y * 5 / 100):ZO = 1
420  GOTO 150
442  KT = (C2 * Y - C1) * (Y / (Y - 1))
450  K0 = ( EXP (C3)) / C2
472  Q = K0 * (Y - 1) / KT
```

```
489    GOTO 4000
490    RETURN
        PRINT "VOULEZ-VOUS
        PRINT ""
530    PRINT "ENTRER LES POINTS EXPERIME(TAL            AU CLAVIER:1"
540    PRINT ""
542    PRINT "ENTRER LES POINTS EXPERIMENTAUX           A PARTIR D'UN TABLEAU:2"
560    INPUT EN
568    IF EN - 1 ) 0 THEN  GOTO 1000
570    INPUT "ENTRER LE NOMBRE DE POINTS EXPERIMENTAUX EX=";EX
580    DIM L(EX): DIM M(EX)
590    FOR I = 1 TO EX
700    M$ = "M(" +  STR$ (I) + ")=": PRINT M$
710    INPUT M(I)
720    L$ = "L(" +  STR$ (I) + ")=": PRINT L$
730    INPUT L(I)
740    NEXT I
750    PRINT ""
760    FOR I = 1 TO EX
770    PRINT "M(" +  STR$ (I) + ")=";M(I);"   L(" +  STR$ (I) + ")=";L(I)
780    NEXT I
790    PRINT ""
800    PRINT "VALEURS A MODIFIER?(O/N)": INPUT VA$
810    IF VA$ = "N" THEN  GOTO 840
820    PRINT "ENTRER LES VALEURS TAPER CONT PUIS RETURN EX:M(3)=2:L(3)=4:CONT"
830    STOP : GOTO 760
840    PRINT ""
850    INPUT "NOM DU TABLEAU (EXP):";T$
860    PRINT D$"OPEN";T$
870    PRINT D$"WRITE";T$
880    PRINT EX
890    FOR J = 1 TO EX
900    PRINT M(J)
910    PRINT L(J)
920    NEXT J
930    PRINT D$"CLOSE";T$
940    GOTO 1260
1000   PRINT "NOM DU TABLEAU ?"
1010   INPUT T$
1020   PRINT D$"OPEN";T$
1030   PRINT D$"READ";T$
1040   INPUT EX
1045   DIM M(EX): DIM L(EX)
1050   FOR I = 1 TO EX
1060   INPUT M(I): INPUT L(I)
1070   NEXT I
1080   PRINT D$"CLOSE";T$
1090   FOR I = 1 TO EX
1100   PRINT "M(" +  STR$ (I) + ")=";M(I);"   L(" +  STR$ (I) + ")=";L(I)
1110   NEXT I
1120   PRINT "VALEURS A MODIFIER ?(O/N)": INPUT VA$
1130   IF VA$ = "N" THEN  GOTO 1160
1140   PRINT "ENTRER LES VALEURS TAPER CONT PUIS RETURN"
1150   STOP : GOTO 1090
1160   PRINT "VOULEZ-VOUS STOCKER LE TABLEAU ?(O/N)"
1170   INPUT VA$
1180   IF VA$ = "N" THEN  GOTO 1260
1190   PRINT D$"OPEN";T$
1200   PRINT D$"WRITE";T$
1210   PRINT EX
1220   FOR I = 1 TO EX
1230   PRINT M(I)
1240   PRINT L(I)
1250   NEXT I: PRINT D$"CLOSE";T$
```

```
3010 EC = 0
3020  FOR I = 1 TO EX
3030  EC = EC + ABS (V(I) - F(I))
3040  NEXT I
3050  RETURN
3200 CI = C1 - (C1 * DI / 100):CS = C1 + (C1 * DI / 100)
3210 IN = (CS - CI) / VI
3220 C1 = CI
3030  GOSUB 70
3040  GOSUB 2000
3050  E1 = EC
3060  IF E1 ) E THEN  GOTO 3080
3072 E = E1:CM = C1
3080 C1 = C1 + IN
3090  IF C1 ( CS THEN  GOTO 3030
3100  C1 = CM
3110 C1 = C2 - (C2 * DI / 100):CS = C2 + (C2 * DI / 100)
3122 IN = (CS - CI) / VI
3132 C2 = CI
3135 CN = C2
3140  GOSUB 70
3150  GOSUB 2000
3160  IF EC ) E THEN  GOTO 3180
3170 E = EC:CN = C2
3180 C2 = C2 + IN
3190  IF C2 ( CS THEN  GOTO 3140
3200 C2 = CN
3210 CI = C3 - (C3 * DI / 100):CS = C3 + (C3 * DI / 100)
3212  IF CI ( CS THEN  GOTO 3220
3214 CP = CI:CI = CS:CS = CP
3220 IN = (CS - CI) / VI
3230 C3 = CI
3240  GOSUB 70
3250  GOSUB 2000
3260  IF EC ) E THEN  GOTO 3280
3270 E = EC:CO = C3
3280 C3 = C3 + IN
3290  IF C3 ( CS THEN  GOTO 3240
3300 C3 = CO
3310 U = 1
3320  GOTO 70
3500 IN = 1E - 2 * C1
3502 I0 = IN
3512  GOSUB 70: GOSUB 2000
3515 E0 = EC
3517  PRINT "E0=";E0
3520 C1 = C1 + IN
3525  GOSUB 70: GOSUB 2000
3527  PRINT "EC=";EC: PRINT "C1=";C1
3530  IF EC ) E0 THEN  GOTO 3560
3535 CP = C1:EP = EC
3540 C1 = C1 + IN:E0 = EC
3550  GOTO 3520
3560 IN = IN / 10
3562  IF IN ( (1E - 3 * IN) THEN  GOTO 3569
3564 C1 = CP:E0 = EP: GOTO 3520
3570  GOSUB 70: GOSUB 2000
3575  PRINT "C1=";C1: PRINT "EC=";EC
3580  IF EC ) E0 THEN  GOTO 3610
3590 C1 = C1 - IN:E0 = EC
3600  GOTO 3570
3610 IN = IN / 10
3620  IF ABS (IN) ) ABS (1E - 4 * I0) THEN  GOTO 3610
3630  STOP
```

END

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