Winding Angle and Resin Properties Effects on the Behaviour of CFRP Filament Wound Pipes Part I: Burst Test

B. Ponsot, D. Valentin

CNRS UA 866
Ecole Nationale Superieure des Mines de Paris
Centre des Materiaux P.M. Fourt
B.P. 87
91003 EVRY Cedex, France

ABSTRACT

The influence of matrix properties on the instaneous properties (i.e., burst pressure) hoop and axial moduli of CFRP tubes has been investigated. Two types of winding angle were considered: ± 75° and ± 88°. The behaviour of the tubes was characterized both by extensometry and acoustic emission. The number of events and the amplitude of each event were recorded. It has been shown that a softer matrix improves the burst properties of ± 75 tubes whereas a contrary effect is obtained with ± 88 tubes. This difference in behaviour can be explained by consideration of the acoustic emission and the mechanisms of degradation involved.

I. INTRODUCTION

Numerous studies have been carried out on filament wound pipes made from glass reinforced plastics /1,2,3/. These materials have a number of obvious potential advantages over pipes made, for example, from steel. Most of these works are concerned with weepage due to first ply failures of the material. Since under service conditions pipes are likely to be subjected to a range of stress conditions, some authors have examined different modes of loadings; close end testing, restrained or unrestrained end testing. All these conditions lead to specific failure modes /1/. For this, a PROT machine is used in most studies. Here, another type of apparatus has been developed. Our construction has the considerable advantage that failure mechanism can be studied in the absence of edge effects. There are no cut fibres at free edges, as is the case with plate specimens, and no tridimensional stresses leading to early edge delaminations. This paper is concerned with the failure mechanisms during monotonic loading by internal pressurisation of CFRP filament wound pipes in the unrestrained end testing case. This work is part of a continuing programme concerning the role of the matrix in controlling damage during tensile or creep tests of structures in which fibre failure is the main mechanism of breakage /4,5/. So, in this paper emphasis is given to the influence of winding angles and rheology of the matrix on the response during burst tests of (±88) and (±75) tubes. The behaviour of the tubes was characterized both by extensometry and acoustic emission.

II. EXPERIMENTAL DETAILS

Tubes were wound by the Société Europeenne de Propulsion using T6K carbon fibres and two kinds of matrices that had very different viscoelastic properties /6/. The compositions of the two materials are given in Table 1. Araldite CY 208 was used as a plasticizer in the mixture of the two components.

Tensile tests were performed on the two matrix systems (Fig. 1) and the principle results are given in

Table 1: Composition of Materials

	CY208	CY205	Fibres
mat CO	70%	30%	T 300 B
mat Cl	30%	70%	T 300 B

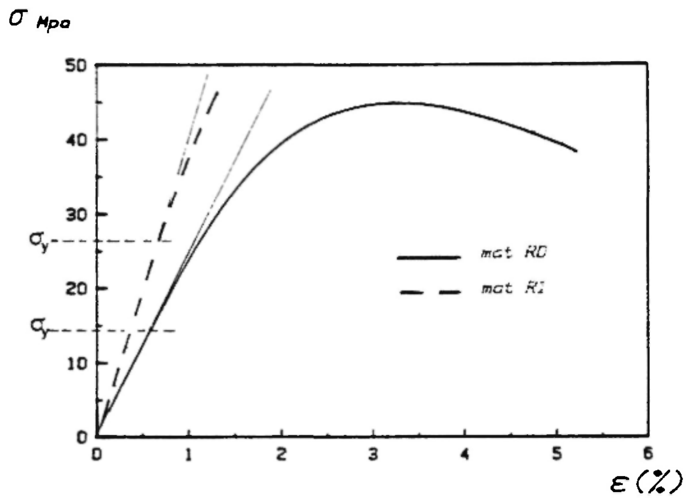

Fig. 1: Tensile tests obtained for the two kinds of matrix.

Table 2. Concerning the tubes, two winding angles were studied: (±88) and (±75) with respect to the tube axis. The tubes consisted of ten crossed layers, five in each direction. The (±88) tubes had an additional 0° layer positioned between the fifth and the sixth layers to increase flexural strength. The lengths of the tubes were always sufficiently long so that continuous fibres encircled the tube at least once (in the case of the ±75 tubes). The main characteristics of the different tubes are compared in Table 3.

The tubes were tested with a special apparatus which enables them to be pressurized without end effect errors. Fig. 2 shows the system of holding and pressurizing the tubes which permitted freedom of movement for the tube in all directions. The tube was slid over a thick walled rubber sleeve which projected into a moveable end fitting (A). The end fitting was under load in the axial direction to compensate for the shortening of the tube under pressure due to the Poisson effect. The axial load applied, as will be shown later, was never more than 5% of the circumferential stress in the tube.

Each tube was instrumented with 6 rosette gauges (KYOWA KFC 10D16) aligned along the major axis and both strain data and the cumulated number of acoustic events were automatically recorded as a function of time.

All acoustic emission monitoring was made with a

Table 2: Main Characteristics of the Resins. The Subscripts R and Y are for Failure and Plasticity, Respectively.

Resin	σ_R (MPa)	ϵ_R (%)	σ_Y (MPa)	ϵ_Y (%)	Young Modulus E (GPa)	Poisson Coefficient ω	Shear Modulus G (GPa)
R0	40	4	13	0.6	2.2	0.33	0.83
R1	50	1	25	0.6	4	0.27	1.57

Table 3: Main Characteristics of the Tested Tubes. (D_i = internal diameter, L = length, t = thickness)

Tube	Angles	Dimensions (mm) L x E x D_i	CO
PC 105	± 88°	100 x 2 x 96	CO
PC 104	± 88°	100 x 2 x 96	C1
PC 107	± 75°	140 x 2 x 96	CO
PC 106	± 75°	140 x 2 x 96	C1

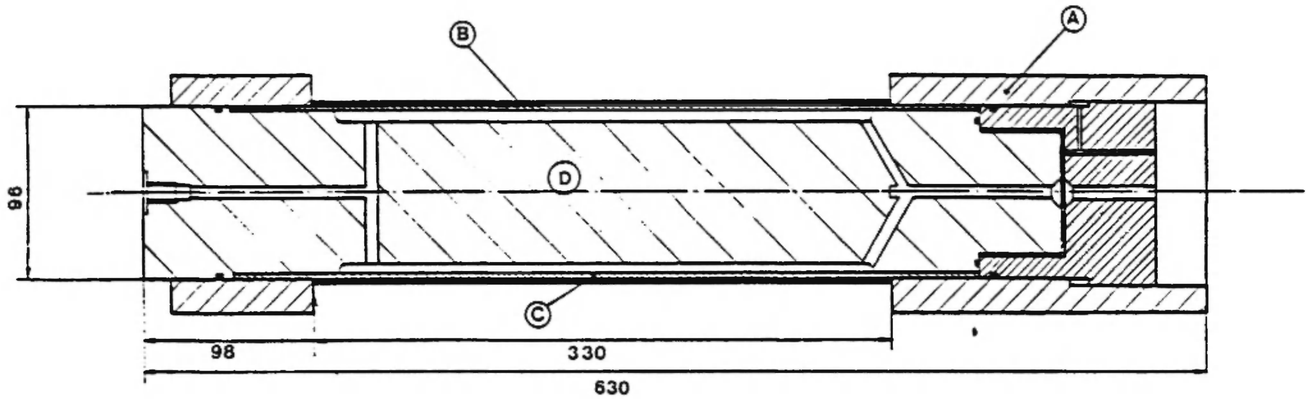

Fig. 2: Test apparatus for pressuring a tube of length equal to 330 mm. Part D can be adapted for the different lengths considered.

3000 series Dunegan system which consists of a 40 dB preamplifier, an amplifier with adjustable gain and an impulse detector which transforms all peaks exceeding the output threshold (25 dB) into digital pulses. The dB measurements were given in reference to a 1μV signal at the transducer. The analysis system was set to have a dead time of 100 μs which allowed one event only to be counted for each series of pulses separated by less than 100 μs.

III. RESULTS OBTAINED ON ±88 WOUND TUBES

Extensometry results

The stress-strain curves obtained during burst tests (Fig. 3) show linear elastic behaviour. The moduli obtained are nearly equal for both kind of tubes but the stresses at rupture are different. The maximum hoop strains at rupture are 0.86% and 0.78% for PC 104 and PC 105 tubes, respectively, with stress at rupture equal to 1200 MPa and 950 MPa. All the failures were sudden and brittle in character. These values are relatively lower than those obtained with more conventional matrices /7/. It can be seen that non-linear behaviour can occur along the axis of the tubes (Fig. 4) which may be attributed to either the non-linear behaviour of the matrices or to macroscopic damage. Kamimura /8/ showed that damage can effect the transverse stiffness of $(0.90)_s$ while the longitudinal stiffness remains constant or increases due to the strain hardending of the carbon

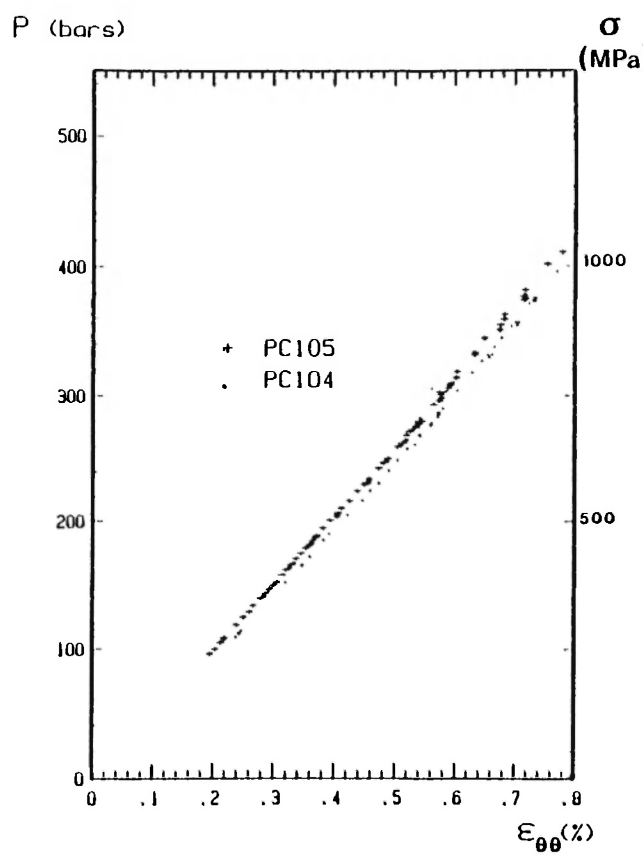

Fig. 3: Stress-strain curves obtained during burst tests of PC 104 tubes and PC 105 tubes.

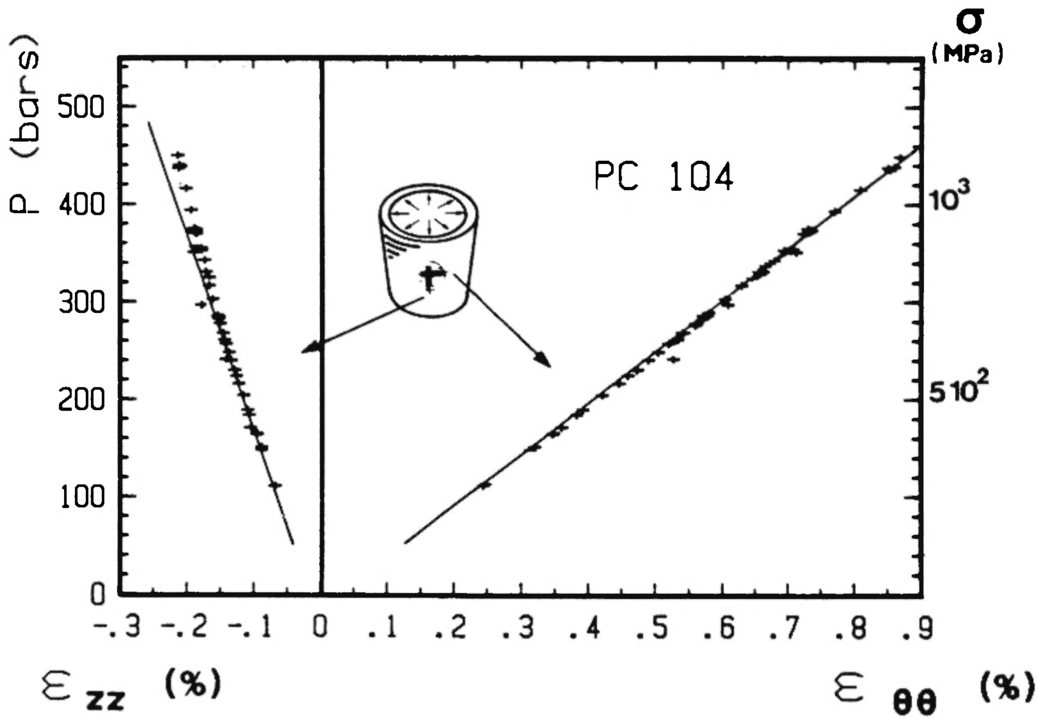

Fig. 4: Axial and hoop strain curves as a function of pressure for PC 105 tubes.

fibres. In fact, a delamination can be observed between the 0° layer and the 5th or 6th layer (fig. 5) and, at higher stresses, other delaminations are observed between external layers. At rupture PC 105 tubes show a less brittle fracture than PC 104 tubes. Intralaminar cracks are more numerous at final failure and lead to a more important energy dissipation phenomenon by the branching of the main crack.

A.E. Results

If extensometry cannot differentiate easily the behaviour of the two kinds of tubes (in terms of modulus), it can be shown that the Acoustic Emission technique is a more sensitive method for monitoring damage during a burst test. From Figure 6 it can be noticed that the damage accumulation is greater for the PC 105 tube. This can be explained if the more viscoelastic character of the RO matrix used for the PC 105 tube and its role at the microscopic level are considered. Unidirectional composites can be understood using the bundle chain model. The length of the bundle, according to Rosen /9/, is proportional to the ratio $(Ef/Gm)^{1/2}$ and is equal to the ineffective length δ of the broken fibres. If the matrix is viscoelastic, this length δ will evolve differently

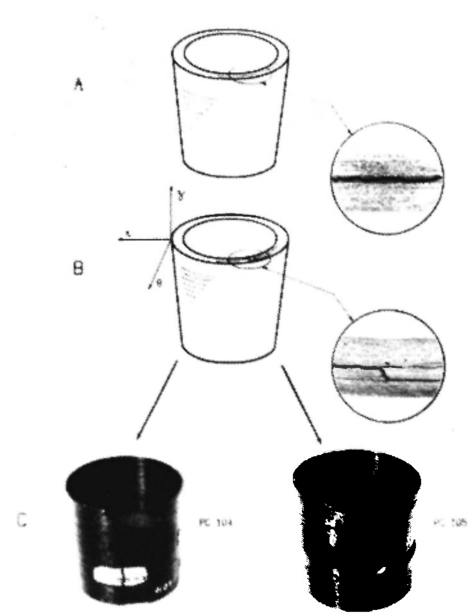

Fig. 5: Failure modes of ± 88 tubes. A) initiation of a macrocrack between the 5th and the 6th layer; B) macrocrack growth in the other layers; C) failure aspect as a function of the matrix system.

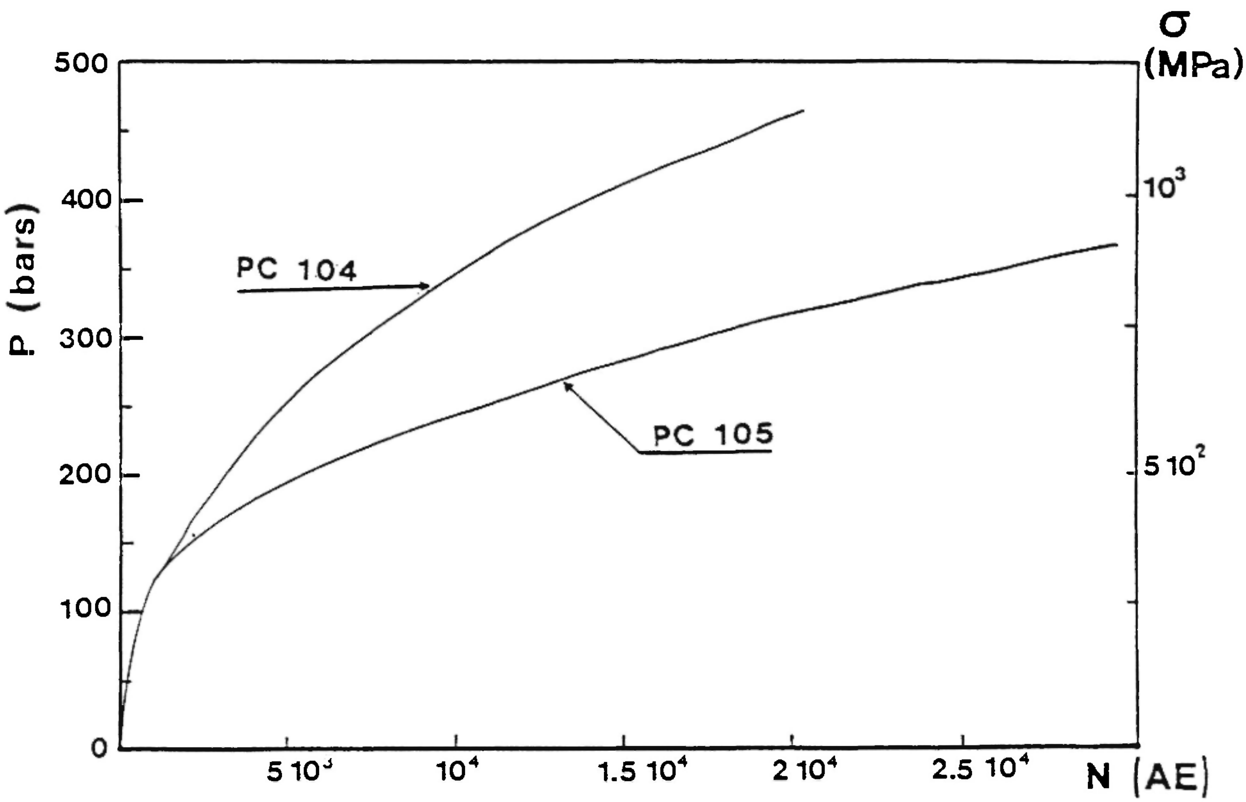

Fig. 6: Cumulative acoustic emission curves obtained during burst testing ± 88 tubes.

during the tensile test for the two kinds of matrices. for PC 105 tubes (R matrix), the ineffective length will be greater than for PC 104 tubes (R_1 matrix), leading to a more important damage accumulation since fibres stressed at rupture obey a Weibull distribution.

$$P(\sigma) = 1 - \exp - \delta(t)\,(\sigma\sigma_0)^m \qquad (1)$$

where σ, δ_0, m are the applied stress, a scale factor and the Weibull parameter, respectively.

Amplitude histograms have been recorded during the burst tests for both kinds of tubes. It can be noticed that the histograms move to higher amplitudes for higher stress levels if the matrix is softer, as is the case with PC 104 tubes (Fig. 7). Initially, the emissions are centred around 25 dB, then, as the applied stress increases, an important greater proportion of acoustic emission is observed in the range 40 to 50 dB. The same tendency has been observed with unidirectional Epoxy Vicotex 108 matrix based CFRP /9/. Amplitude histograms obtained for flat specimens, using the same matrix system (R_0, R_1) have exhibited the same tendency /4/. It has been shown, using frequency analysis /4/, or by comparison with other composites /10/ such as PSP matrix based CFRP where internal stresses are significant, that low amplitude events can be attributed to matrix microcracking and high amplitude to fibre fracture. This microcracking of the matrix must be due to the pre-existence of broken fibres before loading, leading to micro-defects and, consequently, microcracking of the matrix. As a result, a softer matrix (PC 105) produces a less important proportion of 25 dB events at the beginning of the test.

IV. RESULTS OBTAINED ON ±75 TUBES

Extensometry Results

Extensometry measurements show non-linear behaviour in both the axial and hoop directions (Fig. 8). Different mechanisms can cause this phenomenon. Firstly, non-linear behaviour of the matrix and damage accumulation which introduce a decrease in transverse and longitudinal properties and secondly, reorientation of the direction of the fibres leading to an increase in hoop modulus and a decrease in longitudinal modulus of the tubes. The softer the matrix, the greater should be the increase of modulus. A higher increase in hoop modulus for the PC 106 tubes is observed and this suggests that the non-linear behaviour of the matrix, greater for the CO material, counter-balances the effect of the fibre reorientation.

It can be noticed that, contrary to ±88 tubes, the burst pressure is higher for the PC 107 tube made with a

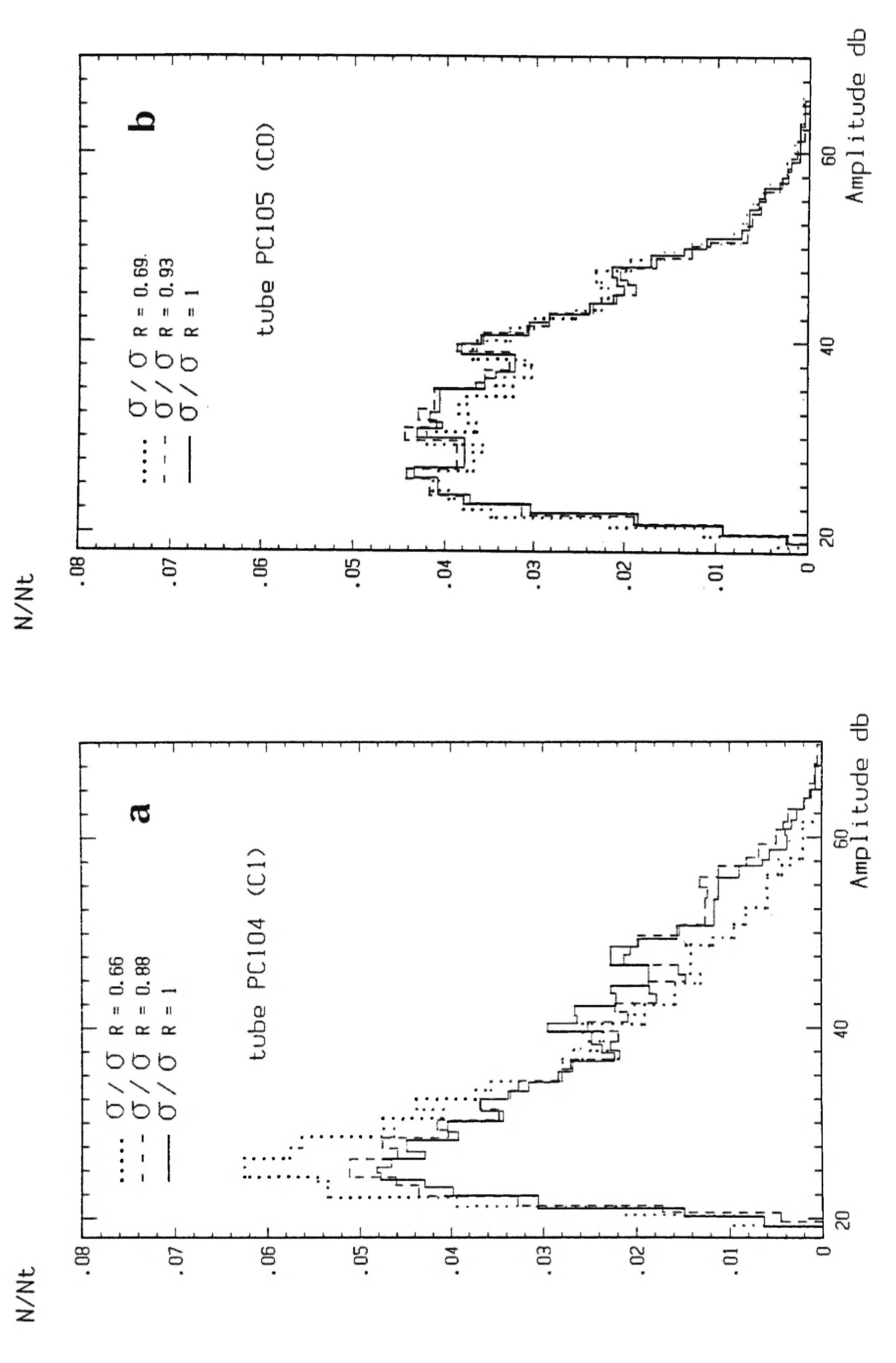

Fig. 7: Amplitude histograms obtained at different load levels for PC 104 (a) and PC 105 (b) tubes. (N_T = total number of emissions).

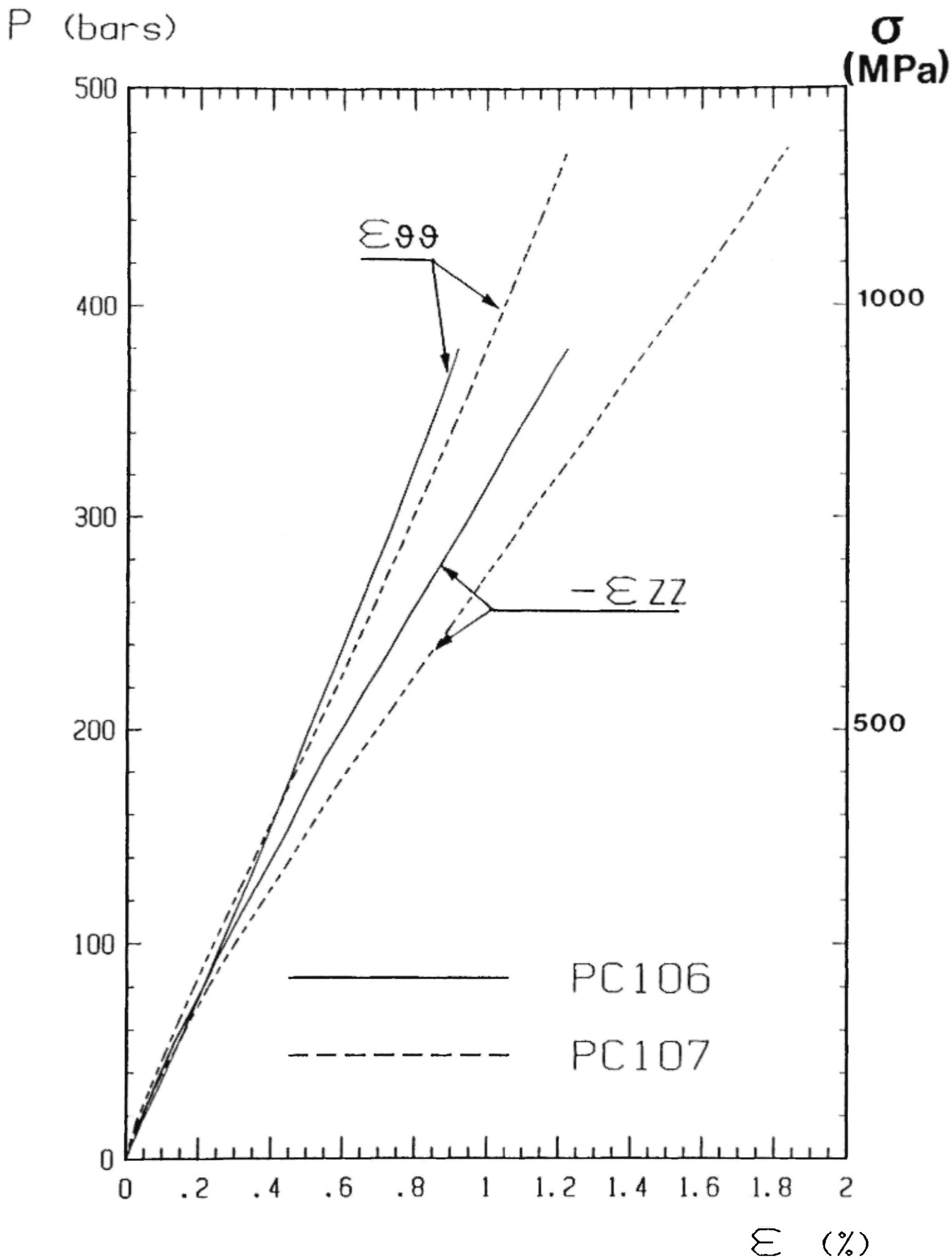

Fig. 8: Axial and hoop strain curves as a function of pressure for PC 106 and PC 107 tubes.

more flexible matrix, since the corresponding hoop stress was equal to 1100 MPa compared to 900 MPa for the PC 106 tube.

A fractography study also shows quite different behaviour for the two kinds of tubes (Fig. 9). For PC 106 samples, the crack propagations follow two types of mode: propagation along the winding angle (zone 3) and along the axis of the tube (zone 2). No delamination was found and no permanent deformation was observed after failure. On the other hand, if the two modes of failure occur in the PC 107 tubes, crack networking is more extensive.

These cracks are not always located along the axis of the tubes or parallel to the winding direction and there are delaminations (zone 5). Some parts of some tubes become permanently deformed (zone 4). This later type of tube presents, therefore, a more dissipative enrgy phenomenon at fracture and a consequent higher burst pressure. Figure 10a shows a scanning electronic micrograph of the fracture surface between two layers of a PC 106 tube: the fibre fractures are numerous and groups into 'n uplet', and the fracture surface of the matrix seems rather brittle. On the other hand, the fracture surface observed on the PC 107 tube shows plastic deformation by shear, resulting in feathering.

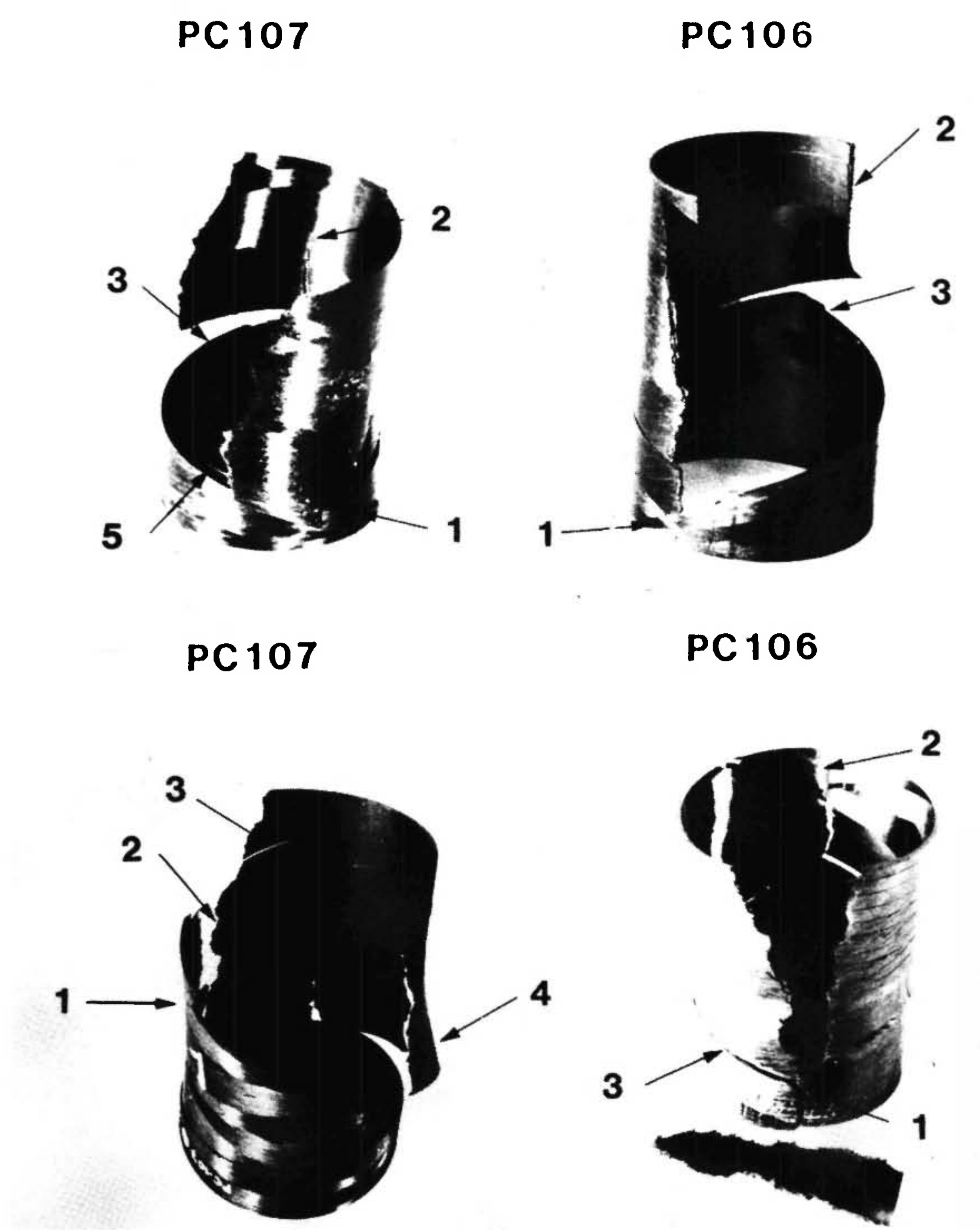

Fig. 9: Failure modes of ± 75 tubes.

Fig. 10: Scanning electron micrograph of the interlaminer fracture surface of PC 106 (a) and PC 107 (b) tubes.

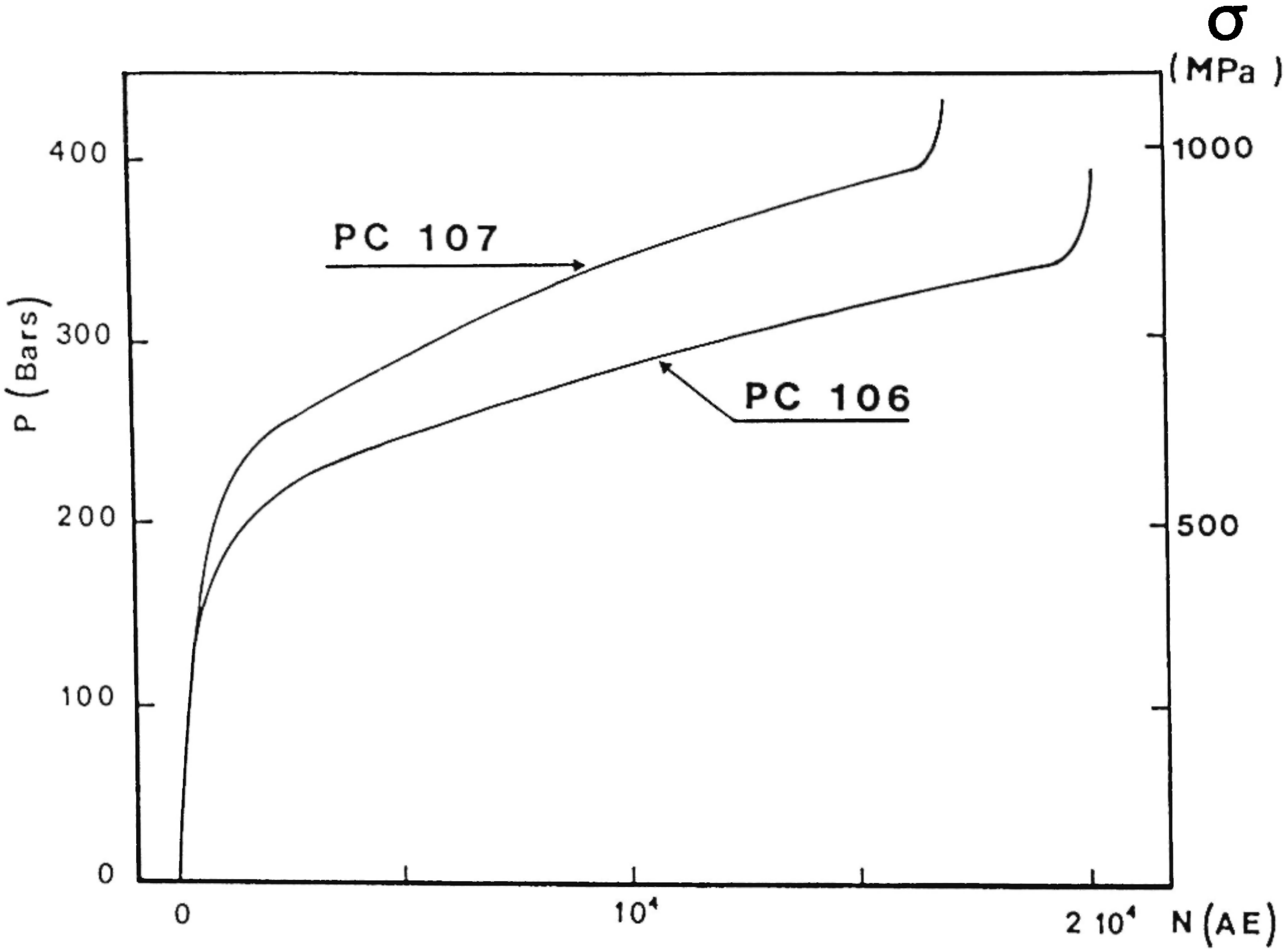

Fig. 11: Cumulative acoustic emission curves obtained during burst testing of ± 75 tubes.

A.E. Results

Contrary to ± 88 tubes (Fig. 11), the damage accumulation is greater for materials constructed from the R_1 matrix (PC 106 tubes). The ductile character of the matrix leads to a lesser amount of microcracking. Therefore, the more pronounced networking observed on PC 107 tubes at failure must have been produced during the last few seconds of the burst test and does not correspond to a progressive damage accumulation. In fact, because of the high rate of damage accumulation at the end of the test, for both tubes, there is a saturation of the Acoustic Emission channel, leading to a cessation of event acquisitions (Fig. 11).

As a consequence of the large amount of microcracking of the matrix, the amplitude histogram is centred around low amplitude values (Fig. 12). This tendency is more significant in PC 106 tubes due to the more brittle character of the matrix, whereas a slight shift towards higher amplitude values is observed for PC 107 tubes. Consequently, 9% of events are around 25 dB for PC 107 tubes, compared to 11% for PC 106 tubes, a relative different of 20%.

CONCLUSIONS

Two types of filament winding tubes were examined and the influence of matrix rheology has been tested with two different resins. When the main failure mechanism is fibre failure, the burst properties increase when the matrix is more rigid (± 88tubes). This can be explained by the bundle chain model and consideration of the viscoelastic properties of the matrix. However for (± 75 tubes), better instantaneous properties will be obtained with the softer matrix where two mechanisms of failure are encounters; matrix and fibre failure. The use of the acoustic emission technique has highlighted the influence of this double mechanism failure. The two mechanisms of degradation produce different amplitude histograms. When fibre failure mechanism is dominating, the amplitude is centred around 40 dB in reference to 1 μV at the transducer, whereas, when matrix failure is dominating, a lower amplitude is observed.

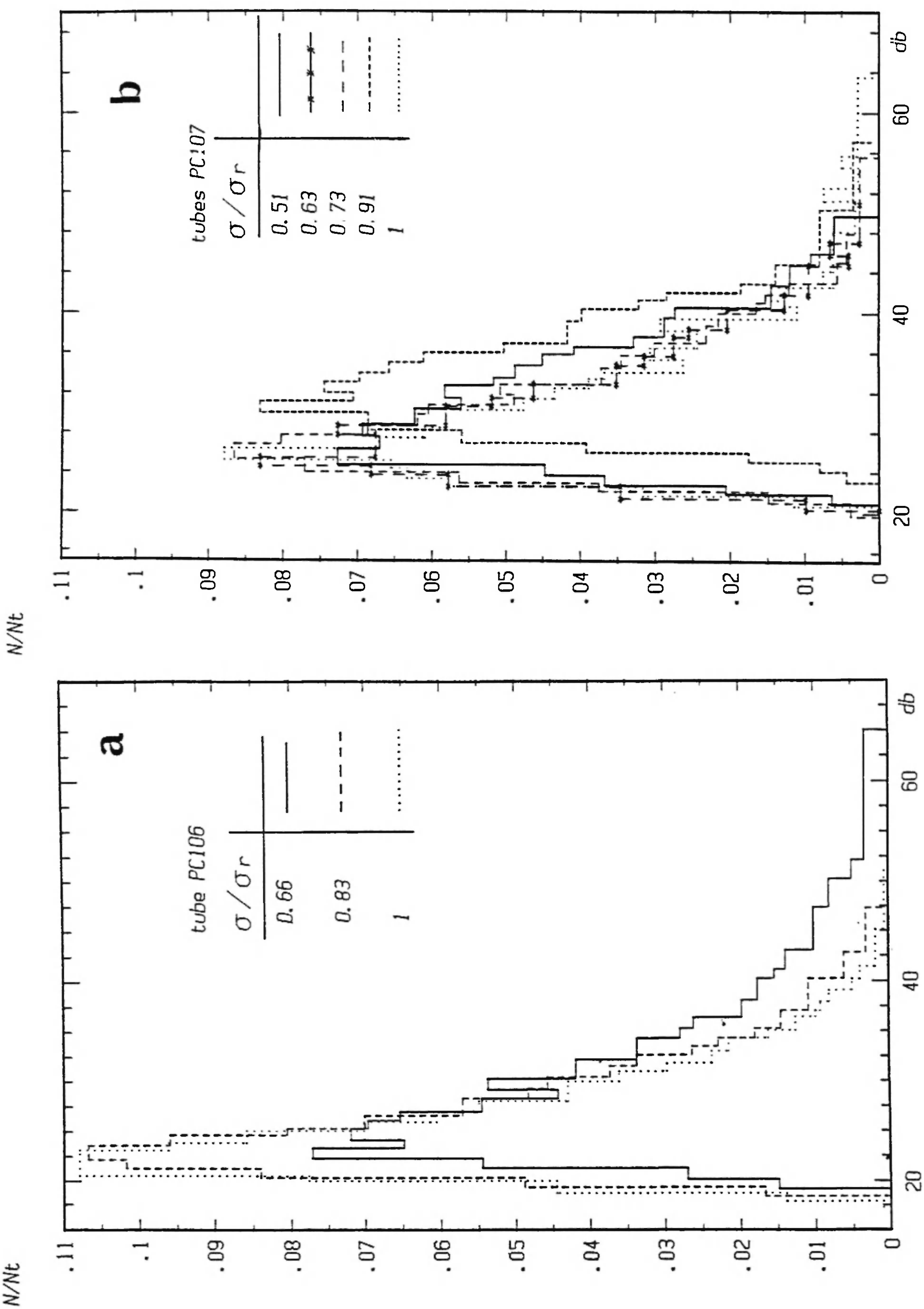

Fig. 12: Amplitude histograms obtained at different load levels for PC 106 (a) and PC 107 (b) (N_T = total number of emissions).

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