Failure Criteria and Acoustic Emission as Applied to Composite Materials

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A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fullfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 1992.

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

(Signature of Candidate)

15 day of April 1992

ABSTRACT

This project involves the comparison of different failure criteria with experimental results for fibre composite materials, and investigates the usefulness of acoustic emission in composite testing. Three sets of specimens were tested to failure in tension. The specimens had various ply orientations and were tested using acoustic emission to determine ply failures. Carbon and glass fibre reinforced epoxy pre-impregnated specimens were used. The testing machine was an ESH testing machine, and a Physical Acoustics Corporation computer and data acquisition unit were used to record data from a piezo-electric sensor. Suitable failure criteria should be chosen on the basis of ply orientation and material type (eg fibre stiffness), a combination of criteria being used if necessary. Acoustic emission was successfully used to detect ply failure in multi-layered laminates.

CONTENTS

NOMENCLATURE

Symbol	Meaning
σ_1, σ_2	principal fibre direction stresses (MPa)
σ_{12}	principal shear stress (MPa)
Q_{11}, Q_{12}, *etc*	reduced stiffness matrix
e_1, e_2, e_{12}	principal fibre direction strains
E_1, E_2	principal fibre direction tensile modulus (MPa)
v, v_{12}, v_{21}	Poisson's Ratio
T	transformation matrix
t	fibre angle (degrees)
σ_x, σ_y, σ_{xy}	principal laminate direction stresses (MPa)

$\epsilon_x, \epsilon_y, \epsilon_{xy}$	principal laminate direction strains
$\overline{Q}_{11}, \overline{Q}_{12}$, etc	transformed reduced stiffness matrix
K_x, K_y, K_{xy}	curvature in laminate direction (mm^{-1})
$\epsilon_{mx}, \epsilon_{my}, \epsilon_{mxy}$	midplane strains
Z_k	distance between midplane and layer k (mm,
t	thickness (mm)
N	number of layers in laminate
N_x, N_y, N_{xy}	load on laminate (N)
M_x, M_y, M_{xy}	moments on laminate (Nmm)
A, B, C	matrices
S	allowable shear stress (MPa)
Xt, Yt	principal laminate directions allowable tensile stress (MPa)
Xc, Yc	principal laminate directions allowable compressive stress (MPa)

A_{12}, A_{22}, etc.	tensor term coefficients
UTS	ultimate tensile strength (MPa)
w	width (mm)
F_{ut}	ultimate tensile force (N or kN)
FPF	first ply failure force (N or kN)
SPF	second ply failure force (N or kN)
LPF	last ply failure (N or kN)
b	amplitude parameter
a	amplitude level (dB)
n(a)	number of emissions
a_o	constant

1 INTRODUCTION

1.1 Composite Materials

Composite materials are being used increasingly in a wide variety of structural applications. Their use in the aircraft industry has, in particular, increased rapidly over the past decade, because of their good specific mechanical properties. Knowledge of composite material fracture behaviour is, however, still limited and much work remains to be carried out before a full understanding of failure and failure prediction is achieved.

Two aspects are of particular importance, these being failure prediction and non-destructive testing. These two areas are considered in this report.

Because composite materials are anisotropic and non-homogeneous, special considerations must be taken into account when designing with them. There are two basic methods of analysing composite materials; namely micromechanics and macromechanics. In micromechanics the individual fibre and matrix properties are used to predict lamina properties. In macromechanics the individual lamina properties are used to predict laminate properties, this procedure being known as Classical Lamination Theory. Both of these are used to a certain extent in laminate strength analysis.

When predicting laminate strength, The state of stress within each lamina must be calculated and compared to some failure criterion. If this lamina has failed, then its effects on the overall laminate must be altered accordingly before continuing with the analysis (1).

1.2 Acoustic Emission

1.2.1 History

Acoustic emission was originally widely observed in the metallurgical field, such as in the formation of martensite in steels. The first instrumented acoustic emission experiment was carried out by Charles S. Barrett in 1947 on metals.

Acoustic emission is becoming popular as an NDT technique, especially for composite materials. Many papers have been published and research is being carried out overseas on topics such as testing of composite aircraft in-flight with acoustic emission. Standards on NDT testing using acoustic emission have been compiled such as ASME acoustic emission examination of metallic vessels during pressure testing, and similar standards for testing of composite vessels. In the USA there are courses for training of acoustic emission testing personnel.

Computer based instrumentation designed specifically for monitoring acoustic emission is manufactured by a range of companies in the USA, such as Physical Acoustics Corporation, Dunegan Endevco and Hartford Steam Boiler Inspection Technologies. These machines can measure the various acoustic emission parameters which are examined in order to establish material behaviour, according to requirements.

Establishing failure modes may be an important use for acoustic emission, especially in composite materials. Some work has been carried out in this field (2,3), and research is continuing.

1.2.2 Acoustic Emission in Composites

Acoustic emission (AE) in materials is the stress wave generated by a material when an event such as a small volumetric change occurs due to the material being subjected to stress. Each acoustic emission event, or occurrence, corresponds to a single point source of mechanical deformation (4). The stress wave travels to the surface of the material, from where a sensor picks up the signal. The signal can then be amplified, filtered, analysed and recorded.

A material must have elasticity to allow the stress wave to propagate. Heat and sound are created through dissipation of the stress wave due to internal friction. High frequency waves attenuate faster than lower frequency waves. A high frequency sensor therefore detects events over a smaller area than a low frequency sensor.

There are different types of waves that travel in a material, such as surface waves, transverse waves and longitudinal waves. Longitudinal waves travel the fastest, followed by transverse waves. Surface waves travel slowest. Acoustic waves refract and reflect from material surfaces. They also may partially change mode during scattering or interfere with other waves and change accordingly. Therefore the wave recorded by the transducer is not likely to be very similar to the wave as it was generated by the source especially in FRP materials. Attenuation of AE signals could be due to factors such as part geometry (eg reflecting surfaces), mode conversion, energy absorption (which increases with frequency) and energy scattering eg due to inclusions, voids and at grain boundaries.

Fibre reinforced plastics have high stress wave attenuation compared to metals due to their non-homogeneous nature.

Therefore AE amplitude measurements even small distances from the source can be useless. When measuring AE over large distances, many high frequency sensors must be used, or fewer low frequency sensors. It has been shown that acoustic velocity across the fibre direction is much lower than along the fibre direction in FRP whereas attenuation is higher across the fibre direction (5). Figure 1.1 shows amplitude variation with distance from the sensor for two different frequency sensors in a typical fibre composite.

The acoustic emission sensor (or transducer) is of the piezoelectric type, consisting of a crystal with a certain resonant frequency. Since the acoustic emission event frequency spectrum is generally white noise (all frequencies), the crystal is excited and an electrical pulse is generated, such as that shown in figure 1.2 (4).

The number of counts is defined as the number of threshold crossings during the pulse and the energy is proportional to the area of the pulse envelope. Its units in this report are as obtained from the AE machine. The units are called MARSE (Measured Area Rectified Signal Envelope) and are sensor dependent.

Lack of homogeneity due to porosity or inclusions increases the AE response of a material (5), and as such fibre reinforced plastics generally generate large amounts of acoustic emission compared to homogeneous materials like met. . This is because of differing stiffenesses between constituent materials. Some sources of AE in FRP are matrix cracking, fibre-matrix debonding, fibre pull-out, fibre fracture and interlaminar debonding. Large amounts of cracks may be formed in the matrix before significant material failure. This can result in low energy acoustic emission events may occurring typically after

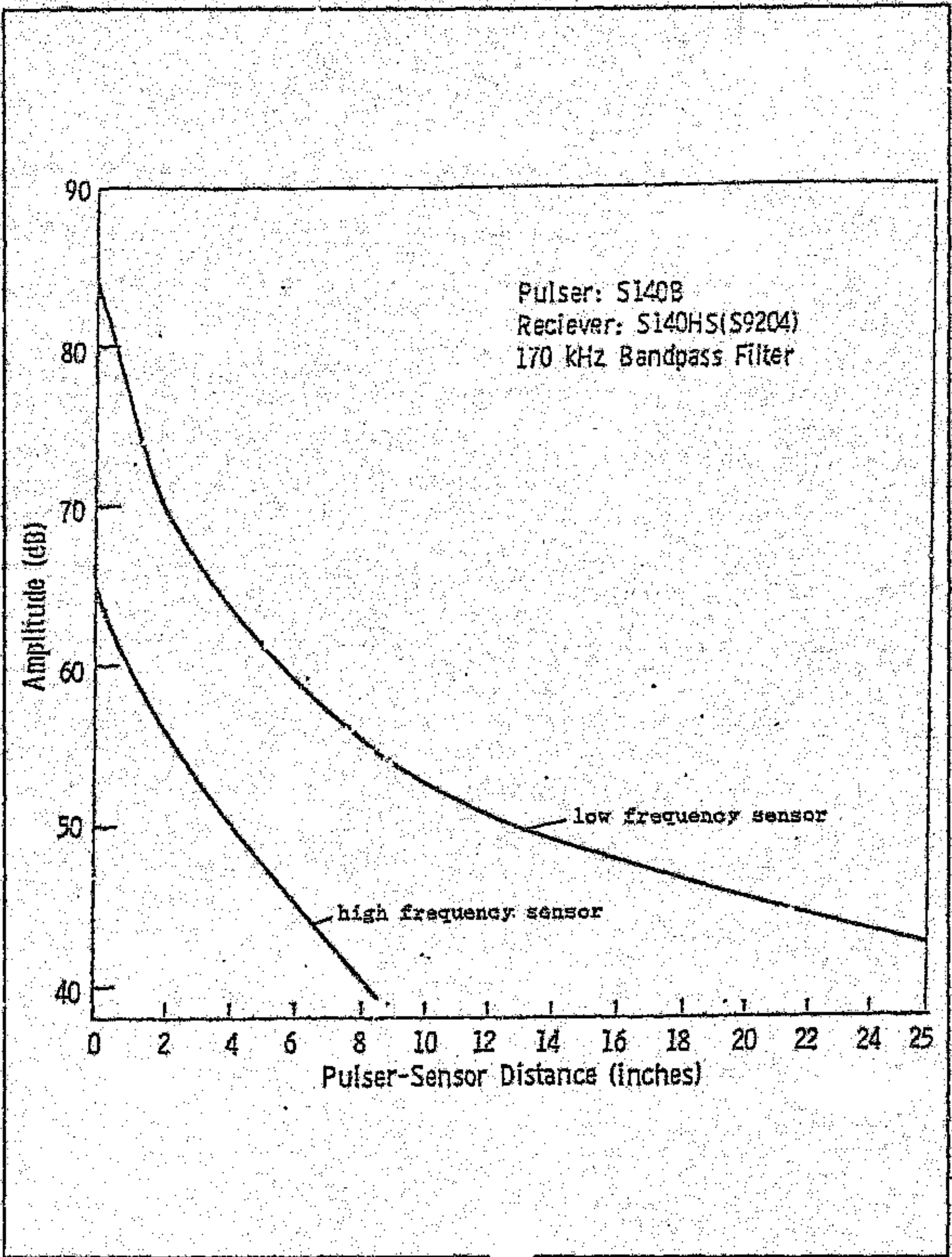


Figure 1.1 Attenuation Plot (5)

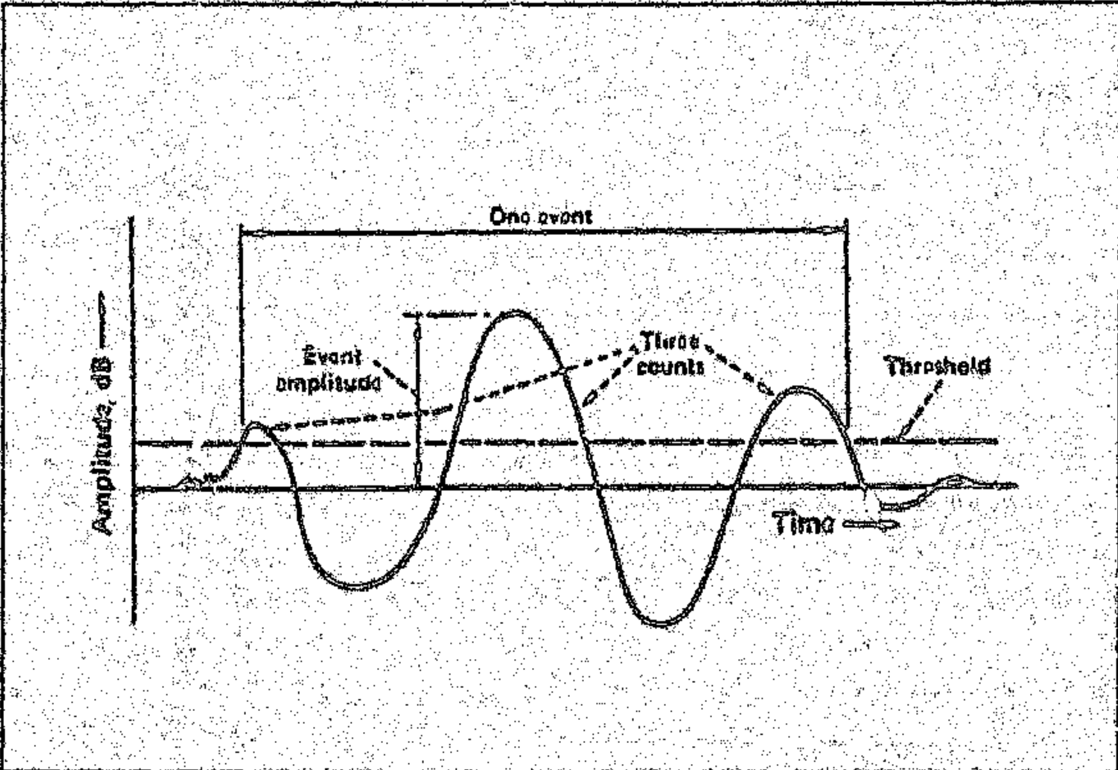


Figure 1.2 Electrical Pulse Generated from Acoustic Occurrence (4)

only one quarter of the ultimate load has been applied in glass fibre reinforced plastics.

1.3 Failure Criteria

Numerous failure criteria have been proposed for composite materials, since the various failure modes of composite laminates are difficult to predict and model with simple mathematical formulae. The criteria are functions of stresses and strengths and are designed to use uniaxial or simple biaxial data to calculate when the failure of a structure occurs under multi-axial loading conditions. Most failure theories are supported by a very limited amount of experimental data. It often happens that a designer may obtain reliable material properties and may analyse material stresses and strains to a high degree of accuracy, but is forced to use a failure criterion of doubtful reliability (6). Therefore there is a need for more research on existing failure theories to allow designers to choose a failure theory with confidence for each particular case.

1.4 Biaxial Testing of Composites

Triaxial loading for composites is difficult to contemplate, but plane stress conditions can be achieved quite easily. There are three practical methods:

(i) Off-axis tensile or compressive testing, which is the cheapest method, but has proved unreliable in some cases.(6)

(ii) Testing of a square plate type specimen or a right-angled cross specimen in biaxial tension. For the right angled cross specimen the thickness can not be reduced in the centre, as is the case for metal specimens, so there are stress concentration problems at the junction.(6)

(iii) Testing of tubular specimens in tension with internal pressure.(6)

Many criteria require biaxial stress data in order to evaluate certain equation term coefficients. Only method (i) was used for obtaining biaxial stress data experimentally for this project, since the equipment required is available at most test facilities. The equipment and specimens required for testing according to methods (ii) and (iii) are expensive and the techniques are difficult and complicated.

2 LITERATURE SURVEY

2.1 Acoustic Emission for Failure Mode Characterization

Figures 2.1 and 2.2 show oscilloscope representations of a matrix and a delamination AE event respectively (5). As can be seen, the two signals are vastly different, and they may be distinguished from each other by their resultant AE data. Similarly, a fibre event should be a very high amplitude relatively low duration time event type. Clearly the main distinguishing parameters between failure modes might then be amplitude and duration time.

There are basically four failure modes involved in composites (2):

1) fibre fracture
2) matrix fracture parallel to the fibres
3) matrix fracture perpendicular to the fibres
4) delamination

There are two modes of fibre fracture ; crack propogation perpendicular to the fibres, and the absence of a continuous crack with isolated fibre fracture.

The energy release depends on the stress level, geometry (eg fibre volume fraction, fibre orientations) and moduli of the fibres and matrix (2).

It is commonly accepted (4) that the peaks on the amplitude vs. events plot relate to the three common failure modes, namely matrix cracking, delamination and fibre fracture. There has recently been some dispute over this. The difficulty is in trying to isolate a typical failure which is definitely of one type. A typical bimodal amplitude histogram is shown in figure 2.3 (Fibre breakage 70 - 80 dB, delamination 50 - 60 dB).

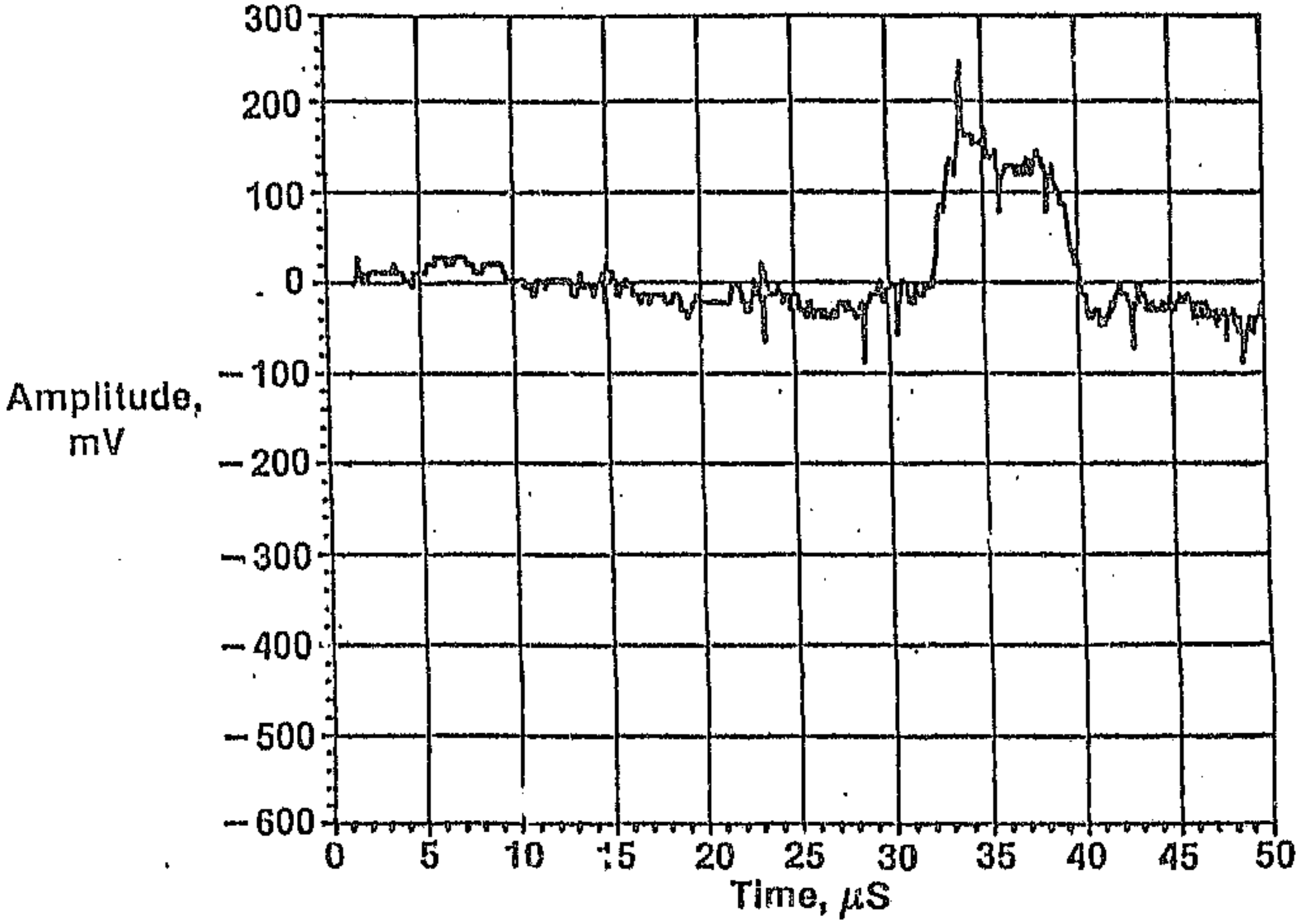


Figure 2.1 Matrix AE Event in Fiber/Epoxy Composite (5)

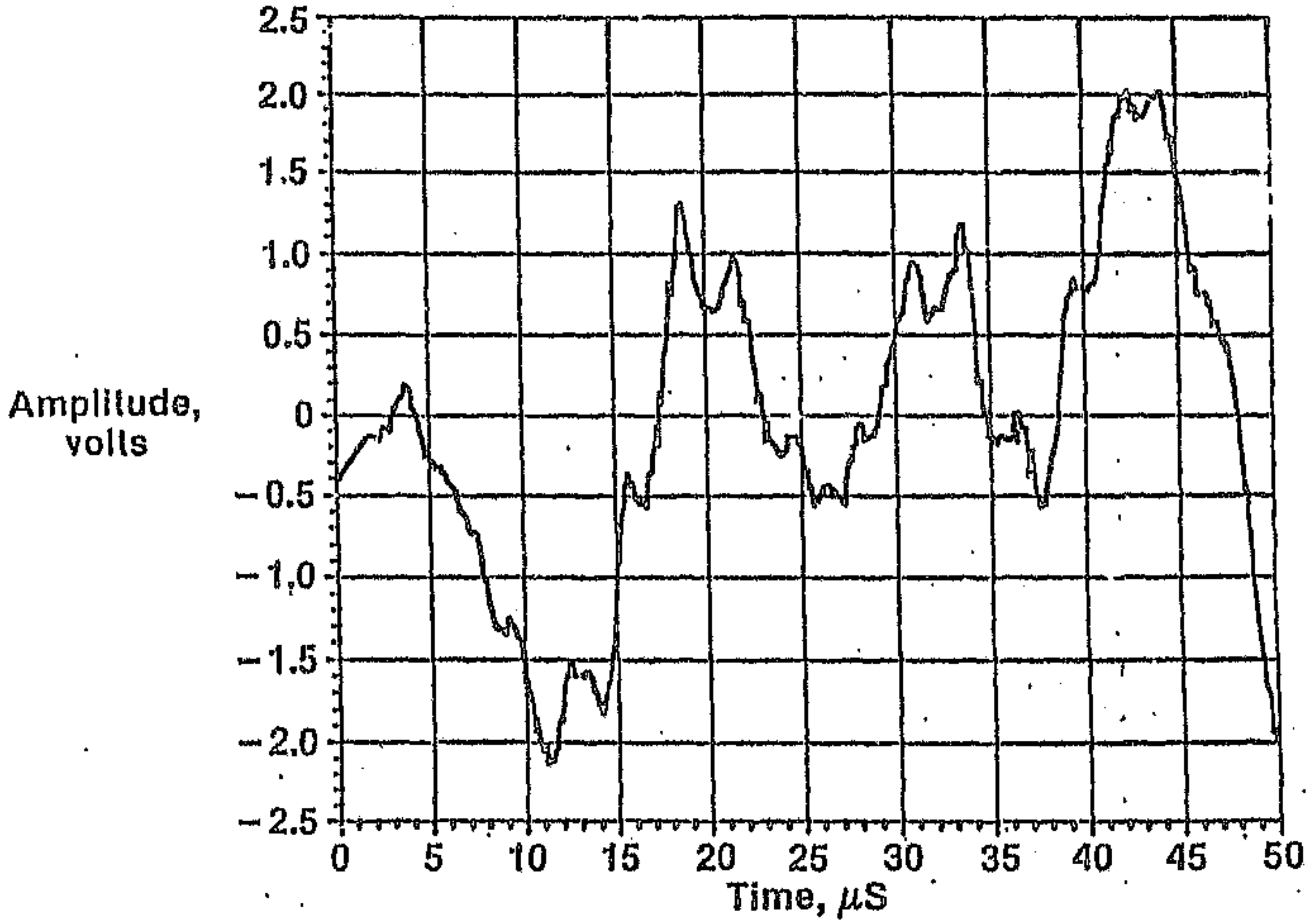


Figure 2.2 Delamination Event in Fiber/Epoxy Composite (5)

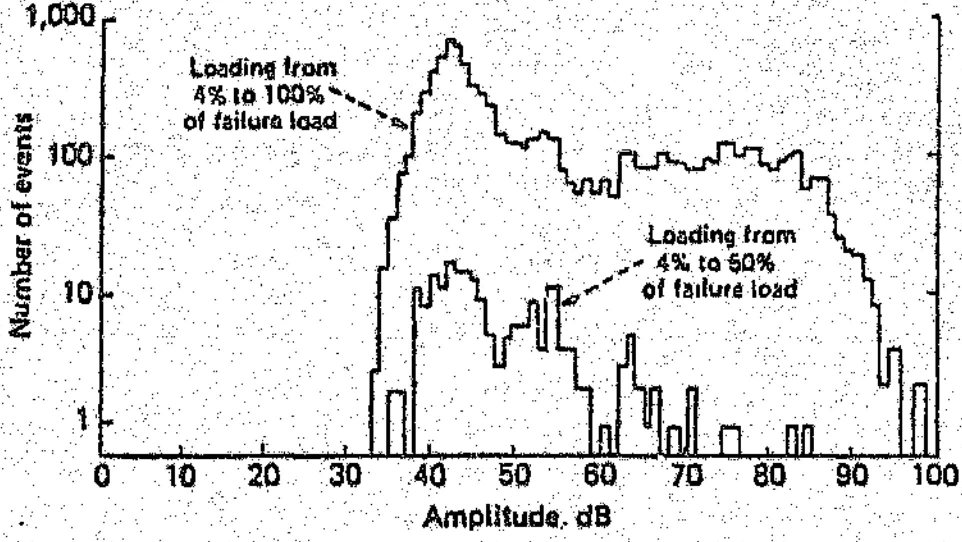


Figure 2.3 Amplitude Distribution for Different Load Ranges (8)

The following theory (2) has been put forward for amplitude analysis:
A log plot of threshold amplitude level 'a' vs cumulative number of emissions exceeding the threshold level gives a straight line. Discontinuities in the slope 'b' may indicate critical points of the amplitude spectrum. b is not affected by the attenuation of sound in the material, if all amplitudes are equally attenuated. A large value of b indicates a predominance of low amplitude events. A small value of b indicates a predominance of energetic events. In reinforced plastics, several types of failure can occur simultaneously, and a single unique value of b is not obtained.(2)

Experiments were carried out (3) to find values of b for different failure modes and different composite materials. Crack propogation was induced in different directions relative to the fibre direction, and the acoustic emission data recorded. The acoustic emission pulses generated by a particular failure mode were found to have a unique amplitude distribution characteristic of the failure mode and the material. The characteristic signature (b) can be found for a particular fracture mode using the log plot described above. This procedure enabled reliable identification of the crack type which initially developed.

It is purported to be possible to set the threshold level sufficiently high such that emissions due to plastic deformation of the matrix are not recorded and in this case one AE count can be correlated to one fibre breakage (9). It is an accepted fact that filament fractures in general generate more energetic events than other failure mechanisms.

Another commonly recorded trend is the increase of AE activity corresponding to the kinks of the stress-strain curve which is due to the increased number of ply failure events occurring at such points. It appears that the various damage mechanisms generate different frequency characteristics, but there is very limited spectral analysis data results. This could be a useful area for future research.

2.2 Acoustic Emission as a Non-Destructive Test (NDT) Method

Acoustic emission has already gained widespread acceptance overseas as a reliable non-destructive test method. Currently there is an ASTM standard on testing of composite structures (10).

Acoustic emission may be used to detect damage mechanisms such as resin cracking, fibre debonding, fibre pull-out, fibre breakage, delamination or bond failure in joints. Unstressed areas and passive defects will not generate acoustic emission.

The basic function of an acoustic emission monitoring system is to detect, locate and classify emission sources. Other NDT methods may then be used to further evaluate the significance of acoustic emission sources (10). Table 2.1 shows the various NDT methods and their usefulness in the field of composites.

Acoustic emission is useful for monitoring structures during service as a means of incipient failure detection. It is applied during proof tests to identify active flaws that could induce failure later.

2.2.1 Quantities Used for NDT

a) Kaiser and Felicity Effects

The Kaiser Effect is the effect whereby there is no acoustic emission upon reloading until the previous maximum load is exceeded (2). This often holds true for metals, and for composites at very low stresses (less than a quarter of their ultimate load).If a composite is not held at load in the elastic region until all the emissions have stopped, but is unloaded, emissions then occur at a load lower than the previous maximum.

Table 2.1 Non-Destructive Tests Applied to CFRP Laminates and Structures (11)

Technique	Void content	Fibre content	Resin content	Fibre orientation	Material homogeneity	Mechanical properties	Delaminations	Fatigue damage	Contamination	Delaminations	Disbonds	Cracks	Debris	Condition of internal components
	Category 1									Category 2				
Radiographic														
Low kV, high definition				o	o				o			o	o	o
Radio-opaque penetrants	o													
Radio-opaque tracers				o										
Gamma		o	o											
Ultrasonic														
Attenuation measurements	o	o				o	o	o		o	o			o
Velocity measurement	o	o		o	o	o								
Goniometry				o	o	o	o							
Spectroscopy	o				o	o	o	o						
Resonance					o	o	o			o	o			
Holography										o	o			
Optical														
Optical holography										o	o			
Speckle photography										o	o	o		
Laser interferometry										o	o			
Others														
Acoustic emission						o		o		o	o	o		
Eddy currents		o		o	o	o		o				o		
Micro waves	o						o							
Mechanical impedance										o	o		o	o

Defect or property evaluated: columns "Void content" to "Contamination" are Category 1; "Delaminations" to "Condition of internal components" are Category 2.

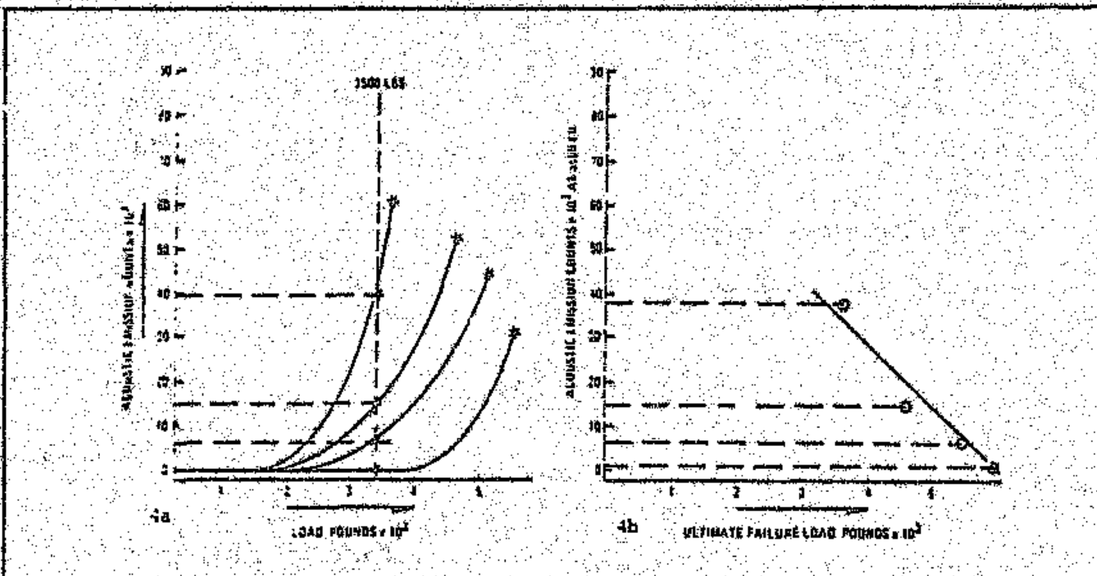
This is known as the Felicity Effect (2).The Felicity Ratio is the ratio of the load at which emissions occur to the previous maximum load. It is indicative of the amount of damage done to the material. A Felicity Ratio below 0.8 is generally not acceptable. By monitoring the Felicity Ratio, one may either check the initial quality of the vessel or, in other cases, stop the tests if the ratio falls below a certain limit (13, 14).

b) Number of Events

Events begin to take place at a repeatable percentage of ultimate load, for a particular lay-up. A lay-up of random glass begins generating emissions at approximatly 25% of ultimate load, while a unidirectional fiber lay-up begins generating emissions at about 50% of ultimate load. (15)

After tests were carried out (16) on fibreglass/epoxy specimens, the acoustic emission events at an arbitrary load of 3500 lbs were noted for each specimen, and plotted against ultimate failure load (see figure 2.4). This curve was used to predict the ultimate failure load of the remaining specimens to within five percent.

Tests were also done on graphite/epoxy structural beams (16). At 41,2% of ultimate load, sufficient data was obtained from the acoustic emission system to estimate final failure strength of the beam to within ten percent. Figure 2.5 shows the plot of events vs stress of the beam. A graphite/epoxy missile cone's ultimate failure was predicted to within eleven percent of the ultimate load.



_igure 2.4 Prediction of Ultimate Composite Failure by Acoustic Emission (16)

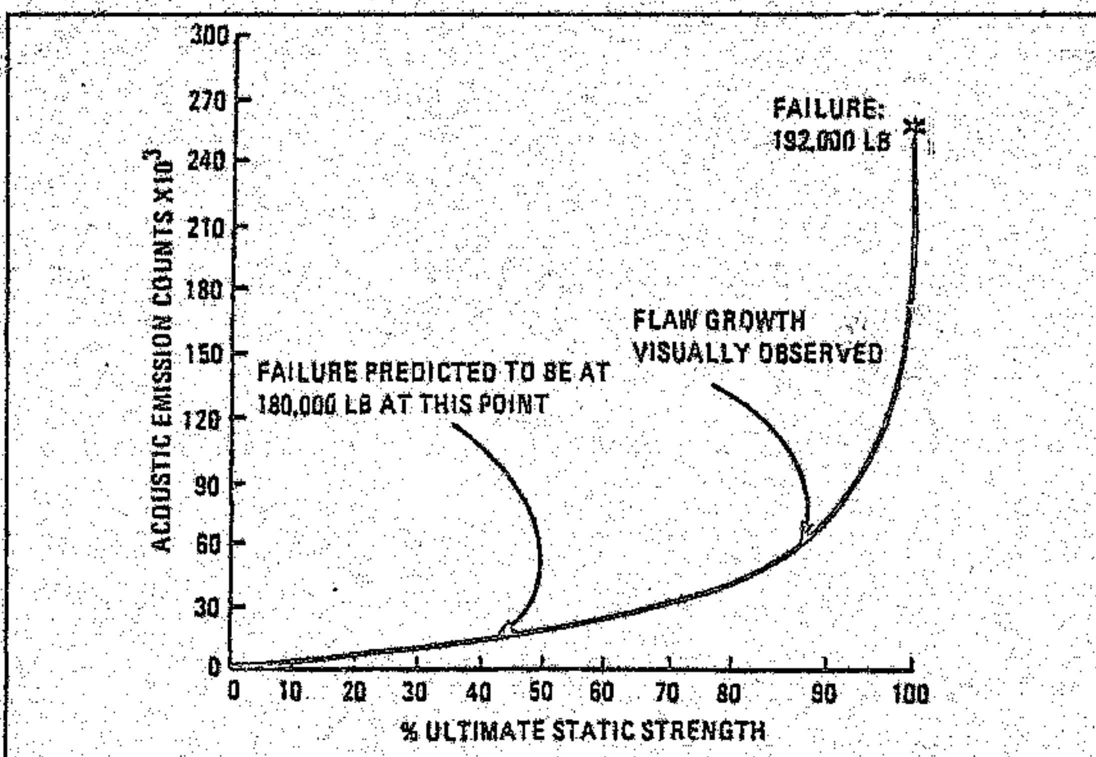


Figure 2.5 Acoustic Emission Signals from Graphite Structure

The following was concluded (16):
1) An ultimate strength prediction curve should be established first, by monitoring several structures to failure and selecting a load value which intersects the events vs load curve.

2) Estimation of the ultimate failure can be made from events vs load curves, provided that previous experience with the composite material has been had. (16)

Other research (17) included the testing in flexure of chopped strand mat panels made using isopthalic polyester resin. The test pieces were loaded to 1/4 of their ultimate load. It was found that all parts which produced very low acoustic emission had acceptable flexural strengths. However, certain specimens which produced high acoustic emission also had acceptable flexural strengths. This indicates that the acoustic emission test will pick out flawed specimens. However, noisy specimens need to be rechecked using some other non-destructive test (NDT) method.

Acoustic emission events may continue under constant load (8). A time plot may be used to determine if this creep deformation is becoming unstable. If event rate increases under constant load, the material being tested is being overstressed and is likely to fail.

It has been suggested (18) that the ratio of counts per event should be monitored; the allowable value depends on the particular situation.

c) Stress Wave Factor

A passive ultrasonic/acoustic method has been suggested for NDT

(12). Conventional ultrasonic methods are limited to finding cracks and discontinuities. Stress waves are induced by injecting ultrasonic pulses through the material and a receiving transducer detects the stress waves. A stress wave factor is found which depends on wave propogation properties of the composite. It varies with microstructural factors such as fibre/resin ratio, voids, delaminations, etc. The stress wave factor is essentially a measure of the efficiency of stress wave energy transmission in the material. Calibration against a standard piece of material is required. The stress wave simulation method requires one side access and immediately returns a number which rates the product, distinguishing inferior material. This method obviously has the advantage of not requiring the material to be stressed during testing.

2.2.2 Pressure Vessels

An important use for AE overseas is in the NDT testing of composite pressure vessels.

The Comittee on coustic Emission from Reinforced Plastics (CARP) have suggested a method for the acoustic emission testing of tanks or vessels (13). The method explained is convenient for on-line use under operating stress to decermine the structural integrity of in-service equipment, usually with minimal process disruption. Guidelines are provided for the acoustic emission examination or monitoring of fibre reinforced plastic tanks or vessels under pressure or vacuum.

A table of acceptance criteria is provided. The parameters which are monitored are:

1) Number of emissions during hold.
2) Felicity Ratio
3) Total Counts

4) Number of events greater than the reference amplitude threshold (threshold which may be found from tests explained in the reference).

ASTM E569-82 (10) provides guidelines for the acoustic emission examination of pressure vessels which are under stress.

Acoustic emission is used widely as a test of new and in-service fibre reinforced plastics overseas (19). Since the Monsanto Co. (USA) started testing all vessels regularly, the number of failures has reduced dramatically. They have not had a case where a defect escaped detection by acoustic emission. Acoustic emission detects defects at an early stage, therefore allowing repair.

The rejection criteria from testing pressure vessels (14) are listed below, but apply to the specific Dunegan/Endevco equipment used in the tests. Slight modification may be required for other equipment. During testing a stepped loading sequence was used. The criteria in order of importance are:

1) Total counts (events) in excess of 5000 (measure of cumulative damage).

2) More than ten events of over 70 dB amplitude (fibre damage).

3) During a load hold, emissions last beyond two minutes (creep stability).

4) A Felicity Ratio of less than 0.95 (previous damage).

2.3 Failure Prediction in Composites

Early work on the strength of anisotropic materials was conducted mainly on wood, single crystals and metals. Interaction equations were developed to describe the strength of wood as a function of grain orientation, eg Hankinson's theory (20) in 1921. It is significant that this theory does not involve the shear strength of the material. Many of the composite strength criteria were influenced by the Von Mises failure theory for metals. Hill generalized the Von Mises criterion to include anisotropy (20). Hill's theory was subsequently adapted in various ays. Initial attempts to develop a strength theory which is invariant with respect to the coordinate system were carried out by Goldenblat and Kopnov and Askunazi (20), and subsequently by Malmeister, Tsai and Wu (22) and others. Cowin's theory (21, was developed for bone and wood, using Hankinson's and Tsai-Wu's theories. Other composite failure theories include Marin, Malmeister, Grant-Sanders, Ashkunazi and Pekker, Chamis, Griffith-Baldwin, Wu-Scheublein, Puppo-Evensen, Tsai-Hill, Hoffman, Norris, Fischer and Puck (20, 27).

It was noted (22) that nearly all the composite failure criteria agree with one another with reference to the principal strengths; i.e. those uniaxial and pure shear test data measured along material symmetry axes. The disagreements generally occur in the combined-stress state.

It was stated (20) that the following are among the greatest deficiencies of current composite strength analyses:
1) lack of a representative but simple lamination theory to take into account interlaminar and non-linear effects;
2) insufficient reliable experimental results.

The following topics are listed (20) which warrant further effort:

1) When a particular ply in a laminate fails, how and to what extent does it unload, and how does this affect the remaining laminate, i.e., how are its loads transferred to the active plies.

2) How to determine laminate failure, i.e., which and how many plies must fail.

3) Determination of the effects of residual stresses relative to failure criteria.

4) Extension of strength theories to include inelastic and nonlinear lamina response.

5) Development of a simple but mathematically rigorous failure criterion whose interaction coefficients can be evaluated easily and with confidence.

6) Failure prediction and fracture mechanics of biaxially loaded composites under cyclic and impact conditions and extreme temperatures.

7) Application of biaxial strength studies to hybrid composites should be undertaken.

2.3.1 Criteria Allowing for Linear Stress-Strain Behaviour

Many different failure criteria have been proposed for predicting the point at which failure in composite materials is likely to occur assuming linear stress-strain behaviour. These various failure criteria may be applied to each layer of a multi-layered laminate to find which are likely to fail under a given loading system. The stresses in each layer can be calculated using the equations given in section 3.2. In this way, the strengths of a multi-layered laminate of different ply orientations and materials can be found.

There are three main types of failure criteria. There are criteria comprising a number of :

1) independent conditions.
2) independent and interactive conditions.
3) fully interactive conditions.

An interactive term is one which contains more than one principal stress. These criteria relate to a single orthotropic layer in plane stress.

The most useful failure criteria involve minimal lamina input data. A normally equipped laboratory should be able to carry out all the tests required. The criteria evaluated in this project were chosen with this in mind, the most unusual test required being the biaxial tension test. A good criterion should account for residual stresses due to fabrication and curing, as well as interlaminar, non-linear and inelastic effects (20).

The following are popular failure criteria that have been used in the past:-

a) Maximum Stress Criterion (22)

Failure occurs when one of the principal stresses reaches its allowable value.

$$\sigma_1 = X_t \text{ or } -X_c$$

$$\sigma_2 = Y_t \text{ or } -Y_c$$

$$\tau_{12} = S$$

where X_t, Y_t = allowable principal tensile stresses
X_c, Y_c = allowable principal compressive stresses
S = allowable in-plane shear stress

b) Maximum Strain Criterion (22)

Failure occurs when one of the principal strains reaches its allowable value.

$$\varepsilon_1 = \qquad or \quad -\varepsilon_{X_c}$$

$$\varepsilon_2 = \varepsilon_{Y_t} \quad or \quad -\varepsilon_{Y_c}$$

$$\gamma_{12} = \gamma_S$$

c) Hill Criterion (34)

$$\left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\sigma_2}{Y}\right)^2 - \left(\frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2}\right) . \sigma_1 . \sigma_2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

d) Puck Simple Criterion (22)

$$\sigma_1 = X_t \quad or \quad -X_c$$

$$\left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

where $Y = Y_t$ or Y_c according to the sign of σ_2

e) Puck Modified Criterion (22)

This criterion involves tensile and compressive interactive terms.

$$\sigma_1 = X_t \quad or \quad -X_c$$

$$\left(\frac{\sigma_2^2}{Y_t . Y_c}\right) + \sigma_2 . \left(\frac{1}{Y_t} - \frac{1}{Y_c}\right) + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

f) Tsai-Hill Criterion (22)

$$\left(\frac{\sigma_1^2}{Y_t \cdot Y_c}\right) - \left(\frac{\sigma_1 \cdot \sigma_2}{X^2}\right) + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

g) Goldenblat-Kopnov Criterion (22)

$$\left(\frac{\sigma_1}{2}\right)\cdot C_1 + \left(\frac{\sigma_2}{2}\right)\cdot C_2 + \sqrt{\left(\frac{\sigma_1^2}{4}\right)\cdot C_1^2 + \left(\frac{\sigma_2^2}{4}\right)\cdot C_2^2 + A_{12}\cdot\sigma_1\cdot\sigma_2 + \left(\frac{\tau_{12}}{S}\right)}$$

where $C_1 = \frac{1}{X_t} - \frac{1}{X_c}$ and $C_2 = \frac{1}{Y_t} - \frac{1}{Y_c}$

h) Puppo-Evensen Criterion (19)

$$\left(\frac{\sigma_1}{X}\right)^2 - F\cdot\left(\frac{X}{Y}\frac{\sigma_1}{X}\frac{\sigma_2}{Y}\right) + F\cdot\left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

or

$$F\cdot\left(\frac{\sigma_1}{X}\right)^2 - F\cdot\left(\frac{X}{X}\frac{\sigma_1}{X}\frac{\sigma_2}{Y}\right) + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

where interaction factor $F = \frac{3S^2}{X_t\,Y_t}$

i) Norris and McKinnon (Interaction) Criterion (22)

$$\left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

j) Norris Distortional Energy (22)

$$\left(\frac{\sigma_1}{X}\right)^2 - \left(\frac{\sigma_1 \ \sigma_2}{X \ Y}\right) + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

$$\left(\frac{\sigma_2}{Y}\right)^2 = 1$$

$$\left(\frac{\sigma_1}{X}\right)^2 = 1$$

where X and Y should be replaced by X_t or X_c and Y_t or Y_c according to the signs of σ_1 and σ_2 .

k) Fischer Criterion (22)

This criterion is a modified form of the Norris distortional energy criterion.

$$\left(\frac{\sigma_1}{X}\right)^2 - \left(\frac{K\,\sigma_1\,\sigma_2}{X\,Y}\right) + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 = 1$$

where

$$K = \frac{E_1 \cdot (1 + \nu_{21}) + E_2 \cdot (1 + \nu_{12})}{\sqrt{2 \cdot E_1\,E_2\,(1 + \nu_{12})\,(1 + \nu_{21})}}$$

2.3.2 Criteria Allowing for Non-Linear Behaviour

Classical lamination theory assumes a linear-elastic, orthotropic constitutive behaviour for a stacked ply laminate. Most orthotropic strength criteria assume linear elastic behaviour, with mathematical 'yielding' being synonymous with ultimate failure. In practice, many composites display non-linear laminate mechanical behaviour, especially multi-orientated ply laminates such as the +-45° lay-up (20).

Composites tend to exhibit non-linear behaviour in longitudinal shear stress-strain relation, while the longitudinal tension and compression stress-strain relation remains linear (23). A set of stress-strain relations was formulated which describes the non-linear shear behaviour. Experiments with off-axis specimens showed reasonable agreement with the theory.

The St. Venant's maximum strain theory for isotropic materials was extended to include anisotropy by Petit and Waddoups (24).

Their theory and the theory proposed by Sandhu (20) provide for non-linear lamina material response.

The Petit-Waddoups theory (24) involves fitting a number of linear stress-strain curves together, such that they are all connected and together resemble the actual stress-strain behaviour of the laminate. Average stresses are applied incremently to the laminate, and the average incremental strains calculated, which are added together to obtain the current laminate strain. A stiffness matrix is calculated for each curve piece. The load is incremented until one lamina fails. A computer program is usually required to do this analysis. Extensive input information is required, including lamina uniaxial tensile and compressive stress-strain data parallel and transverse to the fibres, shear stress-strain data, plus the variation of major Poisson's ratio with principal lamina strain. The analytical procedure was validated through experimentation using Boron/Epoxy laminates in uniaxial tension. 0/90, +-20, +-30 and +-60 degree lay-up laminates were used.

Sandhu's theory (20) uses cubic-spline functions to represent the non-linear stress-strain responses to failure. Ply degradation is based on an energy to failure criterion. The criterion is based on total strain energy. Sandhu's method requires the same input information as the Petit- Waddoups theory.

2.3.3 Tensor Polynomial Theory

This theory proposes the following failure equation (20):

$$A_{11}\,\sigma_1^2 + 2\,A_{12}\,\sigma_1\,\sigma_2 + A_{22}\,\sigma_2^2 + A_{66}\,\sigma_6^2 + B_1\,\sigma_1 + B_2\,\sigma_2 = 1$$

It can be shown that :

$$A_{11} = \frac{1}{X_t \cdot X_c} \qquad B_1 = \frac{1}{X_t} - \frac{1}{X_c}$$

$$A_{22} = \frac{1}{Y_t \cdot Y_c} \qquad B_2 = \frac{1}{Y_t} - \frac{1}{Y_c}$$

$$A_{66} = \frac{1}{S^2}$$

(20)

The material constant A_{12} must be determined by a biaxial test.

For stability, factor A_{12} is limited by the following equation:

$$A_{ii} \cdot A_{jj} - A_{ij}^2 \geq 0$$

The 45-degree off-axis specimen may be used to determine A_{12}. In this case,

$$\sigma_1 = \sigma_2 = \sigma_6 = \frac{U}{2} \quad \text{and} \quad \sigma_3 = \sigma_4 = \sigma_5 = 0$$

where U is the tensile strength of the 45-degree specimen.

Then it can be shown that:

$$A_{12} = \frac{2}{U^2}\left[1 - \frac{U}{2}\left(\frac{1}{X_t} - \frac{1}{X_c} + \frac{1}{Y_t} - \frac{1}{Y_c}\right) - \frac{U^2}{4}\left(\frac{1}{X_t X_c} + \frac{1}{Y_t Y_c} + \frac{1}{S^2}\right)\right].$$

Hoffman (26) proposed the following equation for A_{12}:

$$A_{12} = -\frac{1}{2 X_t X_c}$$

Often this theory is used with $A_{12}=0$ (26).

The Tensor Polynomial Theory has been proposed by various researchers (20, 21, 22, 25). The differences between their criteria are usually in the determination of the combined-stress related coefficient A_{12}. Most researchers suggest a biaxial stress test.

The use of the thin-walled tube specimen subjected to internal or external pressure, longitudinal load and torsion as the most suitable biaxial specimen has been recommended (20). The tube diameter should be large to achieve reasonably flat laminate conditions.

Experimental scatters can be greatly magnified during computation. In the evaluation of the factor A_{12} it was noted (26) that a +-3% variation in an uniaxial off-axis tension test strength at 45 degrees will obscure the entire permissible range bounded by the stability condition. Two methods for critical determination of A_{12} are proposed: 1) Optimum ratios for normal biaxial stresses along longitudinal and transverse directions; 2) Optimum ratios for combined normal stress and shea experiments in the off-axis orientation. The best type o. loading in each case is calculated to achieve a good resolution of A_{12}. For the first method, pressurized tensile tube testing equipment is required, while for the second method off-axis tensile and torsion testing of tubes is required.

The failure theories proposed by Tsai and Wu (20), Cowin (21), Hoffman (26) and Malmeister (20) differ only in their various methods of calculating the polynomial coefficient A_{12}. Since A_{12} is small, it is often taken as zero. It was suggested (23) that the following should be used:

$$A_{12} = -0.5\sqrt{F_{11}\,F_{22}}$$

By assuming that for zero shear stress a non-dimensionalized form of the tensor polynomial theory is a generalization of the von Mises criterion, the following equation for A_{12} was derived (27):

$$A_{12} = -\frac{1}{2}\left(A_{11}\cdot A_{22}\right)^{\frac{1}{2}}$$

Small changes in A_{12} can significantly affect the failure prediction (20).

The Ashkenazi criterion (20) is based on the tensor polynomial theory. The suggested method for finding the interaction coefficient A_{12} is by means of a 45-degree specimen tension test. For highly directional materials, Ashkenazi suggested a fourth-order polynomial. Some of the coefficients must be determined experimentally under three different biaxial states of stress. The extent and complexity of the material evaluation experiments required does not make this version practically useful.

Tennyson et al (28) suggested the use of the cubic form of the Tensor Polynomial Theory. Many of the equation coefficients must be obtained from biaxial stress data and constraint equations. A series of biaxial specimen tests (using pressurized tube specimens) were used to obtain the necessary interaction strength parameters. It was concluded that the quadratic form of the tensor polynomial strength equation was not accurate over the full range of lamina orientations and can yield far too conservative results.

2.3.2 Criteria Evaluation

Biaxial test results were fitted (6) to several failure criteria which included Goldenblat and Kopnov, Tsai Wu, Modified Fischer, Norris and McKinnon, Norris Distortional Energy, Marin and Modified Marin theories. Conclusions were as follows:

(1) The fit of individual failure theories varies from one type of material to another.

(2) The Fischer criterion provided the best fit for the static results.

(3) The Norris distortional energy theory provided the best fit

for simultaneously predicting both static and fatigue results.

(4) Failure theories disregard failure processes and hence cannot allow for interacting failure mechanisms eg microbuckling in compression.

(5) Apparently the fit of failure theor... deteriorates with increasing fatigue life.

Good agreement was obtained (29) between predictions based on the Maximum Stress failure criterion and experimental data from tests on graphite/epoxy 0/+-45/90 degree lay-up biaxial specimens. A tensor polynomial strength criterion proved less satisfactory.

The Tensor Polynomial (Tsai-Wu) and Hoffman strength theories have been evaluated (30). The conclusion was that both the Hoffman theory and the Polynomial theory with $A_{12}=0$ were sufficiently accurate for engineering purposes. Therefore th tests to establish A_{12} are unnecessary. It was noted that A_{12} highly sensitive to small errors in measured stresses. It was reported that after four values of A_{12} were determined through off-axis testing, only one proved to satisfy the stability condition. Tests were conducted on both boron-epoxy and E-glass/epoxy off-axis specimens in tension. Additionally, a 'numerical experiment' was performed on ten different composite materials with six load cases, which were: 1) off-axis tension 2) off-axis compression 3) positive shear 4) negative shear 5) biaxial tension 6) biaxial compression. All experimental results were within 10% of predicted values for both criteria.

In summary, the following points are noted:

- A failure criterion fit is dependent on the type of material.
- The simpler criteria, such as the Maximum Stress, have

proved to be accurate previously.

- Expensive and complicated biaxial testing to establish the property A_{12} may be unnecessary, and a simple off-axis tension test may produce invalid results. Simple approximations have often been found to be adequate.

3. COMPOSITE LAMINATE ANALYSIS (31)

3.1 Single Lamina

In order to calculate the strength of a laminate, the properties of a single lamina must first be established.

Figure 3.1 shows the principal axes on a single lamina where direction 1 is along the fibres, direction 2 is transverse to the fibres in the plane of the plate, and direction 3 is transverse to the fibres and normal to the plate.

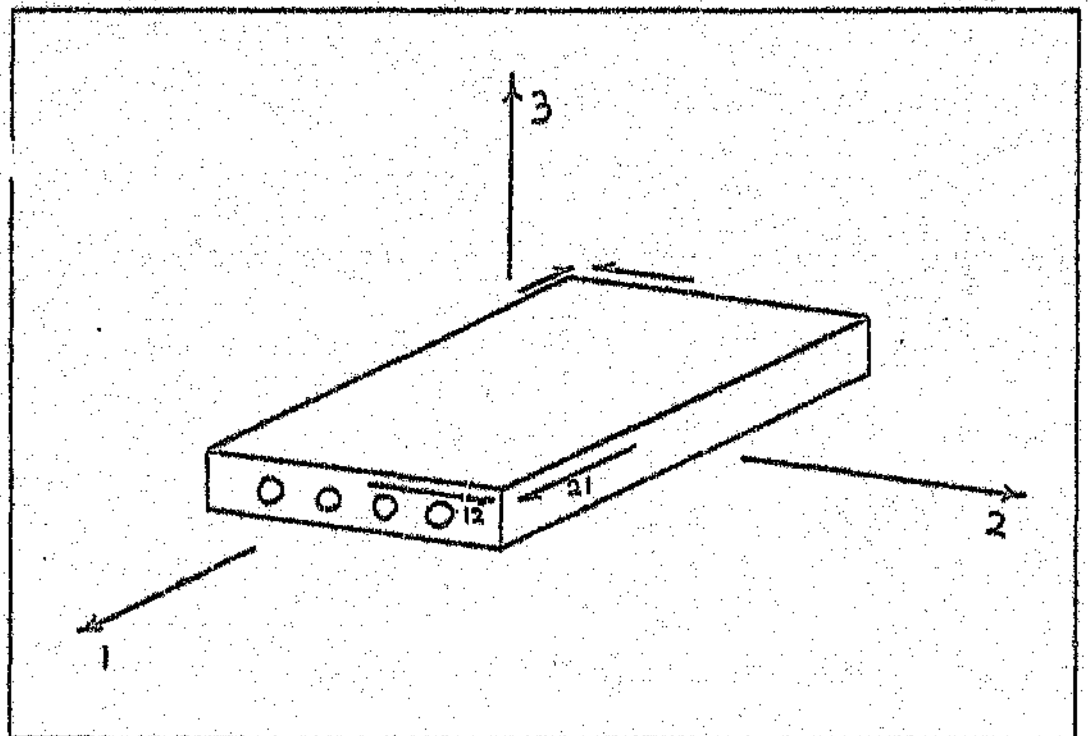


Figure 3.1 Single Layer

The stress-strain relation for a lamina may be written in the following form (derived from standard stress-strain relations for any material) (31):

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \cdot \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{bmatrix}$$

where

$$Q_{11} = \frac{E_1}{1-\nu_{12} \cdot \nu_{21}} \qquad Q_{12} = \frac{\nu_{12} \cdot E_2}{1-\nu_{12} \cdot \nu_{21}}$$

$$Q_{22} = \frac{E_2}{1-\nu_{12} \cdot \nu_{21}} \qquad Q_{66} = G_{12}$$

and E = Young's Modulus

ν = Poisson's Ratio

σ, τ = stresses

ϵ, γ = strains

The Poisson's Ratio in the direction transverse to the fibres and in-plane may be calculated using the following equation :

$$\frac{\nu_{21}}{E_2} = \frac{\nu_{12}}{E_1}$$

A unidirectional fibre lamina of arbitrary fibre orientation is shown in figure 3.2 .

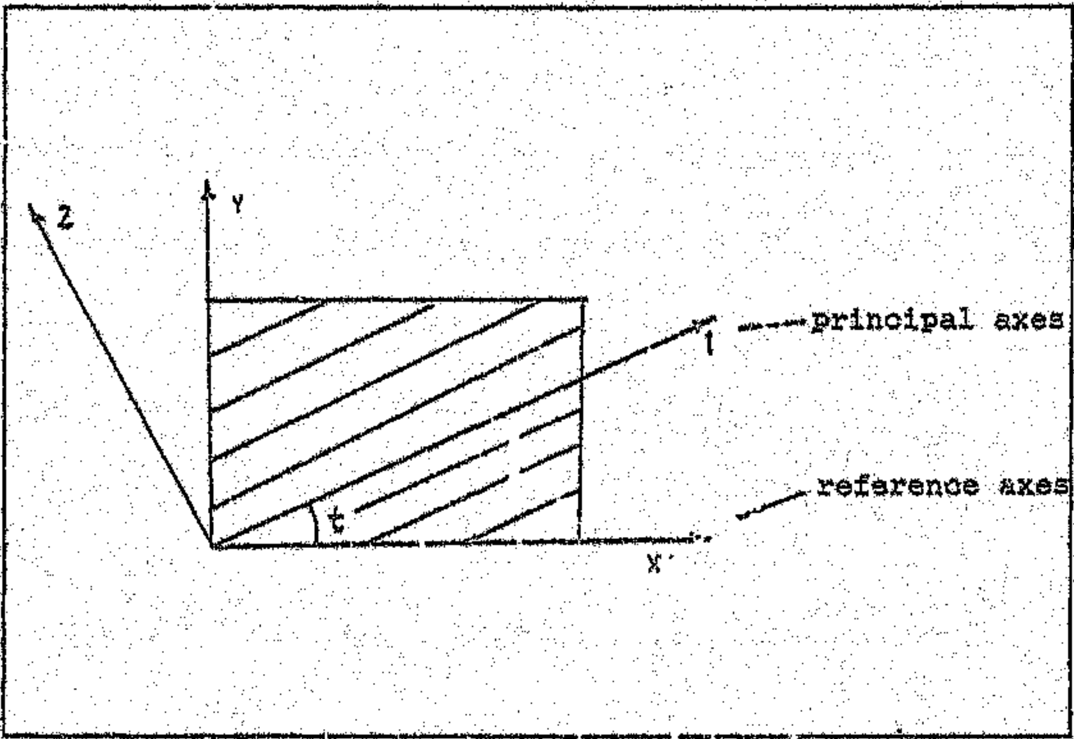


Figure 3.2 Lamina at Angle t

For such a lamina, a transformation matrix must be used:

$$[T] = \begin{bmatrix} \cos^2 t & \sin^2 t & 2 \sin t \cos t \\ \sin^2 t & \cos^2 t & -2 \sin t \cos t \\ -\sin t \cos t & \sin t \cos t & \cos^2 t - \sin^2 t \end{bmatrix}$$

Using this matrix, we can write

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix} = [T]\cdot\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix} \quad \text{and} \quad \begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \frac{\gamma_{12}}{2}\end{bmatrix} = [T]\cdot\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \frac{\gamma_{xy}}{2}\end{bmatrix}$$

Then, using $[R] = \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 2\end{bmatrix}$,

the stress-strain relation may be calculated as follows :

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix} = [T]\cdot\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix} \qquad \begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix} = [T]^{-1}\cdot\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix}$$

By defining

$$[\overline{Q}] = [T]^{-1}\cdot[Q]\cdot[R]\cdot[T]\cdot[R]^{-1}$$

we can write

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [\bar{Q}] \cdot \begin{bmatrix} e_x \\ e_y \\ \gamma_{xy} \end{bmatrix}$$

$[\bar{Q}]$ is called the transformed reduced stiffness matrix. It can be shown that (23) :

$$[\bar{Q}_{11}] = Q_{11} \cos^4 t + 2 (Q_{12} + 2 Q_{66}) \sin^2 t \cos^2 t + Q_{22} \sin^4 t$$

$$[\bar{Q}_{12}] = (Q_{11} + Q_{22} - 4 Q_{66}) \sin^2 t \cos^2 t + Q_{12} (\sin^4 t + \cos^4 t)$$

$$[\bar{Q}_{16}] = (Q_{11} - Q_{12} - 2 Q_{66}) \sin t \cos^3 t + (Q_{12} - Q_{22} + 2 Q_{66}) \sin^3 t \cos$$

$$[\bar{Q}_{26}] = (Q_{11} - Q_{12} - 2 Q_{66}) \sin^3 t \cos t + (Q_{12} - Q_{22} + 2 Q_{66}) \sin t \cos^3$$

$$[\bar{Q}_{66}] = (Q_{11} + Q_{22} - 2 Q_{12} - 2 Q_{66}) \sin^2 t \cos^2 t + Q_{66} (\sin^4 t + \cos^4 t)$$

$[\bar{Q}]$ is a symmetrical matrix.

3.2 Classical Lamination Theory (1)

This theory uses the results from single lamina analysis to calculate the properties for a multi-layered laminate. If the loads on the laminate are known, this theory can be used to calculate the stresses and strains. The theory assumes:

1) A perfect bond exists between each layer in the laminate.

2) The behaviour of the laminate is linear elastic.

3) The plate thickness is small compared to the length and width.

4) Upon deformation, plane sections through the thickness remain plane (strain variation is linear).

5) Each layer is in a state of plane stress.

6) Strains transverse to the plane are assumed zero.

Classical lamination theory can thus only be used at regions in a structure away from stress concentration points (such as points where load is applied), free edges and boundaries (eg joints between materials).

Figure 3.3 shows a cross-section through a laminate.

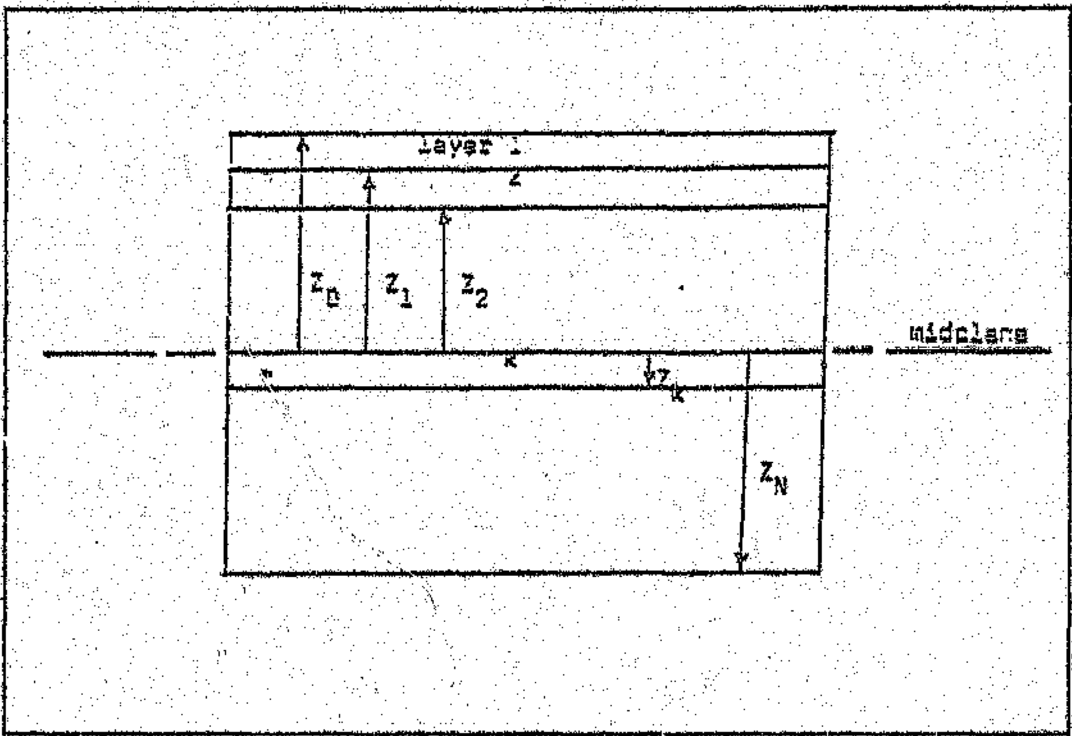


Figure 3.3 Laminate Consisting of N Layers

The strain of the k layer may be written in terms of the midplane strain (denoted by ε_m), the curvature of the midplane (κ) and the distance from k the layer to the midplane (Z) as follows :

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_{mx} \\ \varepsilon_{my} \\ \gamma_{xy} \end{bmatrix} + Z_k \cdot \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \quad \text{---}(1)$$

This is based on the assumption that the strain variation through the laminate is linear.

The stress variation, however, is in general not linear. Figure 3.4 shows possible forces app..ed to a laminate.

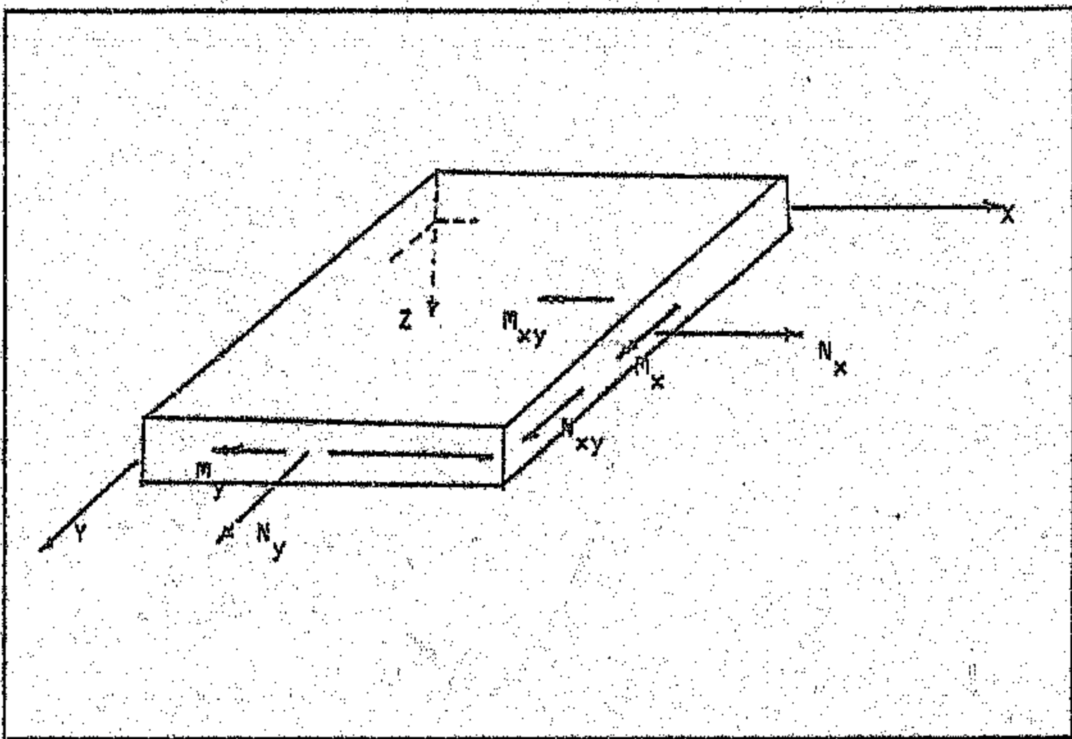


Figure 3.4 Single Laminate of Thickness t

Forces and moments are found by integrating the stress through the thickness t (for unit length) :

$$N_x = \int_{-t/2}^{t/2} \sigma_x \, dz$$

$$N_y = \int_{-t/2}^{t/2} \sigma_y \, dz$$

$$N_{yx} = N_{xy} = \int_{-t/2}^{t/2} \tau_{xy} \, dz$$

$$M_x = \int_{-t/2}^{t/2} \sigma_x \, z \, dz$$

$$M_y = \int_{-t/2}^{t/2} \sigma_y \, z \, dz$$

$$M_{xy} = \int_{-t/2}^{t/2} \tau_{xy} \, z \, dz$$

Therefore

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \int_{-t/2}^{t/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz$$

$$= \sum_{k=1}^{N} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz \qquad \text{-(2)}$$

Similarly

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \sum_{k=1}^{N} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix} z \, dz \quad \text{—(3)}$$

Using equations (1), (2) and (3) we can define three matrices:

$$A_{i,j} = \sum_{k=1}^{N} [\, \overline{Q}_{i,j}] \, (Z_k - Z_{k-1})$$

$$B_{i,j} = \frac{1}{2} \sum_{k=1}^{N} [\, \overline{Q}_{i,j}] \, (Z_k^2 - Z_{k-1}^2)$$

$$C_{i,j} = \frac{1}{3} \sum_{k=1}^{N} [\, \overline{Q}_{i,j}] \, (Z_k^3 - Z_{k-1}^3)$$

Then

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{16} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} * \begin{bmatrix} \varepsilon_{mx} \\ \varepsilon_{my} \\ \gamma_{mxy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}$$

In most applications, a symmetrical laminate is used to eliminate coupling terms (B matrix).If many layers are used, the coupling terms D_{16} and D_{26} tend to zero, and may be ignored.

3.3 Theoretical Failure Prediction

The stresses and strains in a multi-layered laminate may be calculated using the theory presented in sections 3.1 and 3.2, provided that the material properties (eg ultimate stresses and stiffnesses in principal directions, Poisson's Ratios, etc) are known, and that the applied loads are known.

The material properties may be found from tests on the material. Provided a symmetrical laminate is used, the applied loads on the laminate during a tensile test are easily monitored, since there is no coupling.

When the stresses i [illegible] inate have been calculated for a certain load case, [illegible] iterion may be applied to each layer of the lam [illegible] ertain whether failure has occurred. If it has no [illegible] ween the stress in the layer and the ultimate stress fo [illegible] er (as given by the failure criterion) may be used to increase the loading system by dividing the loading system by the ratio. A new loading system is thus obtained which will cause the layer to just fail. This load is then the load predicted by the failure criterion to cause failure in the layer.

Therefore this new load is applied to the laminate, and the stresses and strains are calculated in each layer as before. This time the failure criterion will predict one or more layer failures. The effects of the failed layers on the overall laminate strength are removed by reducing the failed layer stiffnesses to zero. The layers fail only in one principal direction, so they may still have stiffness in the unfailed principal directions.

After one or more layers have failed, the stresses and strains must be recalculated for the altered laminate, and the failure criterion again applied. If no further failure occurs, the load may be increased again.

If the analysis is done on a computer, a low initial load can be applied which will definitely not cause failure. The computer can then increase the load to determine the predicted failure points for a certain failure criterion, and save the stress, strain and load data at each ply failure.

4 EXPERIMENTAL METHOD

4.1 Equipment

4.1.1 Tensile Testing Machine

An ESH tensile testing machine was used (see figure 4.1). It had force ranges of 25, 50, 100 or 250 kN. The specimen holding jaws were wedge type which tighten as the load increases. The control panel had facilities to control the rate of loading, displacement range and load range. The machine was operated at constant displacement rate. Figure 4.2 shows the testing machine and control panel.

A Roell and Korthaus KG SM 2000-5AB extensometer was used for strain measurements. Its free length was 50mm, and could be mounted on a specimen fitted to the testing machine. It operates using a Precision Instruments ITA 3000 power supply and voltage display unit.

A Houston Instrument model 200 XY recorder, as seen in figure 4.2, was used for plotting load and extension during testing.

4.1.2 Acoustic Emission Equipment

The acoustic emission equipment (see figure 4.3) consisted of:

1) A Physical Acoustics Corporation 3000 acoustic emission computer with two disc drives, keyboard and screen. This machine utilized a Z80 microprocessor and an in-house CP/M operating system, which was incompatible with any other commercial computer. It had an 'RS232' serial communication port for printing, with a special non-standard pin configuration. Software was supplied which included facilities to record data and print data files and graphs.

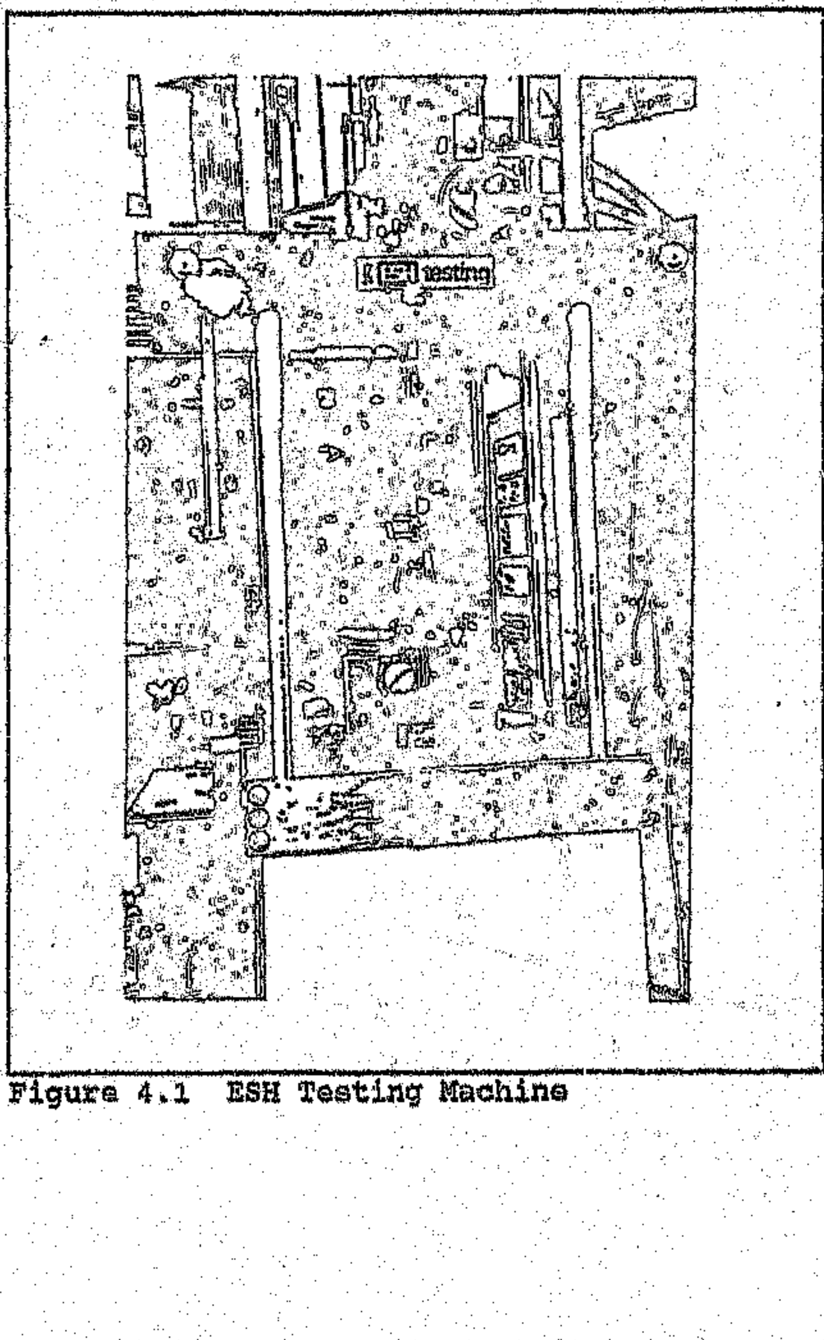


Figure 4.1 ESH Testing Machine

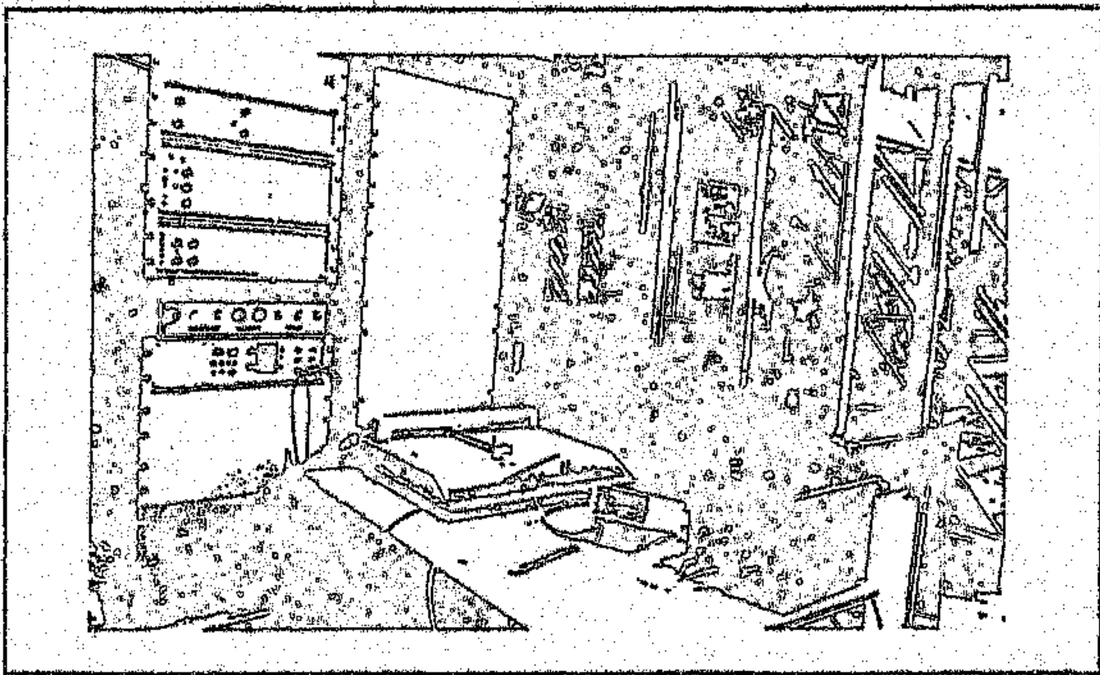


Figure 4.2 Testing Equipment Layout

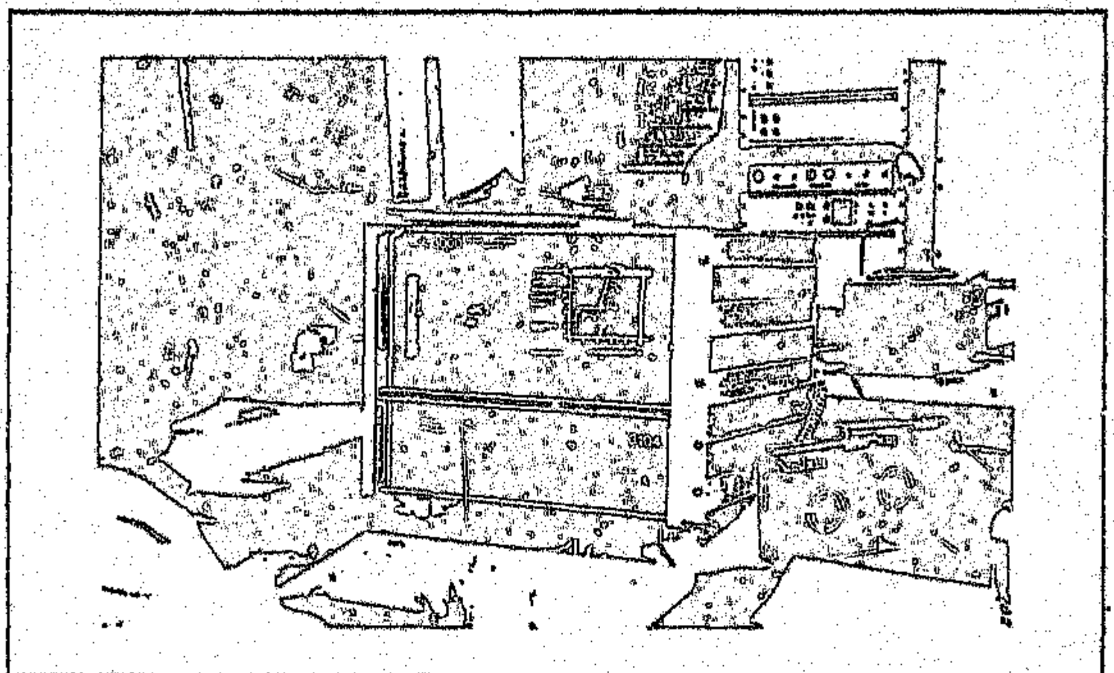


Figure 4.3 Acoustic Emission Computer and Acquisition Unit

2) The computer was interfaced to a Physical Acoustics Corporation 3104 four channel acquisition unit.
3) A modified Fujitsu printer was provided for graph and data printing. This printer had a specially wired serial port for connecting to the computer serial port.
4) A piezoelectric acoustic transducer mounted on the specimen, and linked to a model 1220A pre-amplifier was used. The pre-amplifier signal was fed into channel 1 of the data acquisition unit via co-axial cable. Both items were made by the Physical Acoustics Corporation.
5) A RS232 serial communication cable was used to transfer data from the AE machine to an IBM compatible personal computer through the printer port. The cable had been especially modified, as the AE machine employed non-standard pin configurations on the communications port. A commercial data transfer package was used on the PC to capture the data.
6) An IBM compatible PC was used for data manipulation. Programs were written in Turbo Pascal for AE data manipulation and graph printing and plotting. Lotus 123 was used for other results and tables.
7) An Amdek Amplot II and a Hewlett-Packard Paintjet were used for plotting and printing AE graphs in colour.

4.1.3 Autoclave

A P.V.Descroizilles autoclave was used for laminate curing (see figure 4.5) and consisted of :

- control board with automatic timer.
- vacuum pump.
- fan for even heat distribution.

4.1.4 Test Specimens

Carbon fibre prepreg was used to make the first set of specimens (see figure 4.4). The material used was Fibredux 920C-T300, which is a high strength type carbor fibre prepreg. The specific prepreg used had a high nominal resin content (44% by mass), since it was originally intended for bonding to honeycomb.
The carbon fibre prepreg was supplied in a roll 300 mm wide. The following laminate lay-ups were used :

1) 0 degrees
2) 90 degrees
3) +-45 degrees
4) 0/90 degrees
5) 0/+-45 degrees
6) 0/90/+-45 degrees
7) 90/+-45 degrees

Sufficient 300 mm lengths were cut from the roll to manufacture seven square 16 layer laminates. The lay-ups were then placed on an autoclave tray, with a layer of tooling cloth on either side. Four layers of bleeder cloth were placed on top. Sealing tape was used around the edges to seal the vacuum) . t which enclosed all the layers. The vacuum ports were fitted to the bag, and the vacuum pipes fitted. The laminates were cured in he autoclave (see figure 4.5) for 1,5 hours, using a pressure 500 kPa and a temperature of 125 degrees C. After curing, each lay-up was cut into strips 20 mm thick and thereafter the strips were cut to the required length according to ASTM D3039 section 7. After cutting the specimens to the required size , aluminium strips were bonded onto the ends of the specimens. These strips were clamped down and the glue was cured at 50 degrees C in the autoclave for 1,5 hours, or overnight at room temperature.

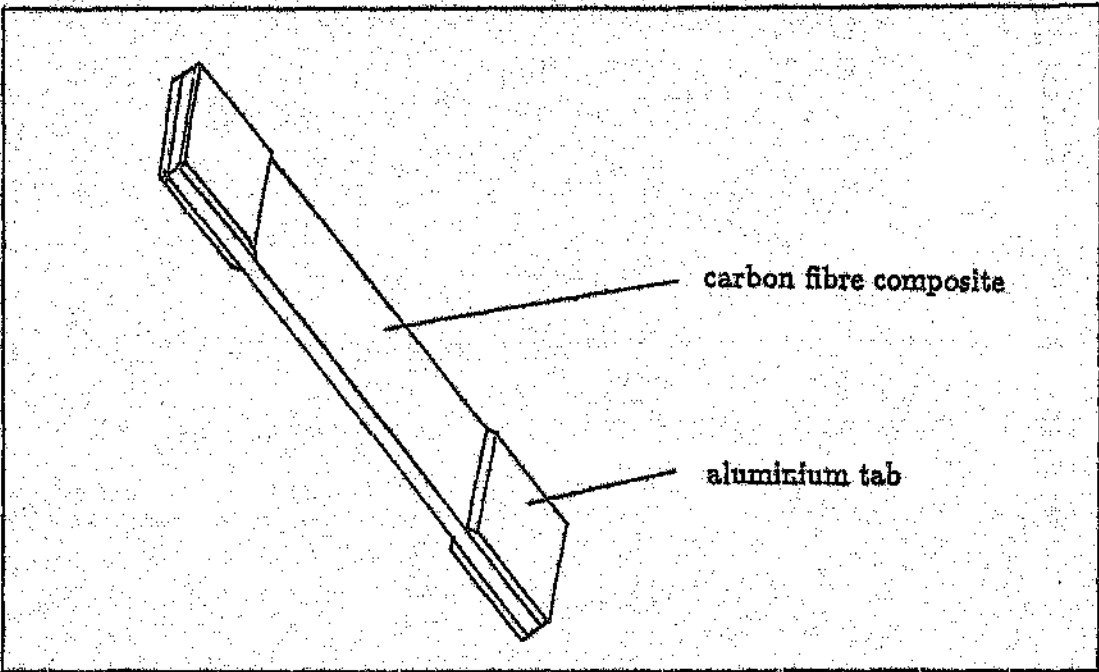


Figure 4.4 Carbon Fibre Tensile Testing Specimen

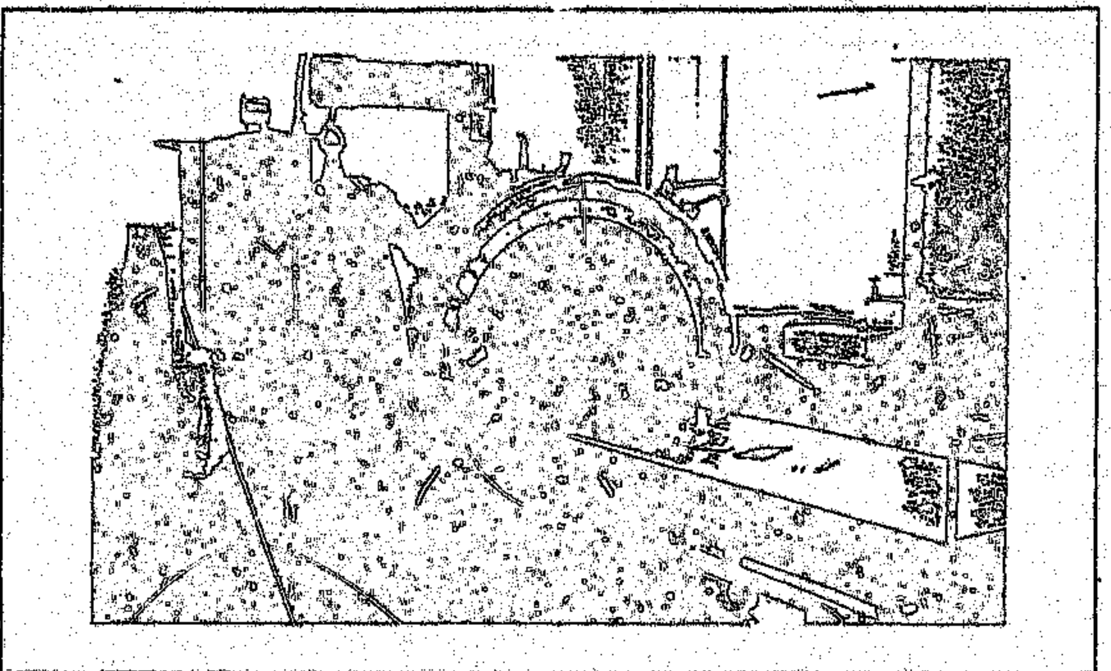


Figure 4.5 Autoclave

Additional specimens for acoustic emission testing were made in a similar way from glass fibre prepreg, Ampreg 75 SP711 AE 250. The following lay-ups were used:

1) +-45 degrees
2) 0/90 degrees
3) 0 degrees

Flaws were purposely introduced into one of the +-45 degree lay-up glass panels to ensure that useful acoustic emission results would be obta ed. The 0 and 0/90 lay-up specimens were cut such that their width (about 10mm) was ha f the standard width, so that th ould be loaded to failure with the acoustic emission sensor a ched, without the chance of damage to the sensor from violent failure.

The second set of glass fibre specimens were made in a similar manner to the carbon specimens except that only 8 layers were used and they were cured at 90 degrees for ten minutes at zero pressure, followe 1,5 hrs at 120 degrees Celsius and 300 kPa pressure. These s ens were made from Vicotex BE M9 glass and epoxy epreg. Each specimen was 20mm wide and around 3mm thick. Similar lay-ups to the carbon specimens were used, with the addition of +45 degree lay-up specimens.

All lay-ups were symmetric with respect to fibre angle lay-up through the thickness to facilitate stress analysis (ie eliminate coupling terms).

4.2 Procedure

4.2.1 Strain Gauge Attachment

The specimen surface was first smoothed with fine emery paper, care being taken not to damage the fibres. The surface was then cleaned, and transverse and longitudinal lines were drawn on the surface to align the strain gauges. Adhesive tape was used to hold and position the gauges. They were bonded using cyanoacrylate adhesive, pressure being applied with a finger for about 20 seconds while the glue dried.

4.2.2 Testing Without Acoustic Emission

1) The specimen to be tested was measured (width and thickness) with the micrometer.
2) The testing machine was reset, and the specimen set in the grips, the grips tightened and the testing machine zero set.
4) The extensometer was fitted to the specimen and the output checked to ensure a zero initial setting.
5) The plotter X and Y axes were set to zero and the plotter pen was set to the down position.
6) The testing machine was started.
7) If the ultimate tensile strength of the specimen was approximately known, then when the applied force equalled about half that value, the extensometer was removed to prevent it from being damaged during specimen fracture. To do this, the plotter pen was first lifted, the extensometer was removed, and the plotter X axis zero adjusted to get it in line with the curve, before setting the pen down again. If the tensile strength of the specimen was not known, the

first specimen was tested to failure without the extensometer fitted to prevent accidental damage.

8) The specimen was then tested to failure.

4.2.3 Testing With Acoustic Emission

1) Before starting the tests, one computer disk was formatted on the acoustic emission computer for every two specimens to be tested.
2) The specimen to be tested was placed in the testing machine jaws, and the jaws tightened.
3) Dow Corning vacuum grease or silicon sealant was applied to the acoustic sensor surface, and the sensor placed against the specimen surface and held there using masking tape.
4) The specimen was tested as detailed before. The acoustic sensor was removed from the specimen prior to failure if the specimen was likely to fail violently, such as failure of specimens with some zero degree layer orientations. When testing weaker specimens (such as 90/+-45 ply orientations) the acoustic sensor was left on the specimen during final failure.

4.2.4 Testing of First Set of Glass Fibre Specimens

These tests were conducted in order to evaluate methods of failure prediction using Felicity Ratio and number of events at a specific load.

These specimens were tested without the extensometer or the plotter. All the glass fibre specimens were tested using the acoustic emission equipment. A voltmeter connected to the load output of the testing machine was used to monitor the force manually in order that the force could be released at the required step intervals. The first specimen of each lay-up type was tested to failure without releasing the force at step intervals, in order to ascertain the ultimate load and thereby calculate suitable force intervals.

4.2.5 Testing of Second Set of Glass Fibre Specimens

Before testing of the second glass specimens commenced, a steel specimen was tested to 65kN to evaluate background noise. There was a small amount of emission. On re-applying the load, no emission was recorded, indicating that the emissions were from the metal specimen (Kaiser Effect).

A series of pencil tests on a composite specimen using two AE sensors at each end of the specimen showed a negligible drop in amplitude over the length of the specimen. The amplitude drop was a maximum of 1 dB, but the measuring system accuracy is only around +-1dB.

The amplitude threshold was set higher than before to reduce the amount of data recorded and to reduce the effects of varying coupling efficiencies by only recording the higher energy events.

5 RESULTS

5.1 Carbon Fibre Reinforced Specimens

5.1.1 Material Properties

The acoustic emission results for the +-45^{o} specimens were used to obtain the shear strength of the material (Sae) by using the load at which acoustic occurences began to occur near failure (Fae) to calculate Sae. This was done by first inspecting the plots of amplitude vs force (Appendix B.1) and recording the force corresponding to the point where the final 'cloud' of events occurs, with events in excess of 84 dB. This force was compared with the force corresponding to the point on the hits vs force cumulative histogram where the number of events rises dramatically, and with the forces corresponding to the points on the cumulative energy and cumulative counts vs force results where the slope increases sharply. In most cases the forces thus obtained were similar. The shear strength corresponding to the beginning of final failure was therefore calculated and recorded as Sae.

Tables 5.1.1, 5.1.2 and 5.1.3 are results from the testing of 90, +-45 and 0 degree lay-up specimens respectively. These results were used to establish the material properties (see sample calculations in Appendix A.1). The following symbols are used in the tables:

- F_{ut} = ultimate tensile load
- UTS = ultimate tensile strength
- E = tensile modulus
- S_{ut} = ultimate shear strength
- FPF = first ply failure load obtained from AE results
- SPF = second ply failure load obtained from AE results
- LPF = last ply failure load obtained from AE results

S_{ae} = shear strength calculated from last ply failure load
G_{12} = shear modulus

Table 5.1.1 Carbon Fibre/Epoxy Specimens
90 Degree Tensile Test Results

Specimen No.	UTS (MPa)	E (GPa)	Fut (kN)
1	48.82	13.13	2.86
2	44.19	13.73	2.66
3	39.69	12.30	2.39
4	43.43	12.68	2.66
5	41.29	12.75	2.49
6	43.18	10.30	
7	45.93	10.97	
8	39.92	11.32	
9	50.74	10.57	
10	30.73	8.75	
11	22.08	10.29	
12	47.91	10.19	
13	50.28	8.67	
14	59.83	9.50	
15	32.24	10.33	
16	25.43	14.74	
17	42.15	10.22	
average	42.51	10.50	
std dev.	7.78	1.74	

Table 5.1.2 Carbon Fibre/Epoxy Specimens
+-45 Tensile Test Results

Specimen No.	G12 (GPa)	Fut (kN)	Fae (kN)	Sut (MPa)
1	5.01	14.17	10.00	124.80
2	4.69	13.20	7.88	111.73
3	4.99	13.75	8.40	114.80
4	4.88	13.42	9.05	117.32
5	4.62	13.60	8.65	115.23
6	4.72	13.60	9.25	114.30
7	4.87	13.87	9.45	117.06
8	4.08	14.12	10.23	116.23
9	5.06	14.10	10.83	115.14
10	4.48	13.30		112.61
11	4.23	13.40		111.62
12	5.34	13.20		114.36
13	4.57	13.40		112.28
14	4.49	13.10		110.62
15	4.46	13.10		110.83
16	4.55	13.40		111.65
17	4.74	13.40		115.54
18	4.82	13.50		111.66
19	4.66	13.10		113.04
			average	113.10
			std dev.	3.50

Tak' 1.3 Carbon Fibre/Epoxy Specimens
0 Degree Tensile Test Results

Specimen No.	UTS (MPa)	E (GPa)	Fut (kN)
1	1235.48	119.25	74.00
2	1204.17	115.34	72.00
3	1210.23	119.23	72.50
4	1086.90	12'.07	66.50
5	1006.23	116.63	59.50
6	1083.44	112.86	64.00
7	1203.42	122.96	72.50
8	1130.86	125.18	68.40
9	1264.46	122.94	78.61
10	1337.78	123.71	70.60
11	1265.05	122.46	78.86
12	1157.31	121.94	70.65
13	1190.83		71.89
14	1208.93		71.39
15	1177.76		72.64
16	1270.35		78.39
17	1245.70		74.63
18	1265.81		78.11
average	1196.93	120.30	71.95
std dev.	78.58	3.57	4.99

The 90° ultimate tensile strength (UTS) results (table 5.1.1) show a standard deviation of 18% from the average. This magnitude of standard deviation can generally be expected for transverse tensile tests, since failure is due to failure of the matrix only, and the matrix is brittle with a low toughness and low tensile strength.

The $\pm 45^{\circ}$ shear strength values (Sut in table 5.1.2) had a standard deviation of 3.5% from the average.

Since all the plies in a $\pm 45^{\circ}$ specimen should fail at the same time (they are all at the same angle to the direction of load application), only one significant increase in AE events should be found corresponding to the beginning of all the layers failing. This increase in AE activity can clearly be seen in all the $\pm 45^{\circ}$ specimen AE results (see two examples in Appendix B.1). The load corresponding to this increase in activity is the load at which failure begins to occur for that specimen.

Sae was about 3/5 times Sut. It was found after testing the $\pm 45^{\circ}$ specimens that the fibres had failed in all tests, so pure shear did not occur, and the ultimate failures were higher than they would have been if shear failure only had occurred. Since the shear strength obtained from the AE data corresponds to the beginning of shear failure (resin cracking) or final ply failure, it was considered to more accurately represent the shear strength of the material than the strength calculated from the final load of the $\pm 45^{\circ}$ specimen, which is usually used as the material shear strength. For this reason, the shear strength from acoustic emission was used for further calculations (S12). Similar results were obtained previously (21) when testing $\pm 45^{\circ}$ specimens for shear, when torsional specimens produced shear strength values of around 3/5 of the values from $\pm 45^{\circ}$ specimens. Torsional specimens were considered to be accurate since they fail almost purely in shear.

The standard deviations for Sae and G were 8.9% and 5.4% of the averages respectively. The Sae results are dependent on the accuracy of the AE results (see error analysis in Appendix A.2).

The UTS and E values for the 0° specimens were consistent with a 6% and 3% standard deviation from the averages respectively.

The maximum errors in E and G were both just over 10% (see error analysis in Appendix A.2). Since the actual errors should be less, this is not considered excessive.

Sample calculations are included in Appendix A.1.

5.1.2 Experimental Results

- Acoustic Emission Results

The carbon fibre specimens were tested to failure in tension using the AE equipment. The AE data could either be printed out directly or graphs could be drawn on the AE computer and those could be printed. Since each event had numerous parameters and each specimen test could produce over 1000 events, printing the data out and typing it into another computer would not have been practical. Therefore printed graphs were the only form of output obtained from the AE equipment.

The AE computer allowed any of the recorded parameters to be plotted, and the graph type could be cumulative or non-cumulative in the form of histograms, line graphs or point plots. Examples of the AE results for the carbon specimens are shown in figures 5.1.1 to 5.1.5, and in Appendix B.1, where AE plots from two specimens of each type of laminate are included.

In general, the unidirectional specimens were found to emit less AE than the multi-directional laminates. Data plots of AE from two 90° specimens and two 0° specimens are shown in Appendix B.1. In all these graphs, the total events were less than 60, as opposed to around a thousand for a +-45° specimen.

From the plots in Appendix B.1, it is indicated that the number of events recorded varies significantly between specimens, and this is due to varying sensor coupling efficiencies.

Counts were found to show the same characteristic trends as hits (events) and energy, and rise and duration times also showed similar trends.

Figure 5.1.1 shows a typical amplitude vs load result for a 90/+-45^{o} specimen. The graphs have poor resolution which could have contributed to inaccuracies (see error analysis in Appendix A.2). The amplitude varies between 48 and 100 dB. The amplitude limits are defined by the sensor response, the threshold voltage and the amplifiers. Two 'clouds' of events are visible on the graph, which were expected and represent the 90^{o} and +-45^{o} layers failing respectively. The failure load for the 90^{o} layers was taken as the start of emissions from those layers.

Figure 5.1.2 shows the counts (cumulative line graph) vs load result for the same specimen as figure 5.1.1. The steep rises in the slope correspond to the 'clouds' of events seen in figure 5.1.1. The +-45^{o} layers clearly fail over a broader load range than the 90^{o} layers.

Figures 5.1.3 and 5.1.4 show the amplitude vs load and counts vs load results for a 0/90/+-45^{o} specimen. Again, 'clouds' on the amplitude point plot correspond to steep rises in the counts slope. Since the sensor was removed before failure to prevent damage, the two visible failures are the 90^{o} and +-45^{o} layers failing.

Ply failures were taken to be variations in the count vs load result slope corresponding to density variations in the amplitude point plots, and an abundance of high energy events on the energy vs load plots. In all cases, the ply failure experimental result was taken as the beginning of the acoustic emission data variations.

A positive percentage difference in experimental and theoretical results corresponds to an experimental load result lower than theoretical prediction.

In many cases, distinct breaks could not be found between event 'clouds' or distinct slope changes could not be identified. The ply failure loads could then not be reliably identified.

Figure 5.1.5 shows non-cumulative energy vs load line graphs for 90/+-45^{o} specimens. The peaks where the line rises from the zero energy axis substantially define high energy layer failures.

It was found that the number of energy, counts and events to failure differed widely between specimens of the same type. It was therefore impossible to compare these quantities between specimens. The reason for this wide variance may be that a low threshold was used, resulting in a lot of low energy events being recorded when the sensor was well coupled to the specimen, and fewer being recorded for specimens which did not have as good sensor coupling.

The non-cumulative energy vs hits results were inconsistent, with acoustic occurrences starting almost at the beginning of the tests. High energy occurrences frequently occurred at unexpected points on the plots. This could be due to compression of the specimen by the grips or tab debonding. All the results of specimens with 0° layers had more high energy occurences close to failure, which could denote fibre failures, as opposed to the lower energy occurences which may be matrix cracking and failure. The acoustic emission ultimate failure points were taken as where the relatively high energy occurrences began on the non-cumulative energy vs hits acoustic emission graphs.

The energy units on the AE graphs are not standard units, but show relative sizes of energy occurrences.

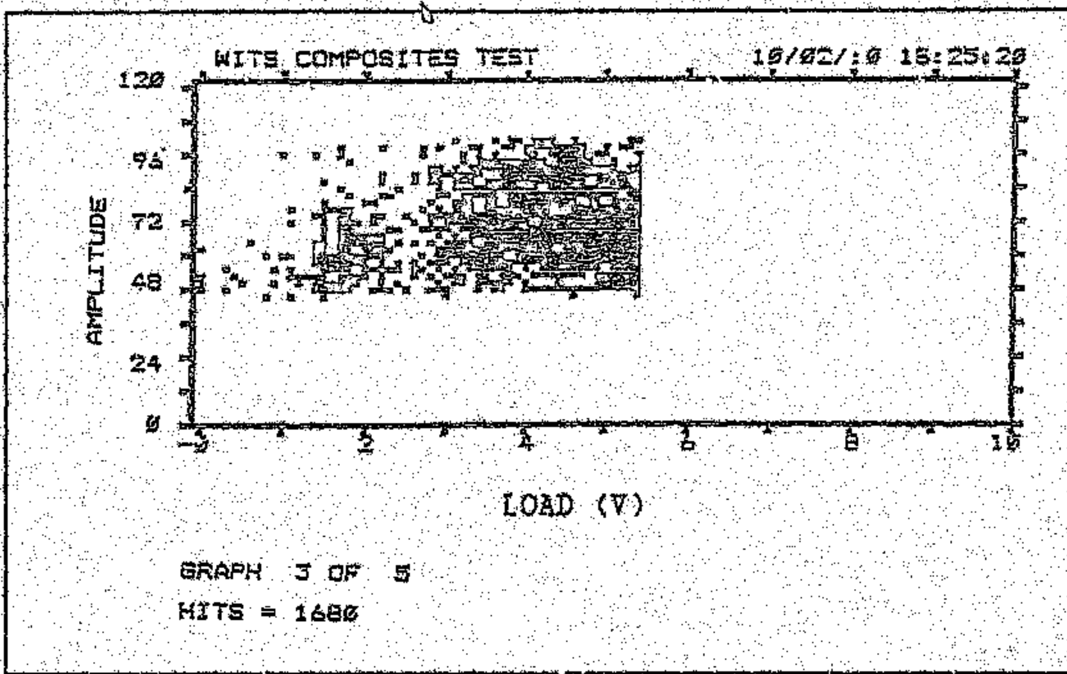


Figure 5.1.1 90/+-45 CFRP Plot

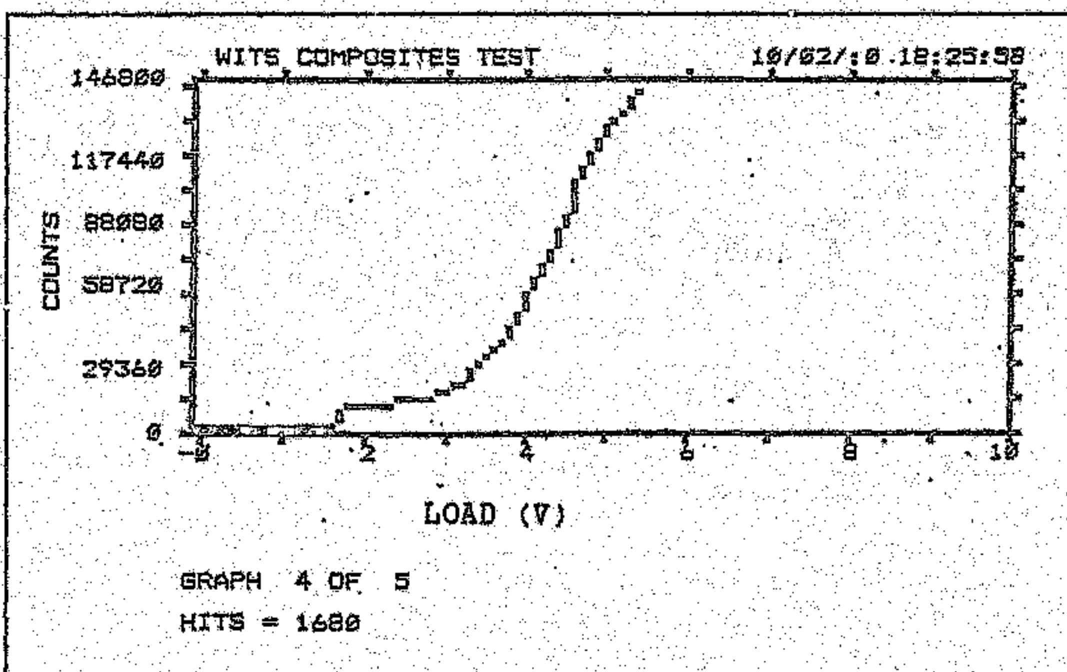


Fig.re 5.1.2 90/+-45 CFRP Cumulative Line Graph

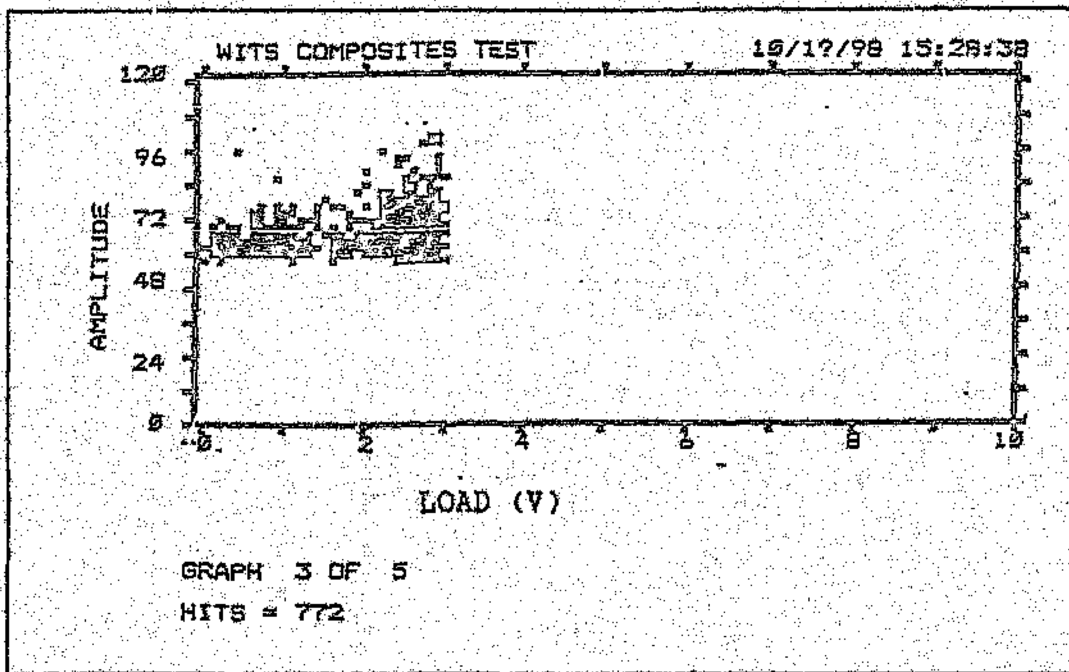


Figure 5.1.3 0/90/+-45 CFRP Point Plot

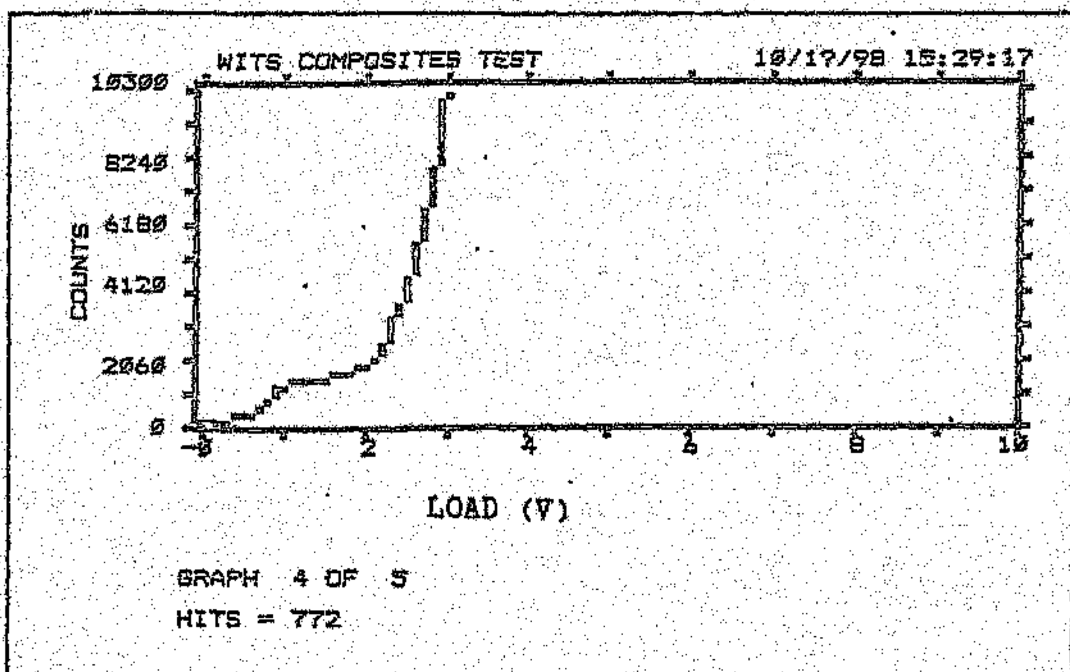
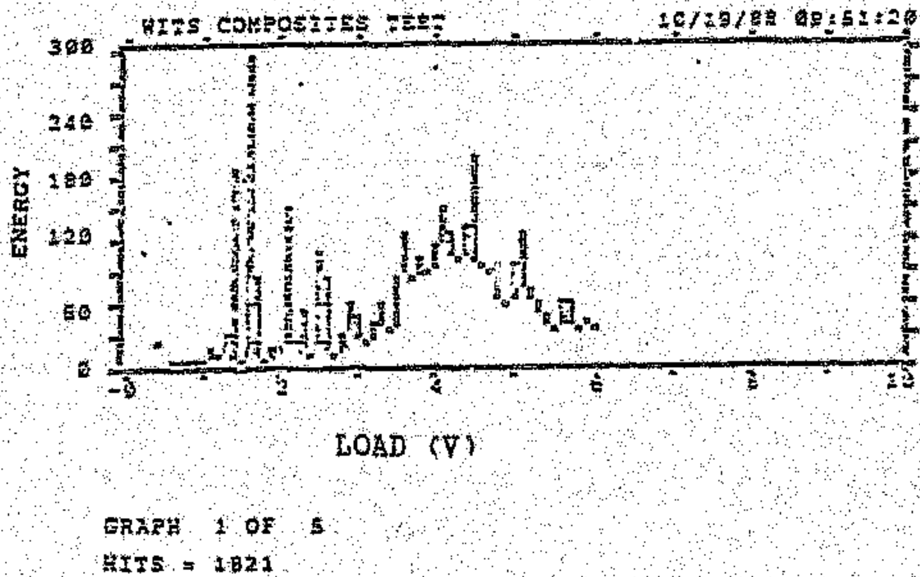


Figure 5.1.4 0/90/+-45 CFRP Cumulative Line Graph



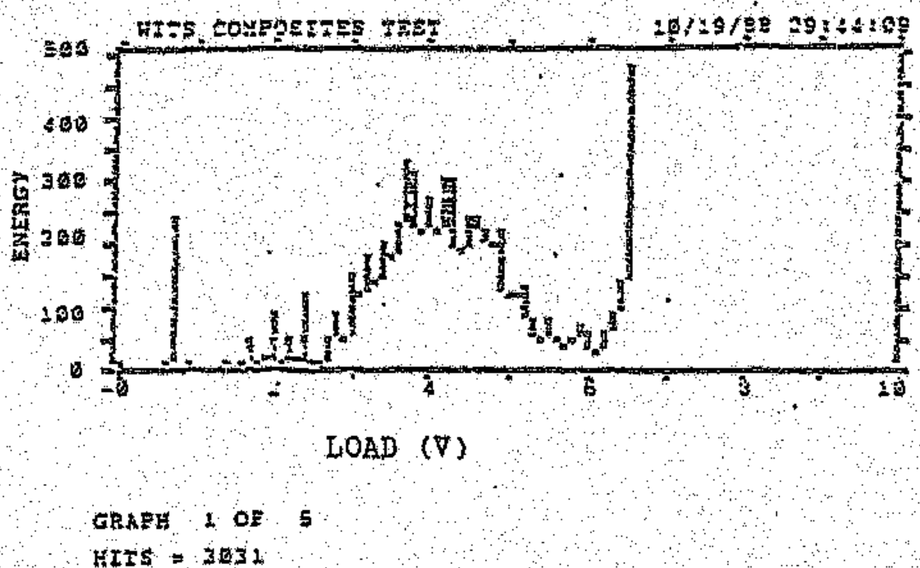


Figure 5.1.5 90/+-45 CFRP Non-Cumulative Line Graphs

- Experimental Results

The experimental results are derived from the acoustic emission results for the ply failures.

Tables 5.1.4 to 5.1.7 are the experimental results for the various lay-ups. The symbols used are similar to those listed in section 5.1.1.

It was decided to use force units for results analysis and for all the figures, since the overall stress in a multi-layered laminate with varying ply orientations is .ot a true representation of the actual stresses involved. The stresses vary dramatically between the layers, and change rapidly during ply failure t.rough the thickness. The stress in a fibre is usually also different from the matrix stress.

Table 5.1.4 Carbon Fibre/Epoxy Specimens
0/90 Degree Tensile Test Results

Specimen No.	FPF(AE) (kN)	Fut (kN)	LPF(AE) (kN)	UTS (MPa)
1	17.30	35.92	33	591.81
2	17.70	36.87	26.2	616.97
3	18.70	37.01	26.1	618.38
4	18.20	36.32	29.3	603.62
5	19.10	38.81	28.1	649.32
6	19.10	34.83	25.3	583.71
7	14.50	36.22	24.2	600.09
8	16.60	40.05	29.1	675.02
9	18.40	41.39	35.5	683.31
10	13.50	36.72	21.5	620.45
11		41.24	26.2	679.31
12		42.64	24	715.91
average	17.31	38.17	27.38	636.49
std dev.	1.83	2.45	3.76	40.96

Table 5.1.5 Carbon Fibre/Epoxy Specimens
0/+-45 Degree Tensile Test Results

Specimen No.	Fut(exp) (kN)	LPF(AE) (kN)	UTS (MPa)
1	46.32	43.8	755.56
2	40.80	40.8	673.27
3	42.19	40.2	695.86
4	39.80	45.7	664.66
5	45.52	32.5	729.85
6	44.13	49.2	716.28
7	35.82		606.58
8	37.61		614.08
9	49.25		793.56
10	39.80		675.51
average	42.12	42.03	690.52
std dev.	3.96	5.22	56.71

Table 5.1.6 Carbon Fibre/Epoxy Specimens
0/90/+-45 Degree Tensile Test Results

Specimen No.	FPF(AE) (kN)	SPF(AE) (kN)	Fut(exp) (kN)	LPF(AE) (kN)	UTS (MPa)
1	7.9	16.4	30.00	29.0	503.61
2	5.3	16.0	30.00	23.5	506.14
3	2.1	14.5	29.60	23.2	491.47
4	5.6	17.2	27.00	25.6	456.30
5	3.0	17.1	29.80	21.3	506.80
6	9.4	14.2	28.00	21.9	462.28
7	3.3	17.2	27.00	22.0	446.44
8	9.4	17.5	28.50	19.1	489.04
9	6.9		29.40	28.9	477.64
10			29.30	21.3	500.55
11			29.00		491.53
average	5.9	16.3	28.39	23.6	484.71
std dev.	2.6	1.2	1.07	3.1	20.21

Table 5.1.7 Carbon Fibre/Epoxy Specimens
90/+-45 Degree Tensile Test Results

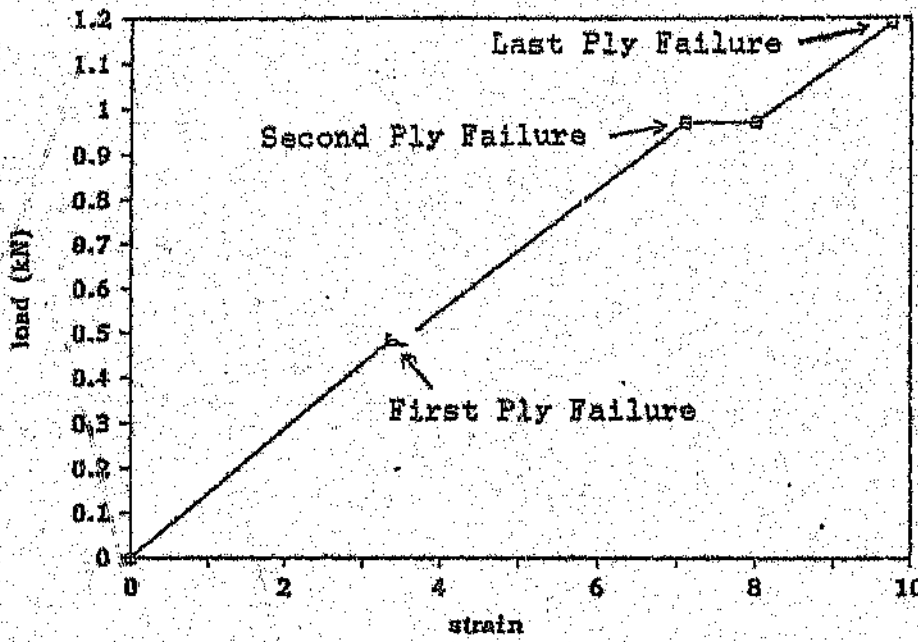
Specimen No.	FPF(AE) (kN)	Fut(exp) (kN)	LPF(AE) (kN)	UTS (MPa)
1	4.0	16.03	7.0	267.13
2	4.4	13.83	7.7	233.65
3	4.5	14.00	7.2	239.08
4	4.1	16.22	5.7	27[illegible].02
5	3.8	15.12	7.3	252.76
6	2.8	13.63	8.1	228.77
7	2.6	15.72	6.5	265.75
8		15.32	7.8	259.51
average	3.7	14.98	7.2	252.83
std dev.	0.7	0.96	0.7	16.16

5.1.3 Theoretical Results

The theoretical results are the ply failure loads predicted using theory to calculate the stresses in the laminate and then applying a failure criterion to establish where failure occurs. The theoretical results where obtained using the computer program in Appendix D, which uses the theory detailed in sections 2.1 and 2.3. The program input data includes the material properties and laminate lay-up, and the program reads this data from the keyboard or from a file. The program allows the loading on the laminate to be specified, calculates the laminate stresses and strains, and then tests for failure using a chosen failure criterion. If no failure does occur, the loads may be increased until failure does occur. After removing the effects of the failed layers (setting their stiffnesses to zero), the program automatically recalculates the new stresses and strains on the laminate. An example of an output file generated by the program is also included in Appendix D. The program also places load-strain data in a data file for incorporation in a Lotus worksheet for plotting if required. Figure 5.1.6 is an example of a curve obtained in this way. In practise the ply failures are not sharp definite points, as shown, but occur gradually over a load range, as indicated by the AE results. The curve is linear up to where ply failure occurs. Then the strain increases under constant load due to the sudden weakening of the laminate, before more load can be taken. The laminate has a lower tensile modulus after ply failure, hence the decreased slope.

It is not uncommon to superimpose events vs load plots with stress-strain curves, in order to relate ply failures directly to acoustic emission activity. This may help in future research to identify types of ply failures using acoustic emission.

Figure 5.1.6 0/90/+-45 Puppo-Evensen



Tables 5.1.8 to 5.1.11 show the theoretical results for each failure criterion. A comparison is made between the theoretical results and the experimental results from AE, and is shown as a percentage difference.

The criteria are numbered as follows:

1) Maximum stress
2) Maximum strain
3) Puck Simple
4) Puck Modified
5) Tsai-Hill
6) Puppo-Evenson
7) Norris-McKinnon
8) Norris
9) Fischer
10) Goldenblat-Kopnov
11) Tsai-Wu

Table 5.1.12 lists the percentage differences for each lay-up for all the failure criteria.

Table 5.1.8 Carbon Fibre/Epoxy Specimens
0/90 Degree Theoretical Results

Failure Criteria	FPF (kN)	% difference	LPF (kN)	% difference
1	16.06	-7.2	35.79	30.7
2	15.93	-8.0	36.10	31.8
3	16.06	-7.2	35.79	30.7
4	16.06	-7.2	35.79	30.7
5	16.05	-7.3	29.24	6.8
6	16.05	-7.3	38.15	39.3
7	16.05	-7.3	28.99	5.9
8	16.06	-7.2	35.79	30.7
9	16.25	-6.1	63.10	130.5
10	15.28	-11.7	24.72	-9.7
11	15.92	-8.0	33.75	23.3

Table 5.1.9 Carbon Fibre/Epoxy Specimens
0/+-45 Degree Theoretical Results

Failure Criteria	FPF (kN)	% difference	LPF (kN)	% difference
1		-0.7	41.72	-0.0
2		-1.7	41.31	-1.7
3	36.31	-13.6	37.47	-10.8
4	33.30	-20.8	37.47	-10.8
5		-14.5	35.94	-14.5
6	28.42	-32.4	36.51	-13.1
7		-14.6	35.90	-14.6
8	37.25	-11.4	37.47	-10.8
9	38.23	-9.0	55.50	32.0
10	16.87	-59.9	46.35	10.3
11		-16.7	35.00	-16.7

Table 5.1.10 Carbon Fibre/Epoxy Specimens
0/90/+-45 Degree Theoretical Results

Failure Criteria	FPF (kN)	% difference	SPF (kN)
1	12,68	115,3	23,53
2	11,48	95.2	
3	12,66	115,3	19,46
4	12,66	115,3	19,35
5	12,36	110,2	16,69
6	9,58	62,9	19,25
7	12,43	111,4	18,83
8	12,66	115,3	21,08
9	14,99	154,9	23.12
10	13.51	129,8	
11	11,20	90,5	20,71

% difference	LPF (kN)	% difference
44.7	23.92	1.4
65.7	26.95	14.3
19.7	23.92	1.4
12.9	23.92	1.4
10.2	23.9	1.4
10.4	23.45	-0.6
11.6	23.91	1.4
20.6	23.92	1.4
42.2	24.14	2.4
309.5	66.59	182.4
27.4	23.89	1.3

Table 5.1.11 Carbon Fibre/Epoxy Specimens
90/+-45 Degree Theoretical Results

Failure Criteria	FPF (kN)	% difference	LPF (kN)	% difference
1	5.51	47.4	7.56	5.6
2	5.22	39.5	10.01	39.8
3	5.51	47.4	6.62	-7.5
4	5.51	47.4	6.34	-11.5
5	5.48	46.4	6.41	-10.5
6	5.57	48.8	6.55	-8.5
7	5.48	46.4	6.41	-10.5
8	5.51	47.4	7.27	1.6
9	6.11	63.2	8.14	13.6
10	8.48	126.7	5.11	-28.6
11	5.14	37.5	7.34	2.6

Table 5.1.12 Comparison of Failure Criteria Predictions

Failure Criteria	Laminate Orientation	FPF % difference	SPF % difference	Fut % difference
Maximum Stress	0/90	-7		31
	0/+-45	-1		-1
	0/+-45/90	115	45	1
	90/+-45	49		5
Maximum Strain	0/90	-8		32
	0/+-45	-2		-2
	0/+-45/90	95	14	14
	90/+-45	41		39
Puck Simple	0/90	-7		31
	0/+-45	-14		-11
	0/+-45/90	115	-93	1
	90/+-45	49		-8
Puck Modified	0/90	-7		31
	0/+-45	-21		-11
	0/+-45/90	115	13	1
	90/+-45	49		-12
Tsai-Hill	0/90	-7		7
	0/+-45	-14		-14
	0/+-45/90	110	16	1
	90/+-45	48		-11
Puppo-Evensen	0/90	-7		39
	0/+-45	-32		-13
	0/+-45/90	62	18	-1
	90/+-45	37		-9
Norris-McKinnon	0/90	-7		6
	0/+-45	-15		-15
	0/+-45/90	111	16	1
	90/+-45	48		-11
Norris (Dist)	0/90	-7		31
	0/+-45	-11		-11
	0/+-45/90	115	30	1
	90/+-45	49		1
Fischer	0/90	-6		130
	0/+-45	-9		32
	0/+-45/90	154	42	2
	90/+-45	65		13
Goldenblat-Kopnov	0/90	-12		-10
	0/+-45	-6		10
	0/+-45/90	129	182	182
	90/+-45	125		-29
Tsai-Wu	0/90	-8		23
	0/+-45	-17		-17
	0/+-45/90	80	27	1
	90/+-45	39		2

5.2 Glass Fibre Specimens (First Set)

Examples of the acoustic emission output obtained from the glass fibre specimens are shown in Appendix B.2. Figures 5.2.1 to 5.2.7 show the acoustic emission results obtained for a typical +-45^{o} specimen. Final (and only) ply failure can clearly be seen on the amplitude vs load point plot and the hits vs load histogram. The counts and energy vs load cumulative line graphs look similar, but are useless in finding failures when viewed independently because the units can not be quantified to specify limits over which failure could be occurring. This is because these parameters depend on sensor response and sensor coupling. The slope changes do however correspond to layer failures, suggesting that event rate may be a useful parameter to study. The rise times and duration times vs hits histograms show most emissions are short, as expected.

These specimens were all loaded in steps in order to obtain hits and counts AE data at various load levels for failure load prediction, and to calculate the Felicity Ratios. The specimens were eventually loaded to failure to establish their strength relative to each other. One AE plot was obtained for each step load, and these plots are all included for two specimens (one +-45° and one 0/90° laminate) in Appendix B.2.

The acoustic emission results from the glass fibre specimens are limited in accuracy by the errors as shown in the error analysis in Appendix A.2.

The Felicity Ratio was calculated from the force at which hits above 15 were recorded. This was done to ensure that the Felicity Ratio obtained was not based on insignificant or background noise. It may cause the Felicity Ratio values to be higher than otherwise, but more consistent results can be

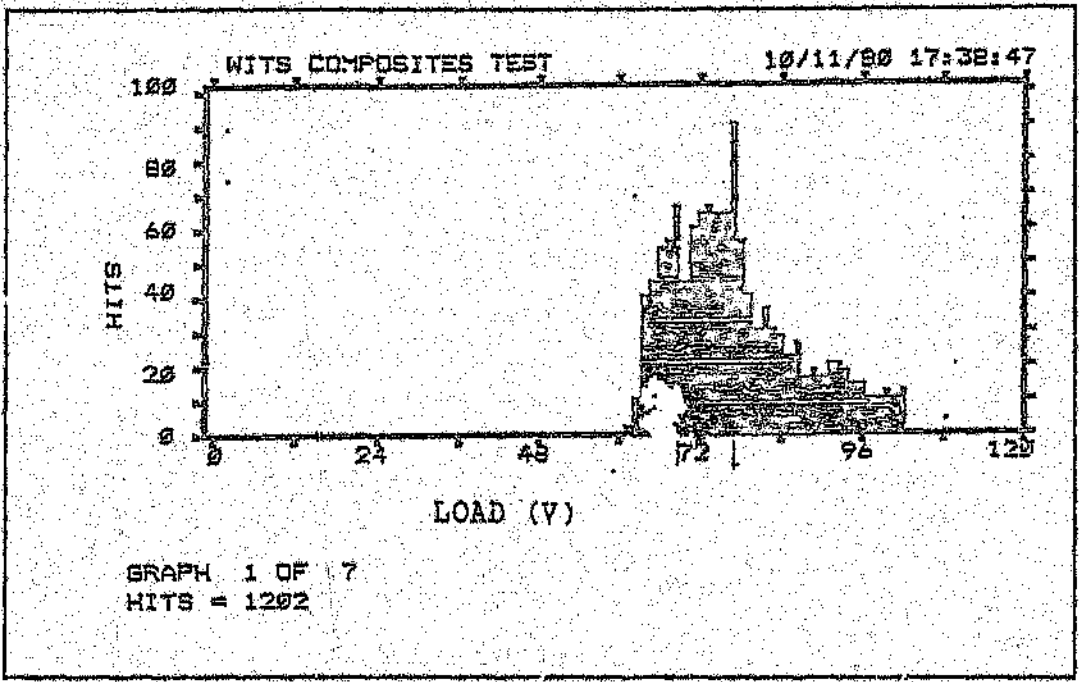


Figure 5.2.1 +-45 GFRP Non-Cumulative Histogram

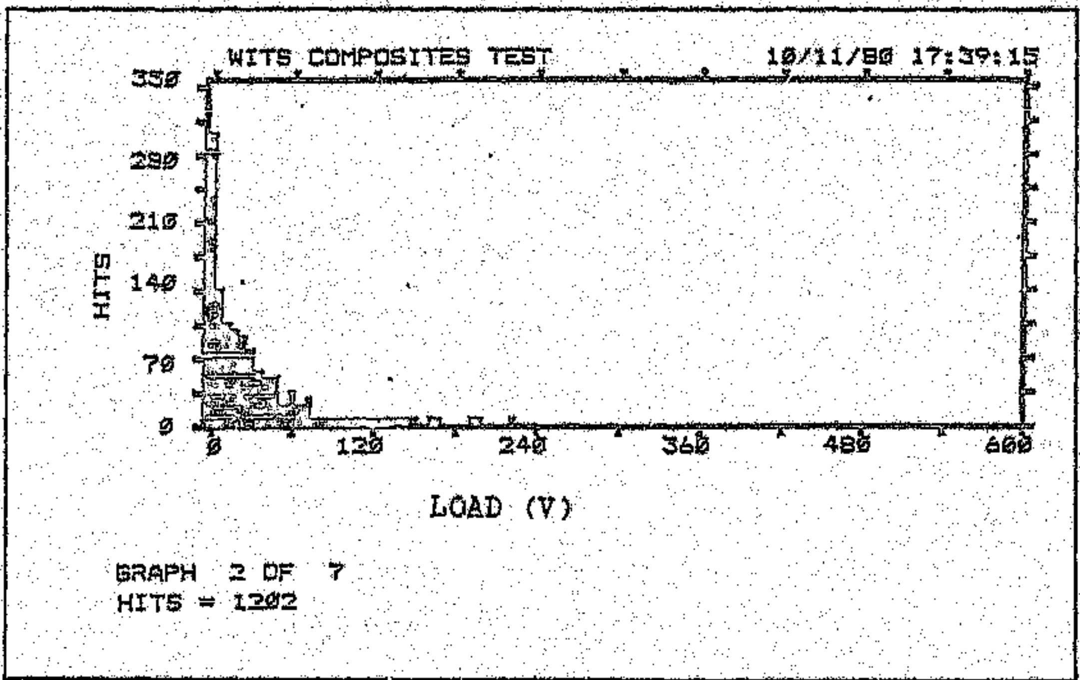


Figure 5.2.2 +-45 GFRP Non-Cumulative Histogram

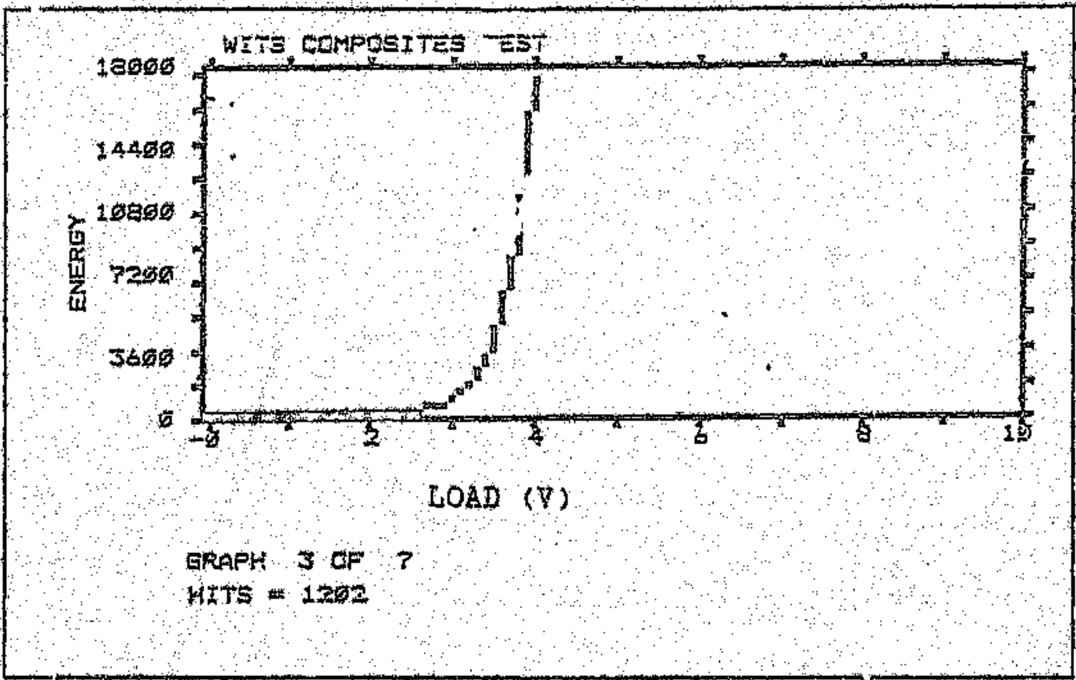


Figure 5.2.3 +-45 GFRP Cumulative Line Graph

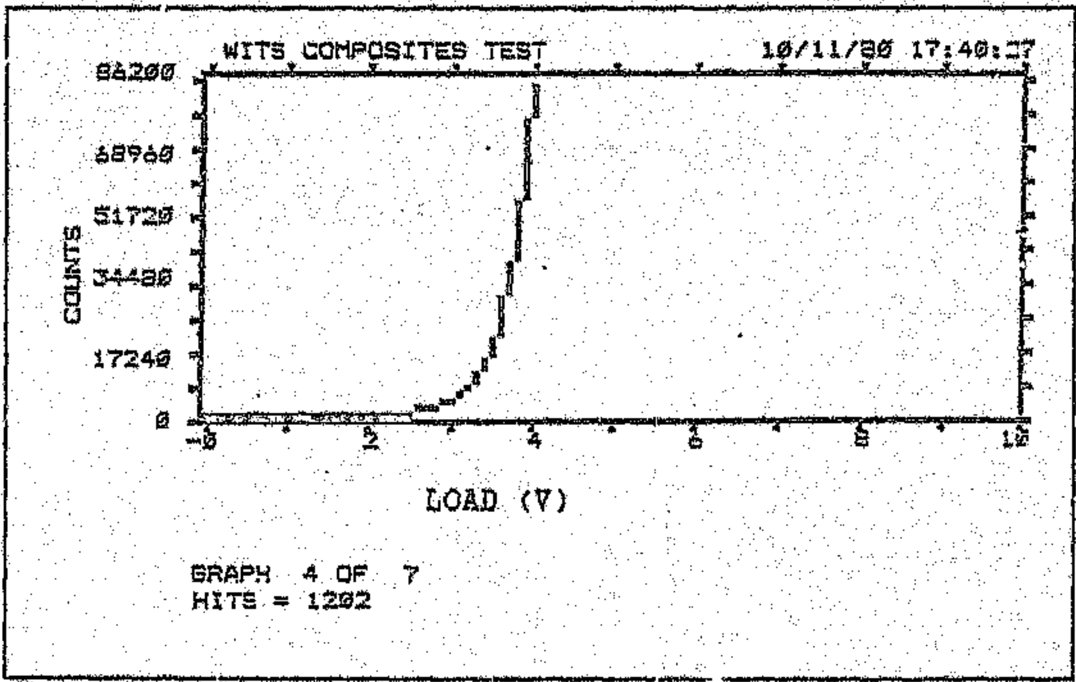


Figure 5.2.4 +-45 GFRP Cumulative Line Graph

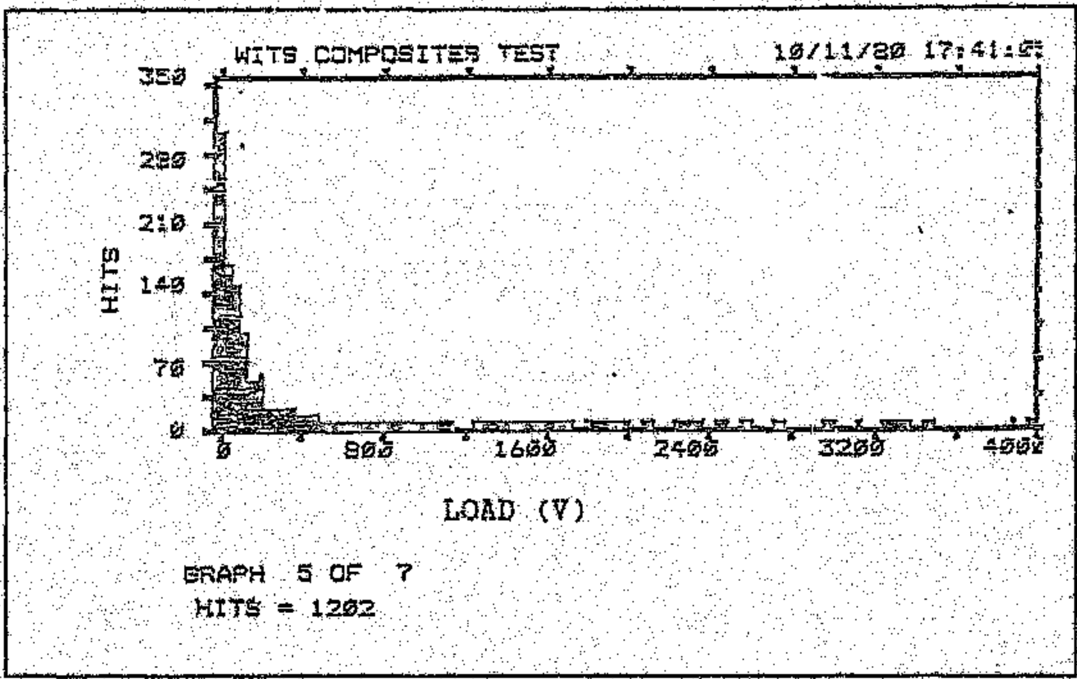


Figure 5.2.5 +-45 GFRP Non-Cumulative Histogram

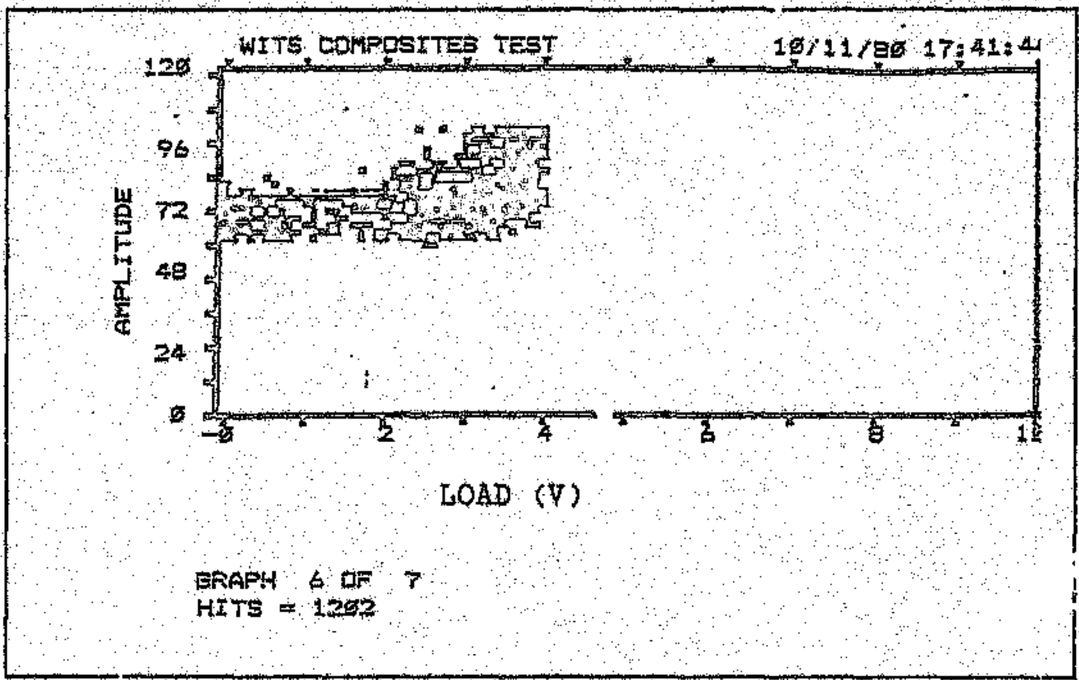


Figure 5.2.6 +-45 GFRP Point Plot

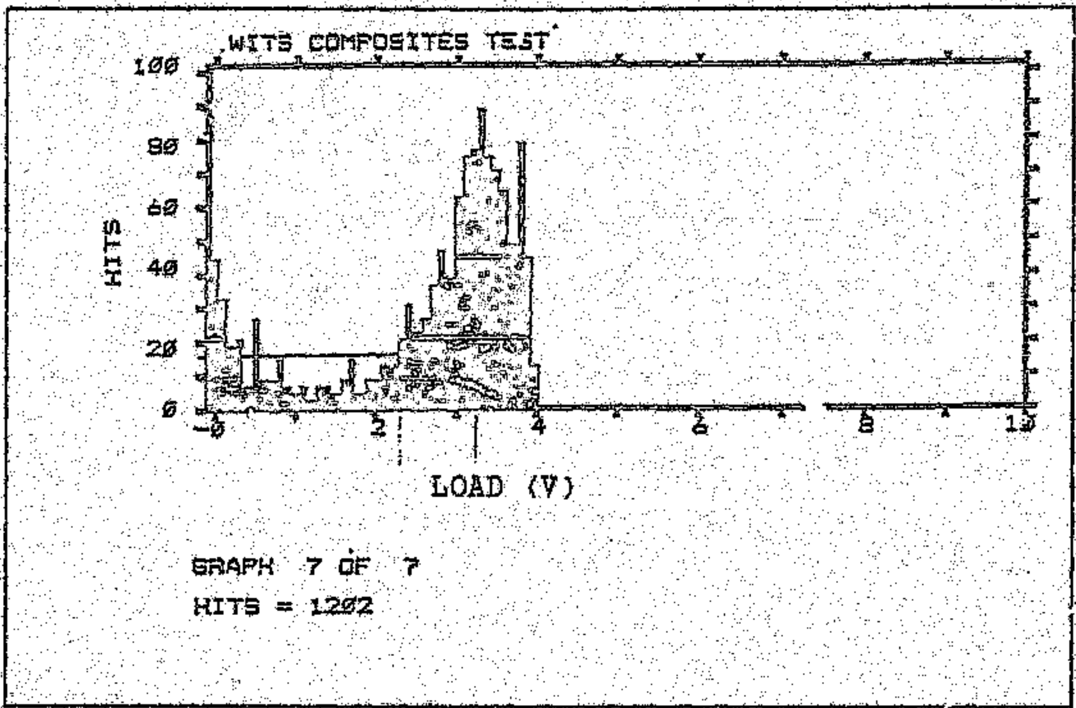


Figure 5.2.7 +-45 GFRP Non-Cumulative Histogram

expected.

Figures 5.2.8 and 5.2.9 are results obtained from the AE data from the +-45 degree glass fibre specimens. They show the cumulative counts vs hits for each specimen at various loads.

Figure 5.2.10 to 5.2.12 show the cumulative hits (events) vs ultimate load results for various lay-ups at various load steps. Figures 5.2.13 to 5.2.15 are similar but show cumulative counts instead of hits.

Figures 5.2.16 to 5.2.18 show the Felicity Ratio vs ultimate load at various load steps.

Figure 5.2.8 GLASS FIBRE PREPREG +-45 LAY-UP

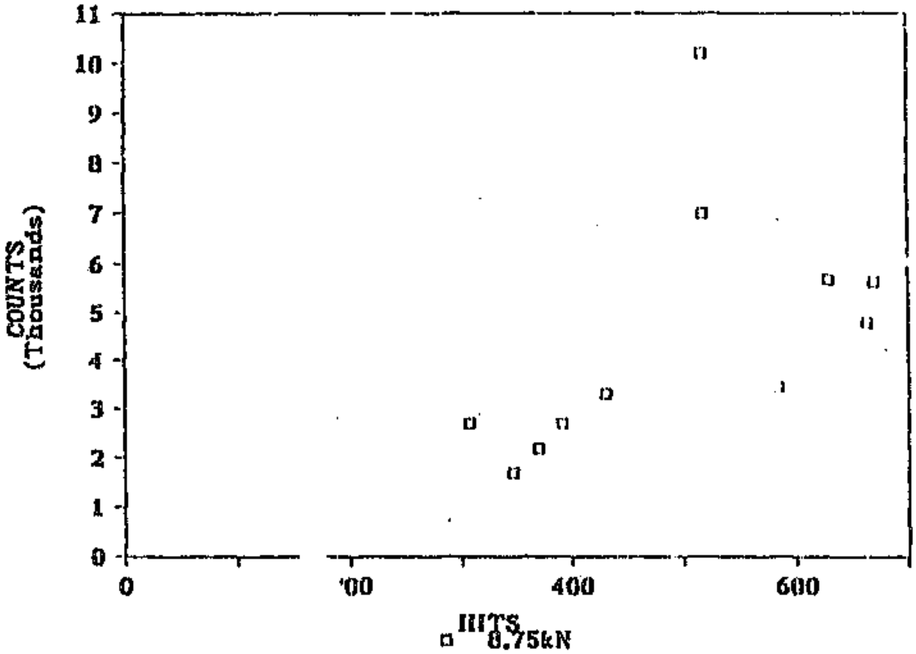


Figure 5.2.9 GLASS FIBRE PREPREG +-45 LAY-UP

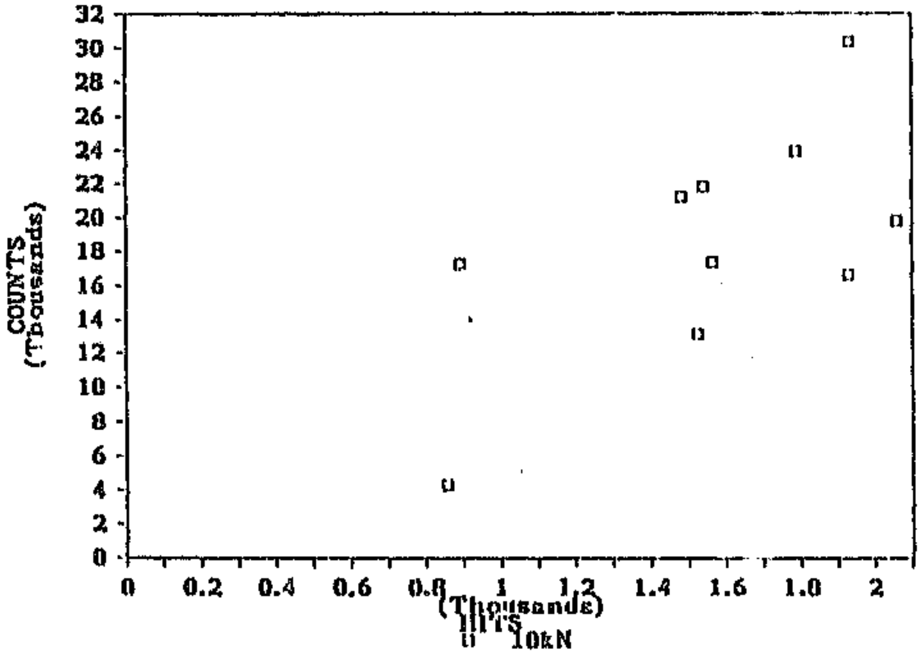
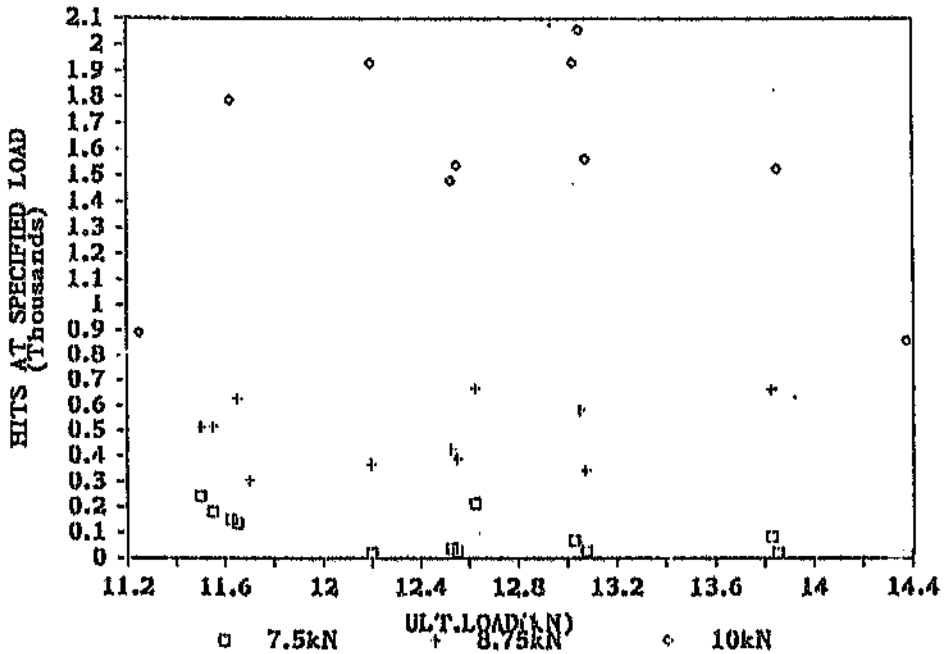


Figure 5.2.10 GLASS FIBRE PREPREG +-45 LAY-UP



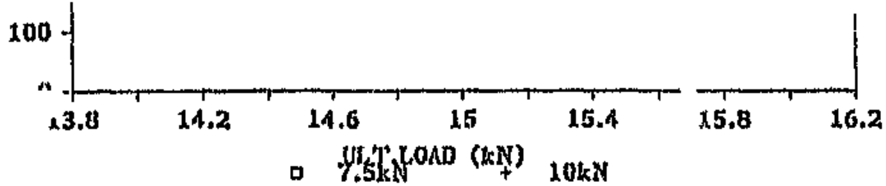

100
13.8
14.2
14.6
15
15.4
15.8
16.2
ULT LOAD (kN)
7.5kN
10kN

Figure 5.2.11 GLASS FIBRE PREPREG 0/90 LAY-UP

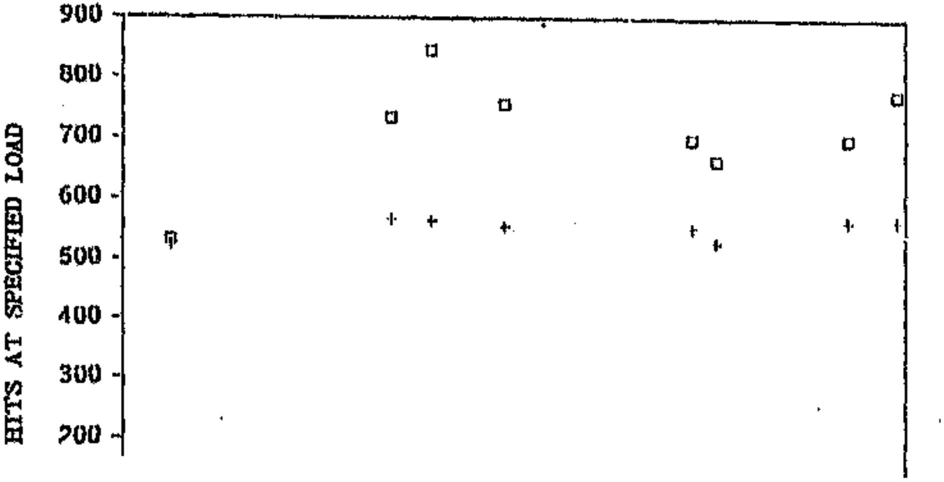


Figure 5.2.12 GLASS FIBRE PREPREG 0 LAY-UP

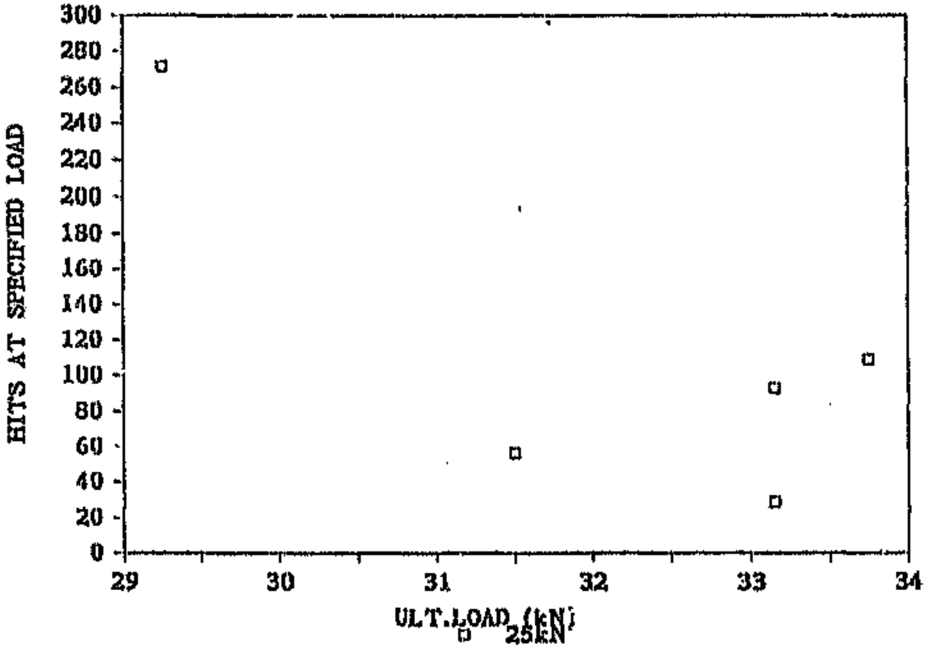


Figure 5.2.13 GLASS FIBRE PREPREG +-45 LAY-UP

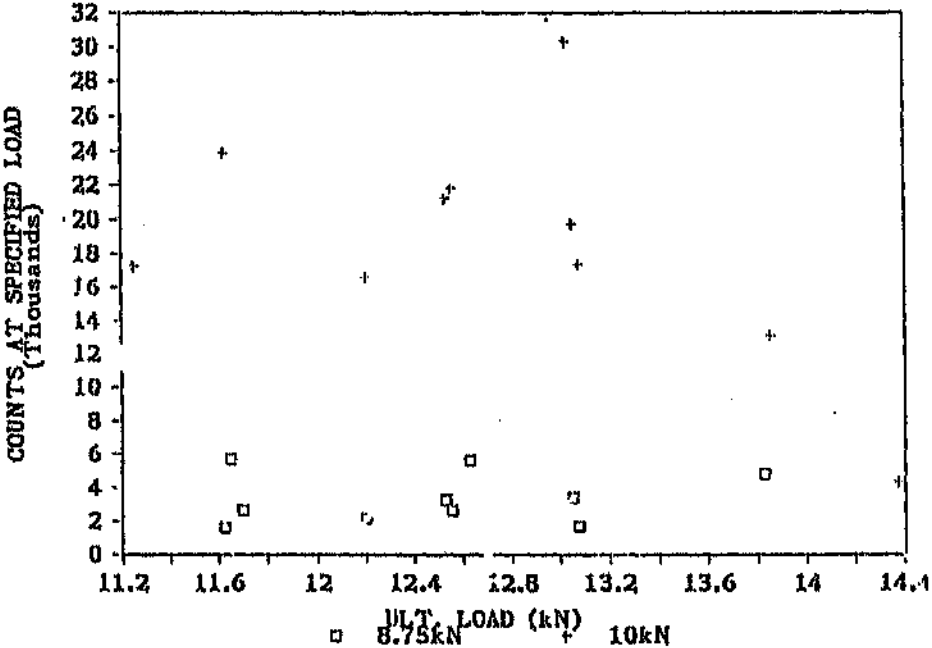


Figure 5.2.14 0/90 LAY-UP

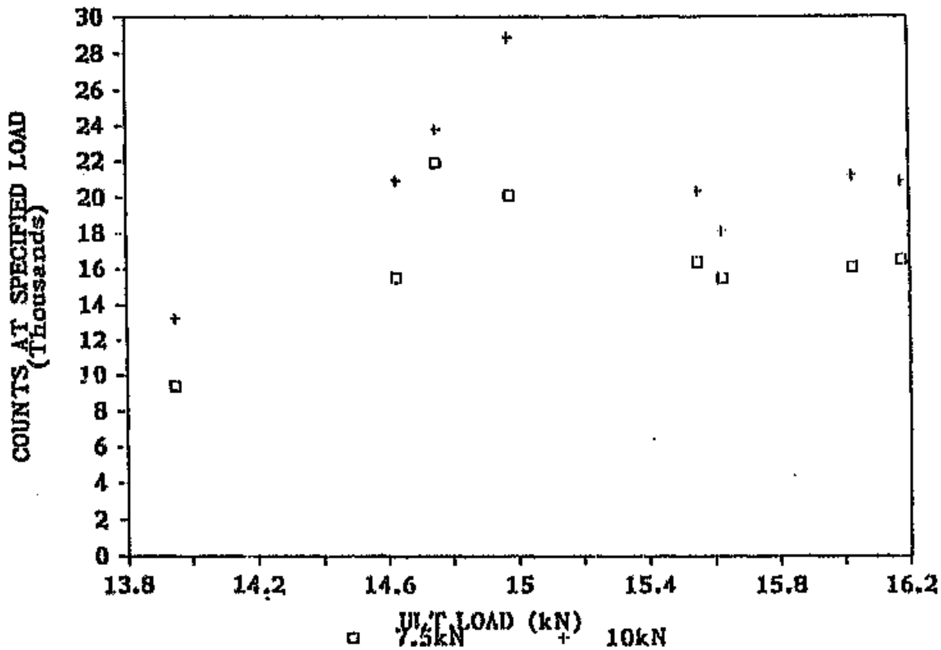


Figure 5.2.15 GLASS FIBRE PREPREG 0 LAY-UP

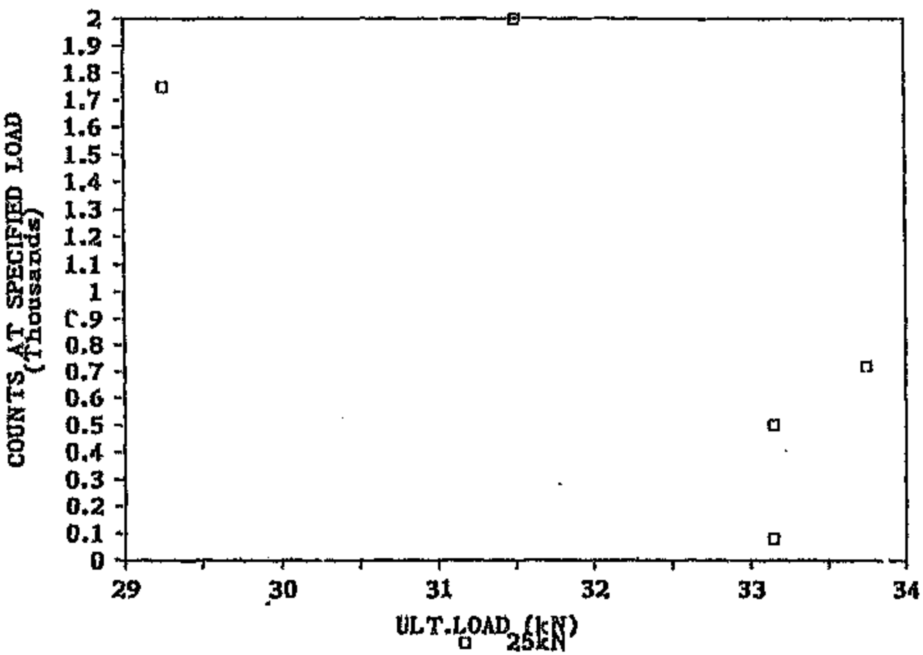


Figure 5.2.16 GLASS FIBRE PREPREG +-45 LAY-UP

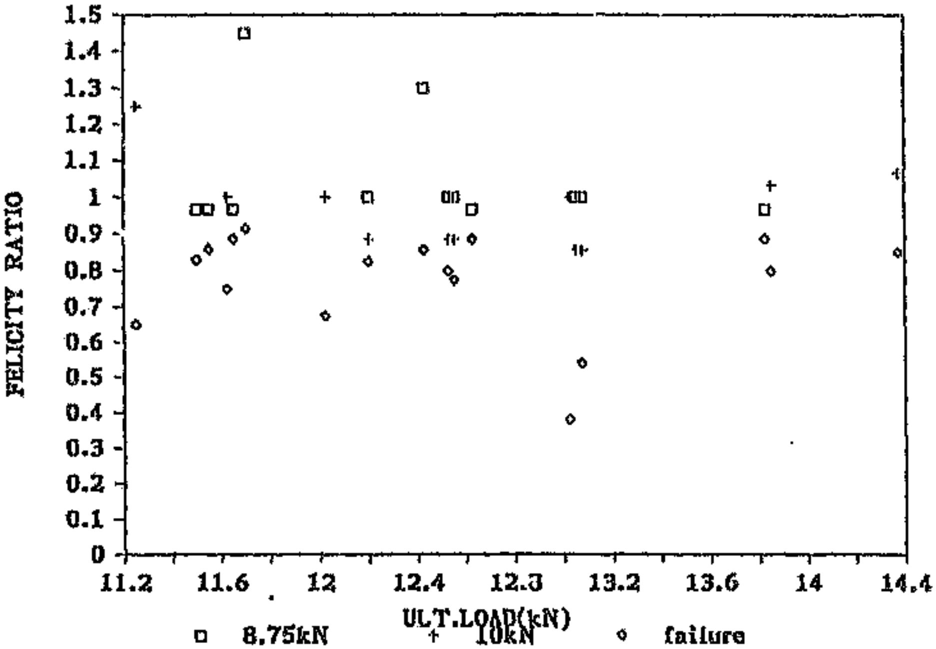


Figure 5.2.17 GLASS FIBRE PREPREG 0/90 LAY-UP

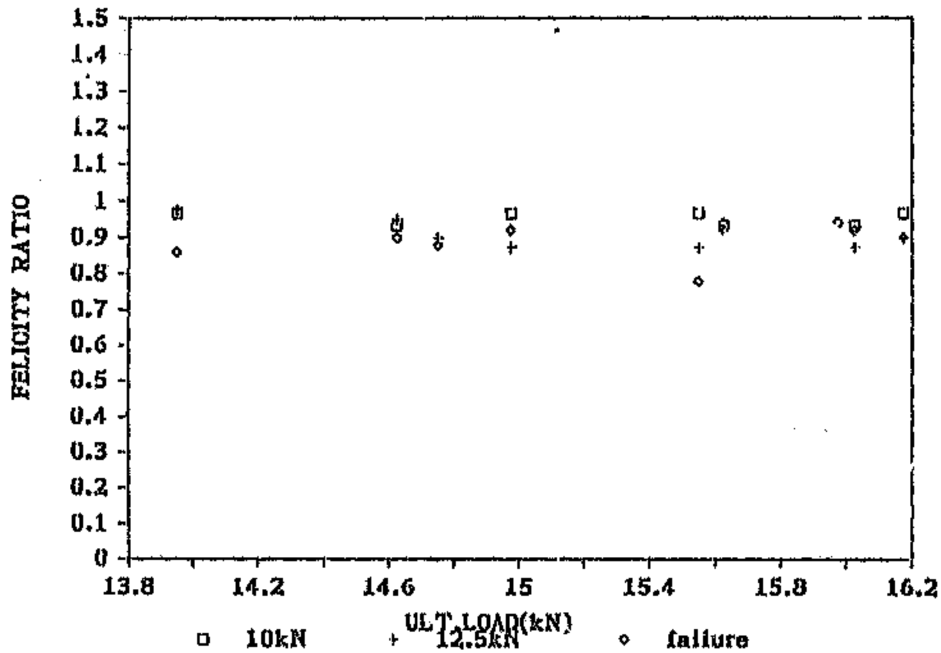
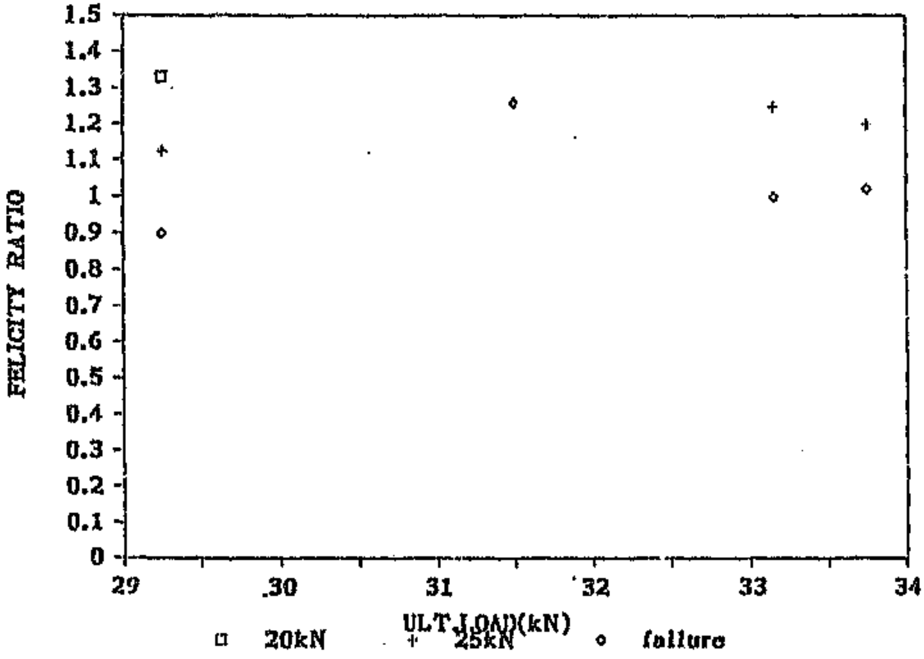


Figure 5.2.18 GLASS FIBRE PREPREG 0 LAY-UP



5.3 Glass Fibre Specimens (Second Set)

5.3.1 Material Properties

Tables 5.3.1 to 5.3.5 show the results from the testing of 0°, 90°, $+-45^{\circ}$ and $+45^{\circ}$ specimens to obtain material properties (see sample calculations in Appendix A.1). Table 5.3.5 lists the shear strengths obtained from the last ply failure results from the AE data.

Table 5.3.1 0 degree tensile test results
Glass/Epoxy prepreg M9

Specimen	Max.Load (kN)	E1 (GPa)	Ult. Stress (MPa)
1	84.0		1348
2	68.0		1276
3	84.0	51.6	1399
4	84.0	55.0	1382
5	71.0	52.8	1270
6	71.3	53.5	1204
7	81.3	56.3	1303
aver.	77.6	53.8	1312
std dev.	6.7	1.6	64

Table 5.3.2 90 degree tensile test results
Glass/Epoxy prepreg M9

Specimen	Max.Load (kN)	E2 (GPa)	Ult. Stress (MPa)
1	3.93	16.7	61.8
2	3.44	17.4	63.8
3	3.23	17.2	64.5
4	3.58	16.4	60.5
5	3.91	15.7	56.8
6	3.70	16.4	62.9
7	3.75	16.2	65.7
8	3.98	16.7	65.1
9	2.75	17.1	66.0
10	3.63	16.9	66.1
11	3.51	16.1	48.4
aver.	3.60	16.6	62.0
std dev.	0.38	0.4	5.1

Table 5.3.3 +45 degree tensile test results
Glass/Epoxy prepreg M9

Specimen	Max.Load (kN)	G12 (GPa)	Shear Str (MPa)
1	5.05	5.05	48.2
2	5.25	4.98	47.6
3	5.50	4.47	42.5
4	5.54	4.75	44.2
5	5.43	4.81	46.3
6	5.40	4.47	46.6
7	5.65	4.73	45.7
8	5.73	4.17	45.5
aver.	5.44	4.68	45.8
std dev.	0.20	0.28	1.7

Table 5.3.4 +-45 degree tensile test results
Glass/Epoxy prepreg M9

Specimen	Max.Load (kN)	G12 (GPa)	Shear Str (MPa)
1	8.50		70.7
2	8.25	4.19	68.1
3	8.60	5.10	68.3
4	8.25	4.95	71.1
5	7.95	4.97	71.5
6	7.98	5.07	69.2
7	8.30	5.37	73.6
8	8.35	4.77	70.7
9	8.08	5.33	72.8
aver.	8.25	4.42	70.63
std dev.	0.21	1.66	1.70

Table 5.3.5 +-45 degree tensile results from AE Glass/Epoxy prepreg M9

Specimen	Max.Load (kN)	Shear Stress (MPa)
1	7.93	67.9
2	7.88	68.9
4	7.88	72.2
5	7.88	71.8
6	7.50	67.4
7	7.60	64.3
8	8.39	67.4
9	8.05	65.1
10	8.20	67.4
aver.	7.92	68.06
std dev.	0.27	2.65

The material properties for the second set of glass fibre specimens obtained from test data are shown in tables 5.3.1 to 5.3.5. The highest standard deviation for stress values was for the 90° tensile properties (11.8%). This is because the 90° failure load is a matrix-dominated prop... resulting in brittle failure and therefore more scattered results. The next highest stress standard deviation was 7.6% for the 0° lay-up properties, and is not considered excessive.

5.3.2 AE Experimental Results

It was clear after evaluating the first set of data from the carbon fibre specimens, that a more reliable method of data analysis was required, since many ply failures could not be clearly distinguished from the PAC produced AE plots, and custom written software was required.

After testing, the AE data was transferred from the AE computer to an IBM compatible computer through the printer port, using a specially adapted RS232 cable at Stellenbosch University. File manipulation programs were written and used to remove meaningless data (such as that with zero energy) and to format the data for plotting. A plotting package was written in Pascal to generate graphs on either an Amplot plotter or a Paintjet printer in colour. It was designed to read data from files, and can therefore plot unlimited data points for up to ten different curves in different files on one graph. A twenty point moving average was done on the data during file manipulation.

After the first test results had been analysed, it was decided to plot energy vs load, event rate vs load and duration vs load. Duration was chosen to evaluate which layers produced more delamination AE (long events), and also to show how its graph vs load differed from energy vs load. It was felt that plotting counts, hits, rise time or amplitude vs load as well would not provide any more useful information, since the curve trends are similar to those for energy vs load (the previous results confirm this). This can be seen intuitively if the diagram of the AE parameters is examined (figure 1.2). The wave envelope related parameters such as energy, counts, duration, amplitude, etc are likely to produce similar trends to each other.

Tables 5.3.6 to 5.3.10 show the experimental results from each lay-up type, obtained from analysis of the AE data.

Table 5.3.6 Acoustic Emission
Experimental Results
+-45 degree lay-up

Specimen No.		LPF (kN)
1		7.88
2		7.88
3		7.88
4		7.50
5		7.75
6		7.94
7		7.86
8		7.89
	avg.	7.82
	std dev.	0.13

Table 5.3.7 Acoustic Emission
Experimental Results
0/90 degree lay-up

Specimen No.		FPF (kN)		LPF (kN)
1		7.85		40.39
2		7.85		39.46
3		7.85		39.23
4		7.62		37.73
5		8.65		36.42
6		7.85		36.12
7		6.92		34.85
	avg.	7.80	avg.	37.74
	std dev.	0.47	std dev.	1.89

Table 5.3.8 Acoustic Emission
Experimental Results
90/+-45 degree lay-up

Specimen No.	FPF (kN)		LPF (kN)
1	3.09		5.15
2	4.34		5.19
3	4.09		5.23
4	4.16		5.27
5	3.92		5.35
6	4.00		5.23
7	4.09		5.31
8	4.00		5.23
avg.	4.60	avg.	5.24
std dev.	0.69	std dev.	0.06

Table 5.3.9 Acoustic Emission
Experimental Results
0/90/+-45 degree lay-up

Specimen No.	FPF (kN)		SPF (kN)		LPF (kN)
1	5.65		10.04		21.00
2	5.65		10.39		21.00
3	6.12		10.39		20.68
4	6.12				20.89
5	5.42		9.12		20.05
6	6.23		8.77		19.73
7	6.81		10.85		20.53
8	5.42		12.12		19.73
avg.	5.93	avg.	10.24	avg.	20.45
std dev.	0.45	std dev.	1.03	std dev.	0.51

Table 5.3.10 Acoustic Emission
Experimental Results
0/+-45 degree lay-up

Specimen No.	FPF (kN)		LPF (kN)
1	33.46		48.88
2	33.46		45.12
3	33.46		46.16
4	35.08		48.88
5	29.54		39.12
6	34.50		46.62
7	32.71		
avg.	33.17	avg.	39.72
std dev.	1.65	std dev.	3.29

5.3.3 Theoretical Results

Tables 5.3.11 to 5.3.14 show the theoretical results obtained with the use of theoretical analysis (using the computer program in Appendix D) for each type of laminate lay-up.

Three additional failure criteria were evaluated for the second set of glass specimens, these being the Hoffman, the Hoffman with A_{12} =0 and the Hill theories.

Tables 5.3.15 to 5.3.18 present the percentage differences between the various failure criterion predictions and the experimental results for each type of lay-up.

Table 5.3.11 Theoretical Results
0/90 Lay-up

Criteria	FPF (kN)	LPF (kN)
Max.Stress	7.99	34.60
Max.Strain	7.92	40.16
Puck Simple	7.99	34.60
Puck Modified	7.99	34.60
Tsai-Hill	7.97	26.38
Puppo-Evensen	7.98	32.72
Norris-McKinnon	7.97	26.07
Norris-Dist.	7.95	34.60
Fischer	7.94	39.48
Goldenblatt-K	29.89	29.89
Tsai-Wu	7.93	35.20
Hoffman	7.96	27.42
Hoffman A12=0	7.96	26.83
Hill	7.98	26.38

Table 5.3.12 Theoretical Results
0/+-45 Lay-up

Criteria	FPF (kN)	LPF (kN)
Max.Stress	21.99	44.08
Max.Strain	21.99	42.99
Puck Simple	16.08	44.08
Puck Modified	14.87	44.08
Tsai-Hill	16.04	31.92
Puppo-Evensen	16.08	28.78
Norris-McKinnon	16.02	32.90
Norris-Dist.	16.53	26.89
Fischer	16.61	26.30
Goldenblatt-K	14.73	23.40
Tsai-Wu	15.79	28.68
Hoffman	15.30	37.12
Hoffman A12=0	15.35	38.51
Hill	16.04	31.92

Table 5.3.13 Theoretical Results
90/+-45 Lay-up

Criteria	FPF (kN)	LPF (kN)
Max.Stress	4.25	4.74
Max.Strain	4.08	5.90
Puck Simple	4.25	4.25
Puck Modified	4.25	4.25
Tsai-Hill	4.23	4.23
Puppo-Evensen	4.24	4.24
Norris-McKinnon	4.24	4.24
Norris-Dist.	4.14	4.14
Fischer	4.13	4.43
Goldenblatt-K	6.91	6.91
Tsai-Wu	4.11	4.46
Hoffman	4.17	4.17
Hoffman A12=0	4.18	4.18
Hill	4.23	4.23

Table 5.3.14 Theoretical Results
0/90/+-45 Lay-up

Criteria	FPF (kN)	SPF (kN)	LPF (kN)
Max.Stress	6.40	11.75	26.78
Max.Strain	6.03	14.65	26.61
Puck Simple	6.40	9.61	26.78
Puck Modified	6.40	9.06	26.78
Tsai-Hill	6.36	9.57	25.80
Puppo-Evensen	6.40	11.26	23.38
Norris-McKinnon	6.38	9.55	26.14
Norris-Dist.	6.16	10.00	23.73
Fischer	6.14	10.07	23.45
Goldenblat-K	10.43	10.43	28.66
Tsai-Wu	6.10	9.67	24.88
Hoffman	6.23	9.47	28.53
Hoffman A12=0	6.24	9.43	29.04
Hill	6.36	9.57	25.80

Table 5.3.15 % Difference between exp. and theor. values
0/90 degree lay-up

Criteria	FPF	SPF	LPF
Max. Stress	2.4		-8.3
Max.Strain	1.5		6.4
Puck Simple	2.4		-8.3
Puck Modified	2.4		-8.3
Tsai-Hill	2.3		-30.1
Puppo-Evensen	2.4		-13.3
Norris-McKinnon	2.3		-30.9
Norris Dist.	1.9		-8.3
Fischer	1.8		4.6
Goldenblat-K	283.3		-20.8
Tsai-Wu	1.7		-6.7
Hoffman	2.0		-27.4
Hoffman A12=0	2.1		-28.9
Hill	2.4		-30.1

Table 5.3.16 % Difference between exp. and theor. values
0/+-45 degree lay-up

Criteria	FPF	SPF	LPF
Max. Stress	-33.7		-3.7
Max.Strain	-33.7		-6.1
Puck Simple	-51.5		-3.7
Puck Modified	-55.2		-3.7
Tsai-Hill	-51.6		-30.3
Puppo-Evensen	-51.5		-37.2
Norris-McKinnon	-51.7		-28.2
Norris Dist.	-50.2		-41.3
Fischer	-49.9		-42.6
Goldenblat-K	-55.6		-48.9
Tsai-Wu	-52.4		-37.4
Hoffman	-53.6		-18.9
Hoffman A12=0	-53.7		-15.9
Hill	-51.6		-30.3

Table 5.3.17 % Difference between exp. and theor. values
90/+-45 degree lay-up

Criteria	FPF	SPF	LPF
Max. Stress	4.6		-9.8
Max.Strain	0.4		12.5
Puck Simple	4.6		-19.1
Puck Modified	4.6		19.1
Tsai-Hill	4.3		-19.4
Puppo-Evensen	4.5		-19.2
Norris-McKinnon	4.5		-19.2
Norris Dist.	2.0		-21.1
Fischer	1.7		-15.6
Goldenblat-K	70.2		31.6
Tsai-Wu	1.3		-15.1
Hoffman	2.7		-20.5
Hoffman A12=0	2.9		-20.4
Hill	4.3		-19.4

Table 5.3.18 % Difference between exp. and theor. values
0/90/+-45 degree lay-up

Criteria	FPF	SPF	LPF
Max. Stress	7.9	14.8	30.9
Max.Strain	1.7	43.1	30.1
Puck Simple	7.9	-6.2	30.9
Puck Modified	7.9	-11.5	30.9
Tsai-Hill	7.3	-6.5	26.1
Puppo-Evensen	7.9	10.0	14.3
Norris-McKinnon	7.6	-6.7	27.8
Norris Dist.	3.9	-2.3	16.1
Fischer	3.5	-1.7	14.7
Goldenblat-K	76.0	1.9	40.1
Tsai-Wu	2.9	-3.6	21.7
Hoffman	5.0	-7.5	39.5
Hoffman A12=0	5.3	-8.0	42.0
Hill	7.3	-6.5	26.1

6 DISCUSSION

6.1 Carbon Fibre Specimens

6.1.1 Acoustic Emission Results

Examples of some of the AE results for CFRP specimens are included in Appendix B.1. Acoustic emission observations on the 90° specimens showed few high energy occurrences. Amplitudes were mainly in the 60 to 70 dB range, indicating that matrix cracking and delamination causes emissons in this range. Rise times were mainly very low, below 60 microsecs. Cumulative energy showed a sudden increase at failure, but was otherwise low, as was expected, since the laminate is uni-directional. Duration times were also low, mostly less than 200 microsecs.

The 0° acoustic results showed scattered high and low energy occurrences. These are likely to be from the breakage of weak and badly aligned fibres and due to matrix cracking. The amplitudes are mainly between 60 and 80 dB, indicating matrix cracking and fibre/matrix debonding. The emission tests were not continued to failure for the 0° specimens to avoid sensor damage, since the CFRP specimens tended to fail violently. Therefore the fibre breakage effect can not be seen. Rise times were short (mostly less than 60 microsecs), and so were durations (mostly less than 200 microsecs). There was not as much matrix failure as occurs with glass FRP, with pieces of laminate breaking with clean tensile type failures. This is due to the fibre stiffness, and tends to reduce the amount of acoustic emission prior to failure.

A significantly low amount of acoustic events occurred during testing of unidirectional fibre specimens, due to the increased homogeneity of a unidirectional laminate compared to a multidirectional laminate. This may limit the use of acoustic emission monitoring in practise to multi-directional laminates.

The 90/+-45° specimens were tested to failure. The energy/load emission results show a rise in high energy occurrences, followed by a reduction until failure, with a sudden high energy occurrence at failure. This peak obviously represents the onset of fibre breakage. The amplitude distribution shows three peaks which may relate to the three failure mechanisms (2); namely matrix crazing at 50 to 68 dB, fibre/matrix delamination at 68 to 85 dB and fibre breakage at 90 to 100 dB. The rise times range from 0 to 180 microsecs. The presence of a significant number of slow rise times indicates delamination and fibre/matrix debonding. Cumulative energy shows an increase in energy rate at a load of about 3 volts, which is also the point at which the high amplitude events began. This suggests the onset of fibre breakage. The numerous large duration times recorded indicate delamination and fibre/matrix debonding.

The 0/90/+-45° acoustic emission results show the onset of high energy occurrences at just over two volts. Most occurrences are in the 60 to 80 dB range, indicating mainly matrix cracking and delamination. The absence of high amplitude occurrences is due to the acoustic sensor being removed from the specimens prior to failure. Rise times were mostly less than 60 microsecs and duration times less than 400 microsecs, indicating more matrix cracking than delamination. The amplitude vs load point plots show two peak areas at two different loads where more emissions occurred than elsewhere, one being just before failure. These high density patches indicate different ply failures. The cumulative counts vs load graphs have slope variations which generally match the areas of high emission hits. This indicates that ply failure may be found by examining the changes in slope of the counts vs load graphs. The absence of long events in these tests may indicate that the long duration dela' .nation events occur very near failu e.

Agai , th sensor was removed from the 0/+-45° specimens prior to the onset of fibre failure, as can be seen from the amplitude distribution. Rise times and duration times were again low. Since far more delamination and fibre/matrix debonding is likely to occur during fibre breakage, the predominance of matrix cracking emissions may be expected. A rise in the counts vs load curve slope matches the increased density area of the amplitude vs point plot, in most of the specimens.

The 0/90° emission results show the onset of high energy emissions at about 2.5 ... amplitude distributions show double peaks indicating ... ing and delamination. There are also high amplit ... (from 85 to 100 dB), indicating some fibre fai... long and short rise and duration times, again in... matrix cracking and delamination. The amplitude/voltage distribution shows high amplitude signals starting at around 2.5 volts, which might be the point at which fibres in the 0° layers began to fail. The sensor was removed from the 0/90° specimens before failure occurred. Two distinct areas of high rates of emissions can be distinguished on most of the amplitude point plots. The count increase is in general uniform and exponential towards failure. The fact that long duration times occurred may be due to the very low strength 90° plies mixed with very high strength 0° plies. A large amount of rubbing and interlaminar debonding is likely to occur when some layers are substantially stiffer and fail after others.

The +-45° specimen results show the onset of high energy events at around 4.5 to 5 volts. These events were also high amplitude, probably fibre failure. The amplitude distributions show mainly matrix cracking and delamination with some fibre failure, as was expected. The rise times and duration times are spread out, indicatir~ a number ~f failure modes. The count vs load results show uniform count in. eases to failure, with no sharp variation in slope. Acoustic emissions begin at around 3/5 of the final load.

6.1.2 Failure Criteria

All the criteria chosen to be evaluated are relatively simple t~ apply, although biaxial tests are required for the additional material property for the Tsai-Wu and Goldenblat-Kopnov criteria. For a failure criterion to take other specific failure modes into account, more com~licated terms may be required which may involve additional material properties and therefore difficult tests on the material. This will obviously reduce its appeal and make it unpopular, although it may be very accurate. The ~rant-Sanders is one such criterion. The most popular criteria involve the common material ~roperties such as the per layer tensile, compressive and shear stiffnesses and strengths. Any other properties required must be simple to evaluate, using common testing equipment.

The terms of the failure criteria ~ormally take a similar form, that being two principal stresses divided by two maximum stresses. Failure has occurred when all the criteria terms in an equation add up to one, whereas they are less than one prior to failure.

An interactive criterion is one which contains more than one principal stress term in the failure equation. A non-interactive criterion considers the various principal stresse~ seperately. The Maximum Stress and Maximum Strain criteria have no interaction equations. The Puck Simple and Puck Modified criteria have both types of equations. All the interactive criteria use the same basic equation, and have extra terms in σ_1, σ_2 or $\sigma_1\sigma_2$. The basic equation is the Norris McKinnon interactive equation:

$$\left(\frac{\sigma_1}{X}\right)^2+\left(\frac{\sigma_2}{Y}\right)^2+\left(\frac{\tau_{12}}{S}\right)^2=1$$

Other differences between criteria are in the additional terms, usually one term in $\sigma_1\sigma_2$ and multiplied by some factor.

Therefore the criteria give similar results when only one principal stress is involved, and differ when interaction between principal stresses occurs.

6.1.3 Experimental Results from Acoustic Emission

- 0/90° Laminate - A high energy 90° ply failure could be found in certain graphs (see examples in Appendix B.1). High energy acoustic occurences close to failure can be seen in all of the graphs. The Norris-McKinnon (interaction) and Tsai-Hill criteria produced the closest predictions to these failure points (5.9% and 6.8% difference above). All the failure predictions (table 5.1.8) except Fischer were higher than Fut. This indicates that interaction between the principal stresses in the layers was significant, resulting in the 0° layers failing earlier than would otherwise be expected. First ply failure was most accurately predicted by Fischer (6.1% difference below) followed by the Maximum Stress, Puck Simple, Puck Modified, Tsai-Hill, Puppo-Evensen, Norris-McKinnon and Norris criteria (all 7.7% below). The first ply failures found by acoustic emission were not consistent and therefore may not be accurate.

- 0/+-45^{o} Laminate - The acoustic emission results for these specimens were very inconsistent and only a few provided information on where final failure was beginning. First ply failure and ultimate failure could often not be seperately distinguished, due to continuous emissions. The Maximum Stress and Maximum Strain criteria produced the most accurate predictions to first ply failure, being only 0.7% and 1.7% out respectively. This indicates that the two ply orientations failed simultaneously, and the criteria with interaction equations and more significant correction factors were less accurate, with FPF occurring later than predicted.

- 0/90/+-45^{o} Laminate - Information on ply failure was difficult to acquire from the acoustic emission graphs, which did not show consistent characteristics. Ultimate failure was well predicted (1.4% error) by all the criteria (see table 5.1.10) except Goldenblat-Kopnov and Maximum Strain. First ply failure was predicted most accurately by the Puppo-Evensen criterion and second ply failure was predicted most accurately by the Puck Modified criterion. Failure predictions were progressively more accurate from first to last plies. This could be at least partly due to the fact that the last ply was the most clearly defined on all the AE plots.

- 90/+-45 Laminate - The acoustic emission graphs for these specimens all show a rise in high energy acoustic occurrences near failure. These noises begin at around half the ultimate load (see table 5.1.11). This is partly due to the fact that the +-45^{o} layer does not fail in pure shear, but the fibres fail as well as the matrix. The first ply failure was indistinct in many of the acoustic emission graphs, and was not predicted well by any of the criteria, due to emissions occurring sooner than predicted by the criteria. The closest prediction was the Tsai-Wu criterion (37,5% overpredicted). Ultimate failure was best predicted by the Norris and Tsai-Wu criteria, indicating principal stress interaction producing early failure.

6.1.4 Failure Criteria Selection

It is clear that there is no universally accurate criterion which is significantly better than the rest. The criteria generally range from being frequently too conservative where minimal principal stress interaction occurs, to the completely non-interactive equations. The failure criterion to be used should be selected according to which ply failure is to be predicted, and what the laminate lay-up is. The values in table 5.1.12 are limited by the accuracy of the acoustic emission results, but the final failure results are dependable in most cases, as discussed above. The Tsai-Wu criterion gives consistent results, but could possibly be improved by choosing a better value for A_{12}. A combination of criteria could be used to achieve accurate predictions.

For a 90/+-45° or 0/90° layer, a simple interactive equation such as the Norris-McKinnon is required. The Maximum Stress criterion is most accurate for the 0/+-45° laminate. A conservative interactive criterion, such as the Puppo-Evensen or Tsai-Wu, is indicated to be most accurate for the FPF in a 0/90/+-45° laminate, with a less conservative interactive equation, such as the Puck Modified or Tsai-Hill, being most accurate for the second ply failure. The Maximum Stress criterion is adequate for LPF.

6.2 First Set of Glass Fibre Specimens

6.2.1 Acoustic Emission Plots

Examples of the acoustic emission results for the first glass fibre specimens are shown in figures 5.2.1 to 5.2.7 and in Appendix B.2. For the +-45° lay-up specimens, the amplitudes range mainly between 60 and 103 dB, which is the full range of amplitudes which the machine can record on a 0.1V threshold setting. An amplitude peak occurs frequently at 74dB, which may be caused by matrix cracking. Higher amplitudes could denote delamination and fibre failure.

The amplitude ranges of the 0/90° specimens frequently reach 103dB, with peaks at 74 dB. The 0/90° specimens in general have less emission occurrences in the mid-amplitude range (74 - 84dB), but more high energy occurrences (90 - 103dB), than the +-45° lay- up specimens. Since a 0/90° specimen experiences more fibre failure than a +-45° specimen, the high energy occurrences could denote fibre failures. Again, an amplitude peak occurs at around 74dB.

The 0° lay-up acoustic emission results again show amplitude peaks at around 74dB. Amplitude ranges are from around 68dB to 90dB. Since little delamination is expected to occur in a 0° lay-up specimen and the 0° lay-up specimens show less high amplitude occurrences (near 103dB) than the 0/90° specimens, the high amplitude occurrences could be caused by a mixture of delamination and fibre breakage.

6.2.2 Counts-Hits Relationship

Figures 5.2.8 and 5.2.9 show counts vs hits plots for the +-45° lay-up specimens at a load of 8.75 kN and 10 kN respectively. The relationship is not as linear as expected. For a specimen with a high number of hits, it is expected that the number of counts should be similarly high. This trend can be distinguished in the graphs. Clearly both hits and counts were substantially higher at the 10 kN load than the 8.75 kN load. The wide scattering is a good indication of the reproducibility of acoustic emission results, and is probably due to varying degrees of sensor acoustical coupling efficiency during testing. The counts/hits ratio does not increase significantly at the higher load, as would intuitively be expected. This essentially indicates that the event duration and energy are not increasing with increasing load, since the count frequency is a function of the sensor resonant frequency, and therefore constant.

6.2.3 Hits / Counts - Ultimate Load Relationship

For the +-45° lay-up, the hits vs ultimate load plot is sh n in figure 5.2.10, and counts vs ultimate load in figure 5.2.13. The weaker specimens should generate more acoustic emissi occurrences than the stronger specimens up to the same load (' This trend is not shown in the graphs. The weaker and stronger specimens show no significant differences in hits or counts. However, the number of hits and counts increase significantly at higher loads. The results for the 0/90° lay-up specimens (figures 5.2.11 and 5.2.14) show similar characteristics. This shows that weak and strong specimens can not be distinguished from the number of hits or counts recorded at some load, where the weak and strong specimen strength difference is about 3kN (around 30MPa). A difference in number of hits or counts between specimens may have been distinguishable for higher stress differences, such as if the flawed specimens had been much weaker.

Figures 5.2.12 and 5.2.15 show respectively hits and counts plotted against ultimate load for the 0° specimens and show no other significant trends.

6.2.4 Felicity Ratio

The Felicity Ratio vs ultimate load plots for the +-45°, 0/90° and 0° lay-ups are shown in figures 5.2.16, 5.2.17 and 5.2.18 respectively. The Felicity Ratio does not vary significantly between weaker and stronger specimens where the strength difference is around 3kN. The Felicity Ratio does reduce as the load is increased. For the +-45° lay-up specimens, the highest Felicity Ratio at failure was 0.93. It was 0.95 for the 0/90° specimens, and 1.25 for the 0° specimens. The Felicity Ratio therefore depends on the laminate ply orientation. The high Felicity Ratio for the 0° specimens indicates that they may be responding according to the Kaiser Effect, at least up until very near failure. Clearly, when testing unidirectional 0° laminates, any high energy emissions may be signalling that failure is about to occur.

6.3 Second Set of Glass Fibre Specimens

6.3.1 Acoustic emission results

The results of AE energy vs load are shown in Appendix C, figures C.1 to C.10. Each colour on the graph corresponds to one specimen (ie three or four specimens on each set of axes). Certain ply failures can easily be seen, such as 0^o and 90^o layer failures. From the +-45^o lay-up results (figures C.1 and C.2), it can be seen that the energy range for a 45^o layer failure is between 0 and 40 units, which is very low compared to a 90^o or 0^o layer failure, whereas the event rate is high (0 to 30 per second, see figures C.11 and C.12). These trends can also be seen on all the AE graphs of lay-ups with 45^o layers in them. This was used to obtain the 45^o layer failures from the AE data. The 90^o layer produces AE of energy between 0 and 120 units, and low event rates of between 0 and 9 per second. This can be seen on the 0/90^o lay-up graphs (figures C.3, C.4 and C.13, C.14). The 0^o layers are always the last to fail and produce very high energys (see figures C.3, C.4, C.7, C.8). Clearly the energy and event rates for the different kinds of layers is quantifiable to a certain extent, but obviously depends on the machine settings and type of material. If these parameters are specified, it may be easy to detect and identify a ply failure during testing.

Conversely, the angle of the ply failing may be deduced from the AE results, and therefore the direction of the stress causing the failure. More tests on laminates with other angled plies need to be carried out to assess the feasability of this.

To summarize, the ply failure detection procedure was as follows:

1) Plot graphs of event rate and energy vs load.
2) Obtain energy and event rate data ranges for the ply

orientations which are being looked for. Unidirectional laminates are no good for this. Use laminates where one ply failure will be obvious, eg 0/90° tension specimen laminate for 90° ply failure data.

3) Decide how many ply failures are likely to occur, and where they are likely to occur, ie. do a laminate failure prediction using a suitable reliable criterion such as the Maximum Stress criterion. Acoustic emission data from plies which fail at nearly the same load is not likely to be seperated, and might be one long set of high energy data.

4) Identify the ply failures by superimposing the event rate and energy vs load plots. Ply failures are characterized by relatively high peaks or groups of peaks.

All the acoustic emission results indicate that ultimate failure is normally preceded by high duration delamination in most of the multi-orientated laminates. These are also high energy occurrences. In unidirectional laminates, where all the layers fail at the same time, it is far more difficult to predict when failure is about to occur. Failure is usually fast. The 0° laminates fail with a brush-type failure, with matrix failing completely well before the fibre failure.

The high event rate and low energy for 45° layers may be due to many small cracks growing quickly in the brittle matrix, but stopping at fibres. There may also be much secondary emissions due to inter fibre and interlaminar rubbing. A 90° layer may have cracks which grow quickly across the entire width of the specimen, causing a high energy occurrence.

From the above, the +-45° layer failure after a 90° layer failure can be seen from where the event rate begins to rise and the energy begins to drop. Energy and event rate vs loa. curves are superimposed on figures 6.1 to 6.4 for the different layed up laminates. The points where the divergences begin can clearly be seen.

On all the AE plots, it can be seen that in general, a steep rise in energy is accompanied by a drop in event rate. This may be due to the instrumentation in that long high energy events take more time to log, causing the data acquisition unit to log fewer of them in a second, especially near failure when long duration delamination events occur. The actual event rate is probably still high for high energy event periods.

Figures C.21 to C.30 show the duration times vs load. If these results are compared to the energy vs load results (figures C.1 to C.10), it can clearly be seen how similar the two parameters are, as predicted. The low duration times in a 45° layer (seen on the +-45° lay-up graph in figures C.21 and C.22) compared to a 90° or 0° layer indicates less delamination, and a predominance of matrix cracking. From the energy graphs it is clear that the main type of failures in a 45° layer are low energy occurrences such as matrix cracking, and very little fibre breakage and delamination. It was observed that the +-45° specimens failed cleanly with minimal fibre breakage. The higher energy occurrences which are seen in a 90° layer failure are probably caused mainly by interlaminar effects such as delamination, since a 90° layer on its own produces very little high energy AE, and very little AE in total.

6.3.2 Failure criteria

Tables 5.3.15 to 5.3.18 show the percentage differences between the theoretical and experimental failure results. It can be seen that certain ply failures were well predicted by most of the criteria, whereas others were in general badly predicted. The following plys were predicted to within 10 % accuracy by most of the criteria:

both 0/90° plys, +-45° ply in 0/+-45° laminate, 90/+-45° failure, first and second ply failures in 0/90/+-45° laminate.

- 0/90° laminate

The first ply was well predicted by all the criteria (<3% error) except the Goldenblat-Kopnov. The last ply failure was predicted well by the non-interactive criteria (<8.5% error). The Norris Distortional, Fischer, Tsai-Wu, Maximum Strain, Puck Simple and Puck Modified criteria produced accurate results for both ply failures. The basic interactive equation with no additional terms was too conservative in predicting last ply failure.

- 0/+-45 laminate

No criterion predicted the +-45° layer failure well, the Maximum Stress being closest with 33.7% underpredicted. The interference between the 0° layers and the +-45° layers may have contributed to the high failure load of the +-45° layers. The 0° layers were well predicted by the non-interactive criteria (<4% error). The interactively termed criteria were too conservative (most over 30% error).

- 90/+-45 laminate

The 90° layer failure was well predicted by all the criteria (<5% error). The +-45° layer failure was best predicted by the Maximum Stress criterion (<10% error), followed by the Fischer and Tsai-Wu criteria (<17% error). The other criteria produced more conservative predictions, most of them underpredicting by 20%.

- 0/90/+-45 laminate

The 90° layer was well predicted by all the criteria (<8% error). The interactively termed criteria produced the best results for the +-45° layer failure. The best predictions for the 90° and +-45° layers were from the Norris Distortional, Tsai-Wu and Fischer criteria (<4% error). The last ply failure overpredicted by around 30% by all the criteria except the Fischer, Norris Distortional and Puppo-Evensen criteria, which overpredicted by less than 16.1%.

From the results, the criteria can be grouped into theories which produce similar results:

(i) Max. Stress, Max. Strain, Puck Simple, Puck Modified (Criteria with non-interactive terms)

(ii) Tsai-Hill, Norris-McKinnon, Hoffman, Hill (Interactively termed criteria with no or less significant correction factors)

(iii) Puppo-Evensen, Norris-Distortional, Fischer, Tsai-Wu (Interactively termed criteria with significant correction factors)

The Tsai-Wu criterion produced more accurate results than the similarly derived Hoffman criterion.

Only one criterion produced substantially different results and was unreliable, that being the Goldenblat-Kopnov criterion. It is also the most complicated of the criteria tested. The value of the material constant A_{12} used in the Goldenblat-Kopnov criterion was deduced from the acoustic emission results for the +-45^{o} specimens. In the Tsai-Wu criterion, the approximation detailed in reference (22) was used. The Goldenblat-Kopnov more conservative predictions, most of them underpredicting by 20%.

- 0/90/+-45 laminate

The 90° layer was well predicted by all the criteria (<8% error). The interactively termed criteria produced the best results for the +-45° layer failure. The best predictions for the 90° and +-45° layers were from the Norris Distortional, Tsai-Wu and Fischer criteria (<4% error). The last ply failure overpredicted by around 30% by all the criteria except the Fischer, Norris Distortional and Puppo-Evensen criteria, which overpredicted by less than 16.1%.

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- (iii) Puppo-Evensen, Norris-Distortional, Fischer, Tsai-Wu (Interactively termed criteria with significant correction factors)

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Certain lay-ups and plys were predicted better by certain theories, eg all the 0/90/+-45° lay-up ply failures were best predicted by the theories in group three above, and the 0/+-45° lay-up ply failures were best predicted by the group one theories. The 0/90° and 90/+-45° ply failures were best predicted by the group one and three criteria. Figure 6.1 shows a 0/90° energy/event rate vs load AE plot with the Maximum Stress and Fischer criteria failure predictions shown. Figures 6.2 to 6.4 show the same plot for 90/+-45°, 0/90/+-45° and 0/+-45° lay-ups. The ply failures can clearly be seen compared to the predicted failure points. These graphs give an indication of the relative accuracy of the failure predictions.

Figure 6.1 0/90 lay-up

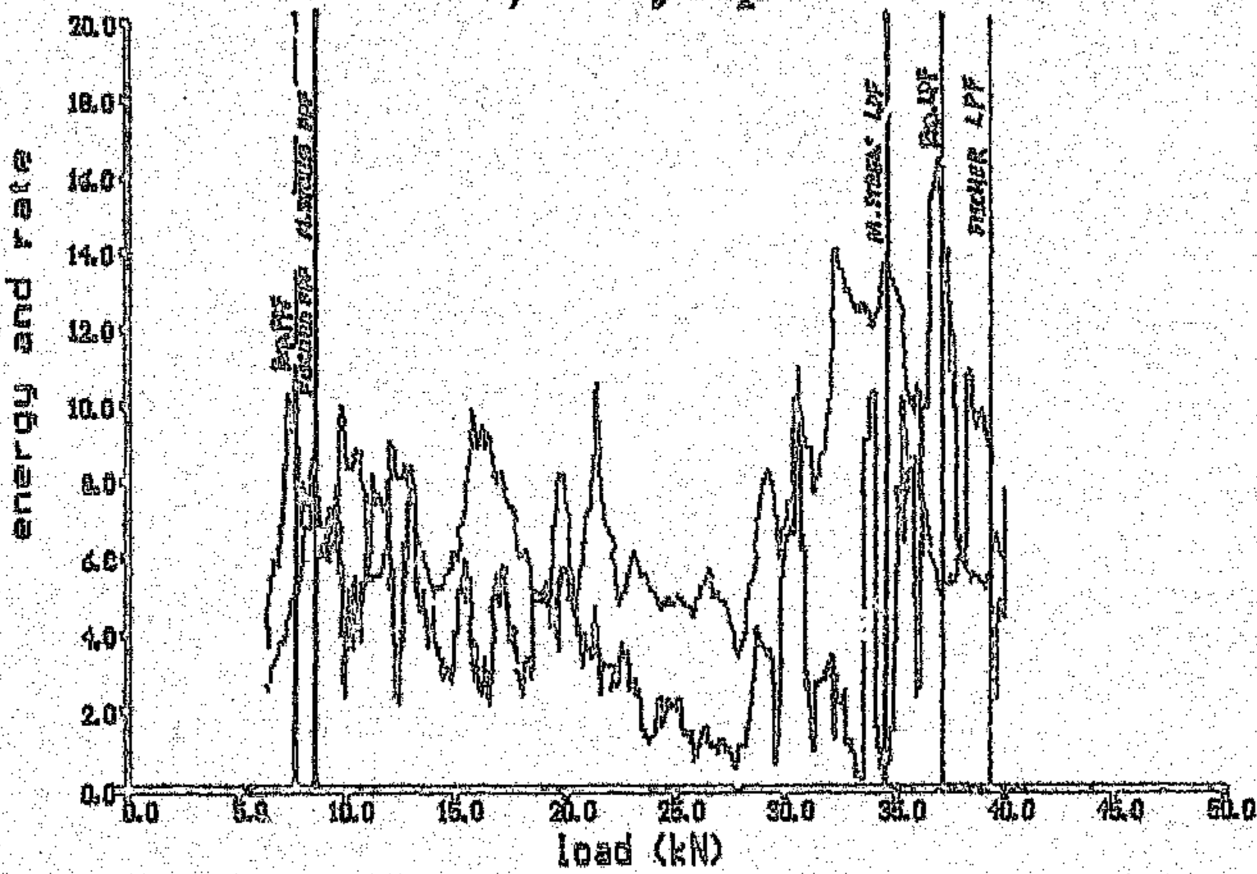


Figure 6.2 90/+-45 lay-up

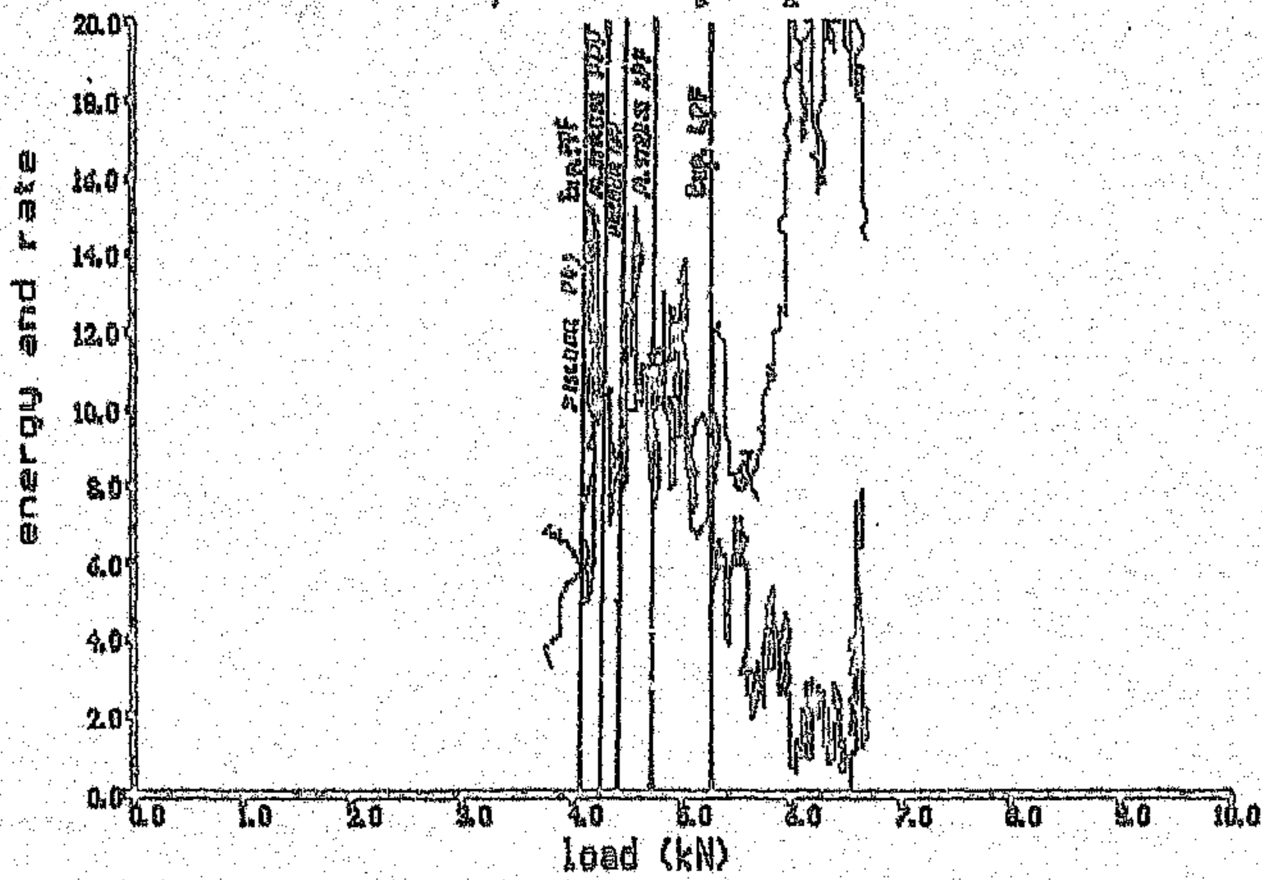


Figure 6.3 0/90/+-45 lay-up

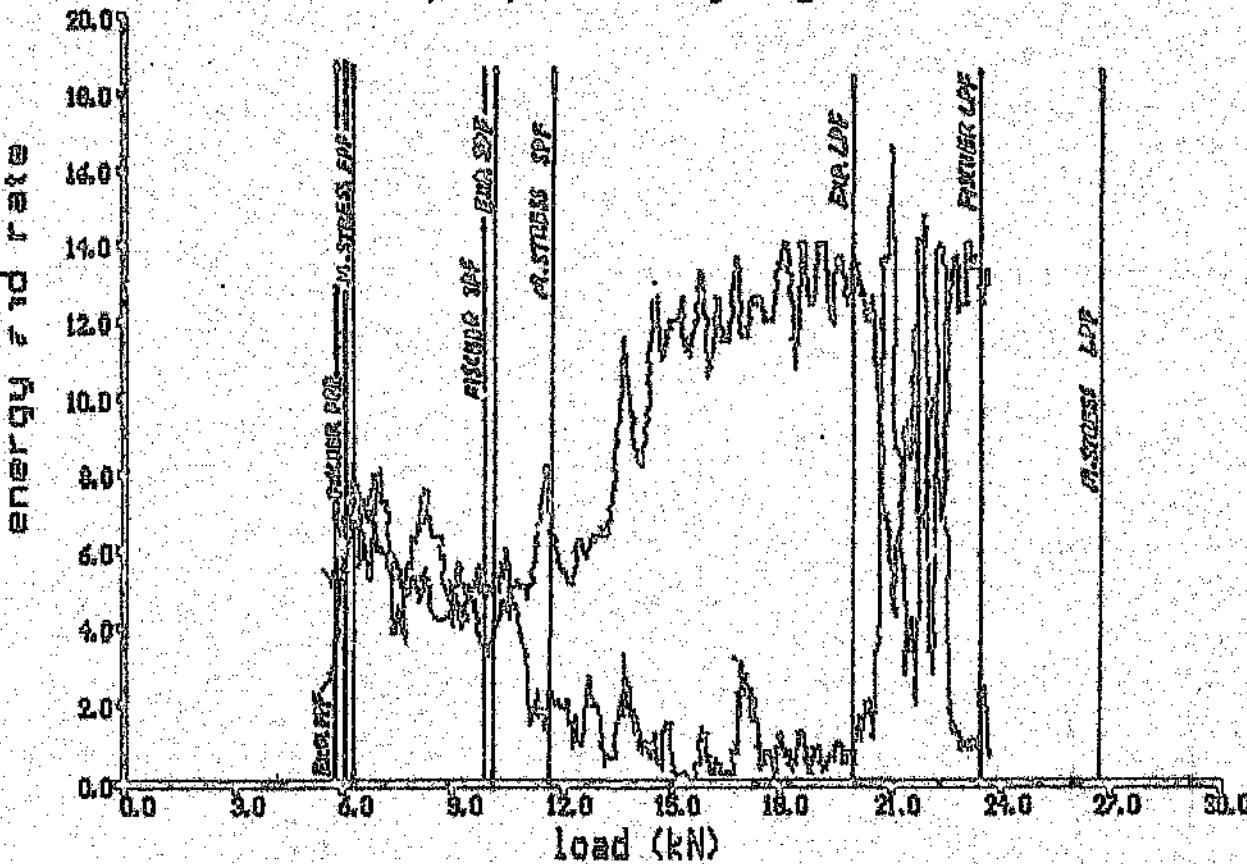


Figure 6.4 0/+-45 lay-up

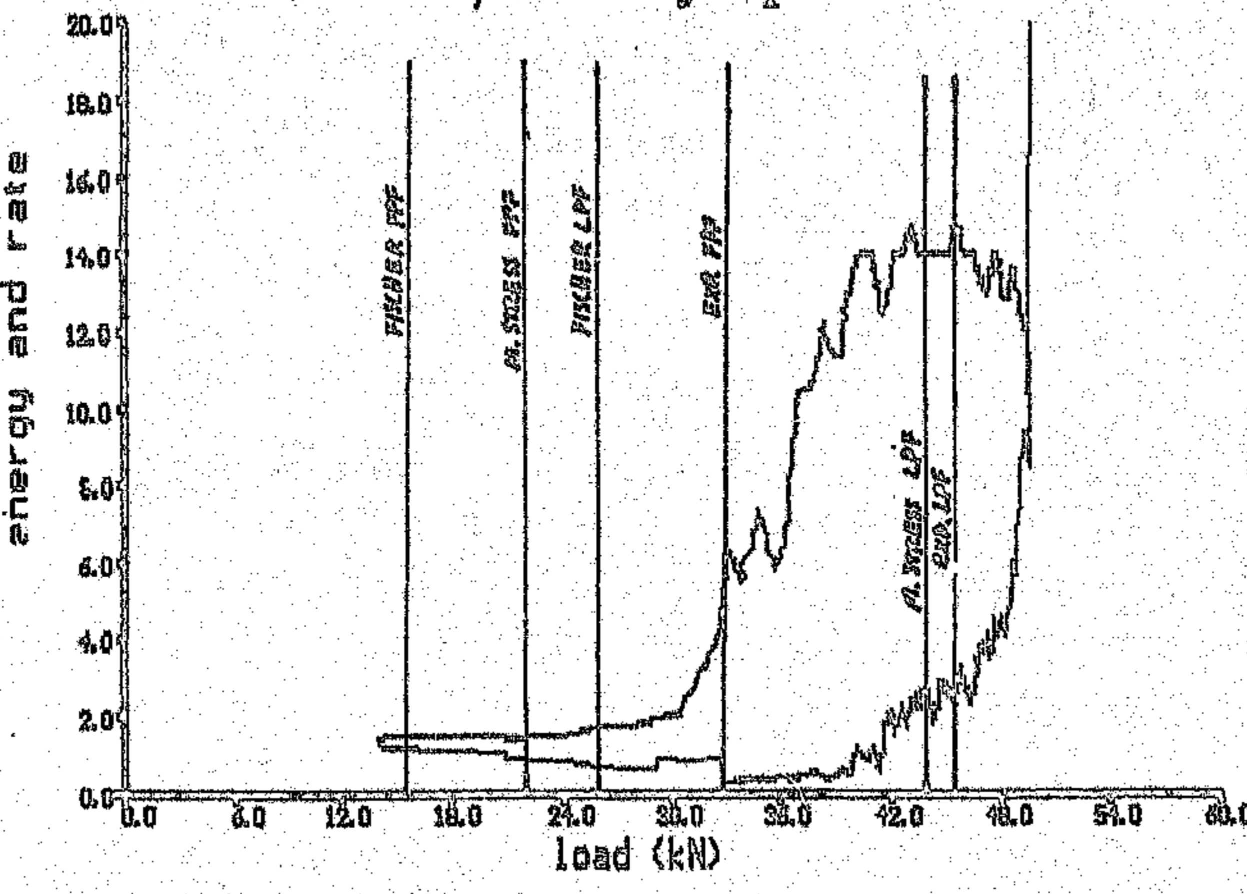


Figure 6.3 0/90/+-45 lay-up

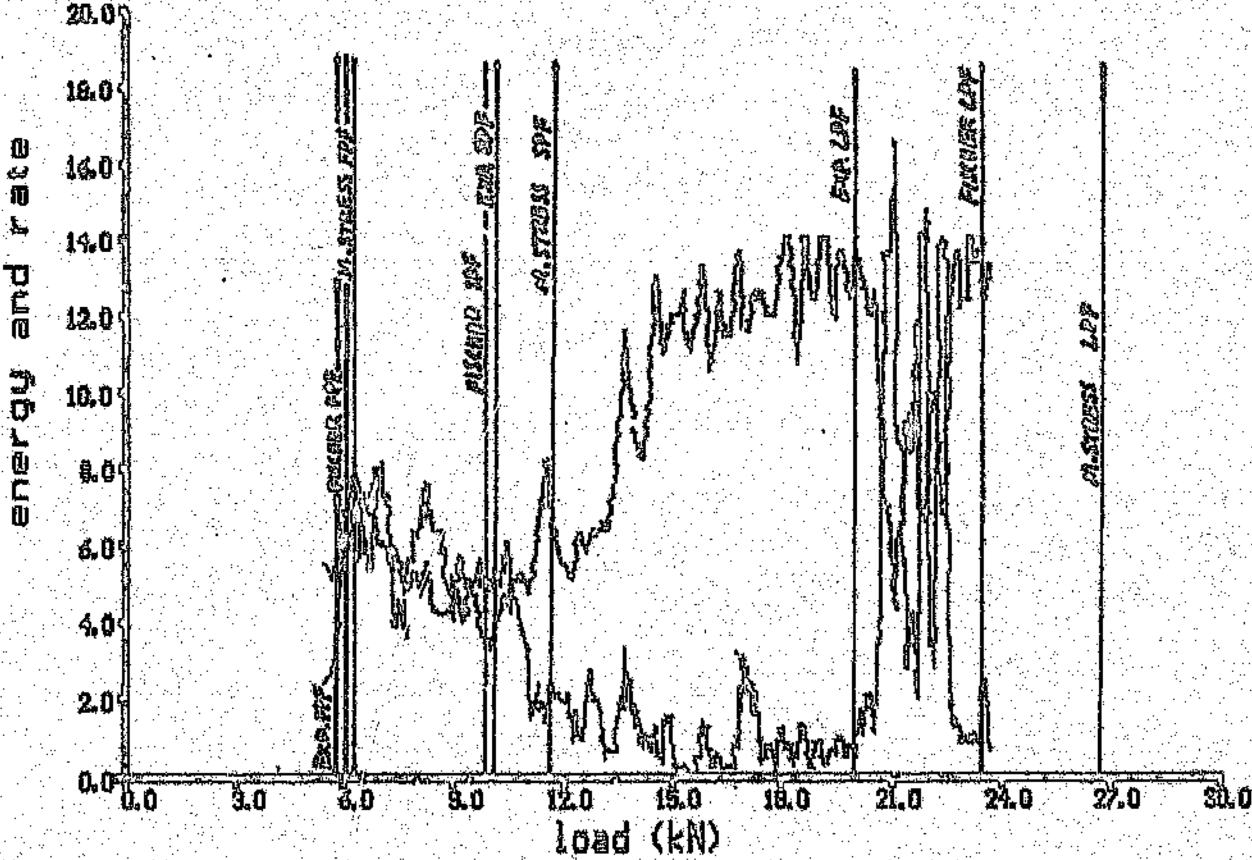
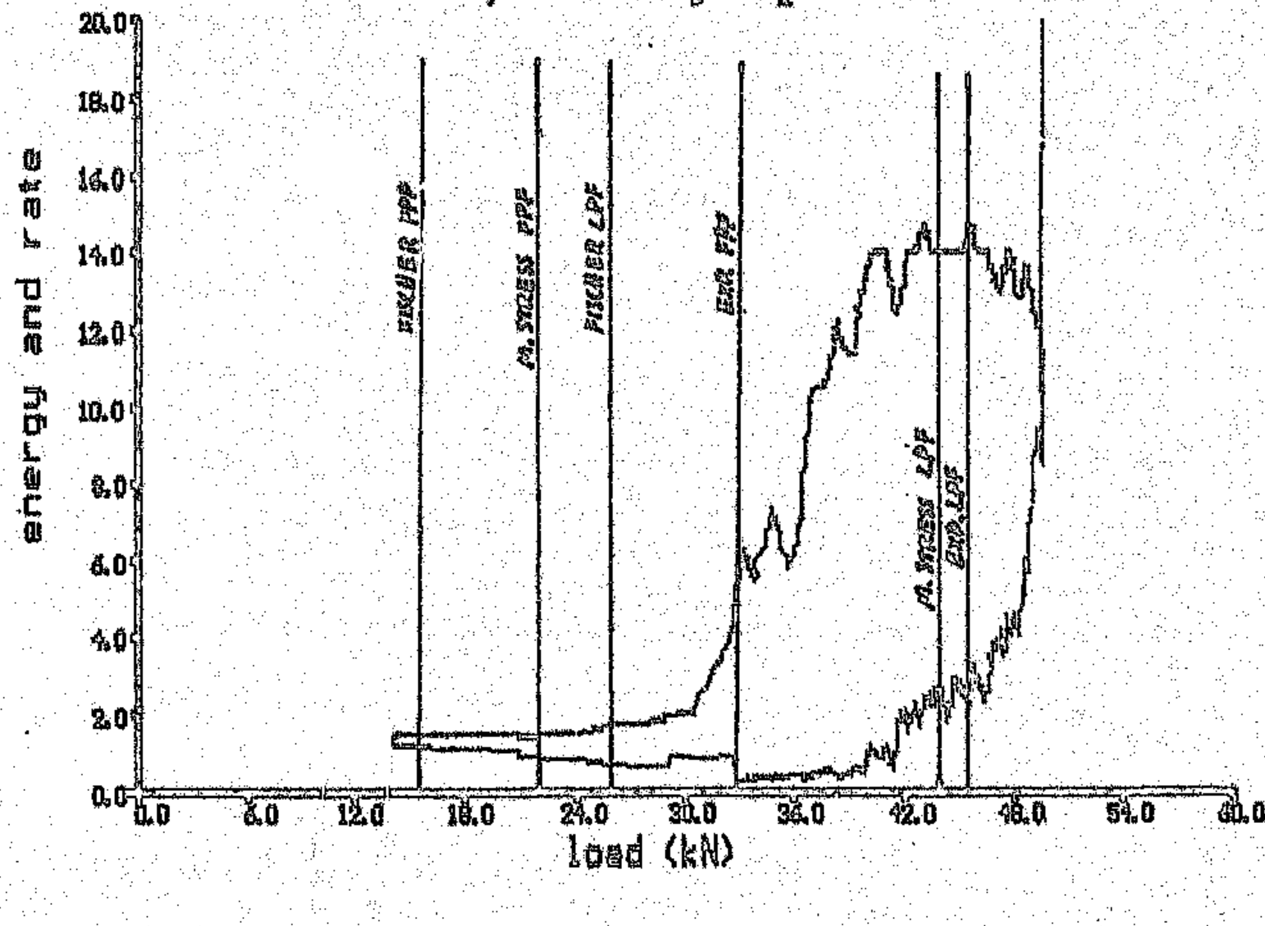


Figure 6.4 0/+-45 lay-up



6.4 Summary of Results

The previous AE result graphs from the first set of tests were printed directly from the AE computer. The data could not be properly analysed and the graphs were of poor quality compared to the second set of data results. This underlines the importance of having the data in an IBM DOS compatible form.

On comparing the failure predictions for the two types of material tested, it is clear that the second set of failure predictions were far more accurate than the first, perhaps partly due to the improved ply failure determination method and better data analysis as discussed above. It may also partly be due to the different material used, carbon fibre RP being very different in nature to glass fibre RP. The stiffness difference between the carbon fibres and the matrix is obviously more than that for the glass fibres. The in-plane shear strength was badly predicted by the +-45° specimen tests in the carbon fibre specimen case, whereas it was well predicted in the glass fibre specimen case. It has been suggested previously (6) that failure prediction accuracy is very dependent on type of material.

Tables 6.1 and 6.2 provide a guide to the best criteria to use, according to the results presented in this report. The same type of criteria should be used for all the laminates for both materials except the 0/90/+-45° laminate, where a group III criterion can be used for the first and last plies of both materials, but a group II criterion should be used for the +-45° carbon fibre layer and a group III criterion for the +-45° glass fibre layer.

Table 6.1 Carbon Fibre

Lay-up Orientations	Layer	Most Accurate Criteria Group +: Overprediction -:Underprediction
0/90	90	I, II and III
	0	+II
0/+-45	+-45	-I
90/+-45	90	+III
	+-45	III
0/90/+-45	90	+III
	+-45	+II
	0	I, II and III

Table 6.2 Glass Fibre

Lay-up Orientations	Layer	Most Accurate Criteria Group +: Overprediction -:Underprediction
0/90	90	I, II and III
	0	-I,II
0/+-45	+-45	-I
90/+-45	90	+III
	+-45	III
0/90/+-45	90	+I, II, III
	+-45	III
	0	+III

Suggested Criteria:
Group I - Maximum Stress
Group II - Tsai-Hill, Norris-McKinnon
Group III - Norris Distortional, Fischer, Tsai-Wu

6.5 Acoustic Emission in NDT

Predicting when failure is going to occur accurately using acoustic emission is a complex problem and will require further research. The onset of high energy failures such as fibre fracture and delamination can easily be detected, using a non-cumulative energy vs hits graph, as was done for the carbon fibre specimens, or by investigating when the high amplitude events begin occurring, using an amplitude vs load plot. Failure occurs at a load after the first fibre failures depending on the fibre orientations. The onset of AE can occur well before final failure, and depends on the fibre orientations in the lay-up.

By monitoring the number of hits at a specified load, it should be possible to determine the remaining strength of the material. This method was found to be unreliable in this research, with such predictions in general not possible, over the strength variation of the specimens tested. This was the case even though some specimens had flaws introduced deliberately during the manufacturing procedure. Nevertheless it may be possible to detect very significant variations in strength, such as those produced by very large flaws.

Using the methods of data analysis used for the second set of glass fibre specimens, it would be possible to determine which ply is failing as it occurs.

At this stage confidence in using acoustic emission is thus limited and a great deal more experience should be acquired before a final decision as to its overall suitability for NDT is made.

7 CONCLUSIONS

1) A failure criterion should be chosen according to the type of laminate and the ply failure to be predicted, and the type of material.

2) Ply failures were detected using acoustic emission energy and event rate vs load graphs. Different ply failures are quantifiable in terms of these parameters, according to the instrumentation settings and type of material. Numerical techniques should be used to facilitate data analysis, since large quantities of widely scattered data are produced from acoustic emission.

4) The Felicity Ratio did not provide accurate or reliable information as to when ultimate failure was to occur. The Felicity Ratio depends on the ply orientations of the laminate.

5) The onset of high energy failures such as fibre failure and delamination near failure can be detected by monitoring high amplitude ocurrences or high energy occurrences.

6) Acoustic emission is an accepted NDT method, but further research is required to understand it more thoroughly.

7) The quantity of counts and hits at a certain load is dependent on coupling efficiency. The counts vs hits results did not provide accurate or reliable information as to when ultimate failure was to occur.

8 RECOMMENDATIONS

1) The amplitude peak events should be correlated with rise times, duration times and counts to establish without doubt what the significance of these parameters with regard to failure modes is. Each event should be classed according to its duration times and amplitudes, and the three failure modes may then be distinguished event for event.

3) The shear modulus for the material should be calculated by means of a +-45° lay-up specimen test and the shear strength should be calculated by a torsion tube test for more accurate results (21). These results may compare favourably with those obtained from AE testing of +-45° specimens.

4) The superimposition of events vs load plots with stress-strain curves may be useful in order to relate ply failures directly to acoustic emission activity. This may help in future research to identify ply failures using acoustic emission.

5) Other ply orientations should also be tested such as laminates with 15°, 30° or 60° layers.

6) The Petit-Waddoups and Sandhu theories should be evaluated for both glass and carbon fibre reinforced specimens.

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APPENDIX A

A.1 SAMPLE CALCULATIONS

A.1.1 Material properties

For 90 degree laminate area = t x w

= 3.03 x 19.81

= 60.02 mm^2

$$E_2 = \frac{\sigma_2}{\varepsilon_2}$$

$$= \frac{\left(\frac{dF}{area}\right)}{\left(\frac{dL}{L_o}\right)}$$

$$= \frac{dF}{area} \times \frac{50}{dL}$$

$$= \frac{2000}{60.02} \times \frac{50}{0.121}$$

$$= 13\,724 \ MPa$$

for +-45 degree laminate

$$\nu_{xy} = \frac{transversestrain}{longitudinalstrain}$$

$$= \frac{53}{80} = 0.663$$

Cross-sectional area

$$area = t \times w = \frac{53}{80} = 0.663$$

$$G = \frac{E}{2.(1 + \nu)}$$

$$= \frac{\left(\frac{dF}{2.area}\right)}{\left(\frac{dL}{} \frac{(1 + \nu)}{50}\right)}$$

$$= \frac{dF.50}{2.area.dL.(1 + \nu)}$$

$$\frac{8000 \times 50}{2 \times 60.02 \times 0.464 \times (1 + 0.699)}$$

$$= 4\,227\ MPa$$

$$\sigma_{12} = \frac{F_{ut}}{2\ .\ area}$$

$$= \frac{13.4}{2 \times 60.02}$$

$$= 111.62\ MPa$$

A.1.2 Results

for 0/90/+-45 degree laminate

$$area = t \, . \, w$$

$$= 2.98 \times 19.99$$

$$= 59.57 \; mm^2$$

$$UTS = \frac{F_{ut}}{area}$$

$$= \frac{30}{59.57}$$

$$= 503.6 \; MPa$$

A.2 ERROR ANALYSIS

A.2.1 Failure Criteria

typical errors are :

D(df) = +- 0.5kN D(dL) = +- 0.001 mm

D(t) = D(w) = +- 0.1 mm

since A = t . w

$$\frac{D(A)}{A} = \frac{D(T)}{T} + \frac{D(W)}{W}$$

$$= \frac{0.1}{3.03} + \frac{0.1}{19.81}$$

$$= 3.81\ \%$$

since

$$E = \frac{dF}{area} \cdot \frac{50}{dL}$$

$$\frac{{}^{J}(E)}{E} = \frac{D(dF)}{dF} + \frac{D(area)}{area} + \frac{D(dL)}{dL}$$

$$= \frac{0.5}{8} + 0.0381 + \frac{0.001}{0.464}$$

$$= 10.3\ \%$$

since

$$\nu_{xy} = \frac{\varepsilon_y}{\varepsilon_x}$$

$$\frac{D(\nu_{xy})}{\nu_{xy}} = \frac{D(dL)}{dL} + \frac{D(dL)}{dL}$$

$$= 2 \cdot \left(\frac{0.001}{0.464}\right)$$

$$= 0.43\ \%$$

$$G = \frac{dF \cdot 50}{2.area.dL.(1 + \nu)}$$

$$\frac{D(G)}{G} = \frac{D(dF)}{dF} + \frac{D(area)}{area} + \frac{D(dL)}{dL} + \frac{D(\nu)}{\nu}$$

$$= 0.0625 + 0.0381 + 0.0022 + 0.0043$$

$$= 10.7\ \%$$

A.2.2 Acoustic Emission Graphs

The errors presented here arise due to the low graphical resolution of the acoustic emission plots, from which the first set of acoustic emission information was obtained.

Maximum error in voltage (para. main)

$$\frac{dV}{V} = \frac{1.3\ mm}{12.5\ mm}$$

(corresponding to one block)

$$= 0.104 \text{ or } 10.4\ \%$$

This error is the same for all the X-axis parameters on the acoustic emission graphs (amplitude, rise time, etc).

The maximum error for the Y-axis parameters is

$$\frac{dY}{Y} = \frac{0.96\ mm}{5.20\ mm}$$

$$= 0.185 \text{ or } 18.5\ \%$$

Obviously the incurred errors will be lower:

The error over the full Y-axis range will be

$$\frac{dY}{Y} = \frac{0.96\ mm}{53.0\ mm}$$

$$= 0.018 \text{ or } 1.8\ \%$$

The error over the full X-axis range will be

$$\frac{DX}{X} = \frac{1.3\ mm}{126.9\ mm}$$

$$= 0.010 \text{ or } 1.0\ \%$$

The errors in the results should be between the full axis range error and the maximum error.

APPENDIX B - Results from AE Computer

B.1 Carbon Fibre Reinforced Specimens

These plots were used to obtain ply failure information. Five plots were done for each specimen:

1) non-cumulative events vs amplitude histogram
2) non-cumulative events vs rise time histogram
3) non-cumulative amplitude vs load point plot
4) cumulative counts vs load line graph
5) non-cumulative events vs duration histogram

Two examples of all the plots of each lay-up type are included.

90° carbon fibre specimens

specimen 1

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HITS

FIRST ARRIVAL

GRAPH 1 OF 5

HITS = 56

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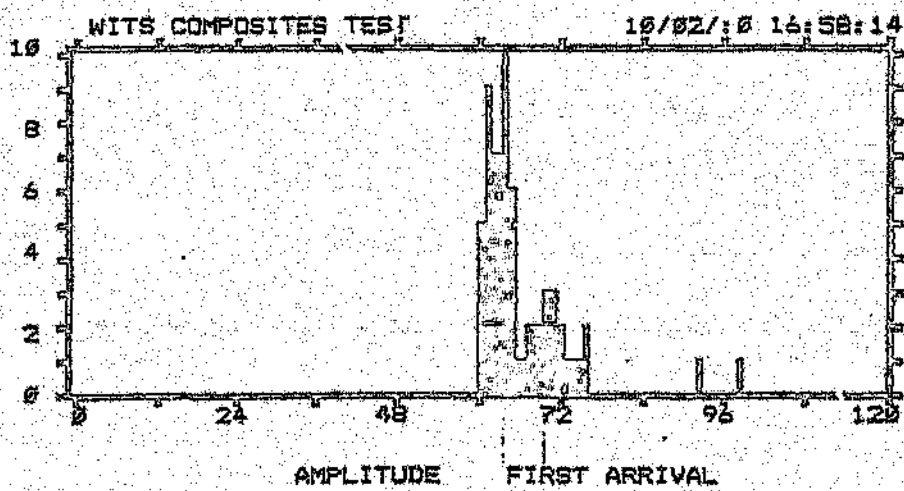

1 CH. A-Dump is ON

HITS

FIRST ARRIVAL

GRAPH 2 OF 5

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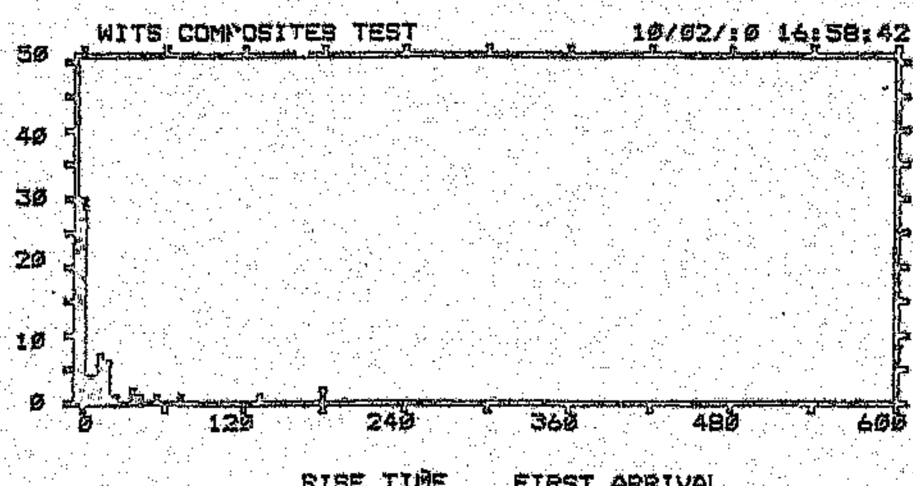

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AMPLITUDE

FIRST ARRIVAL

GRAPH 3 OF 5

HITS = 56

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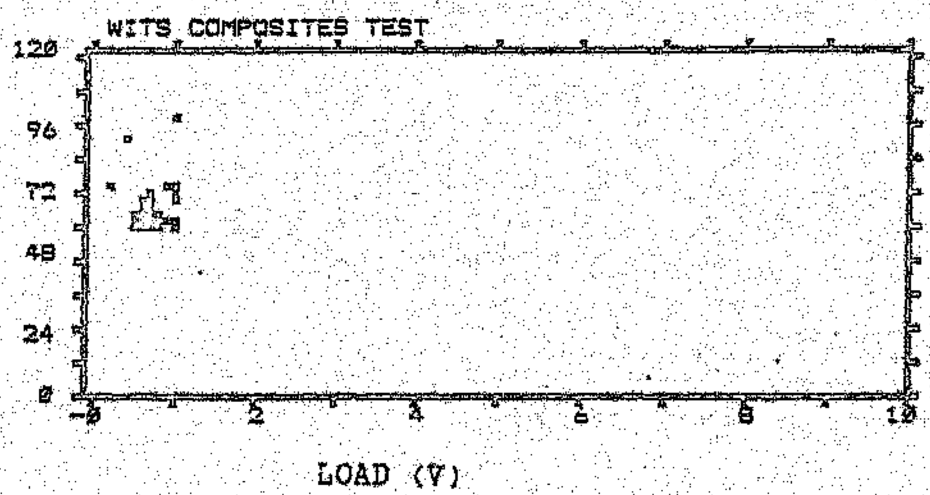

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COUNTS

FIRST ARRIVAL

GRAPH 4 OF 5

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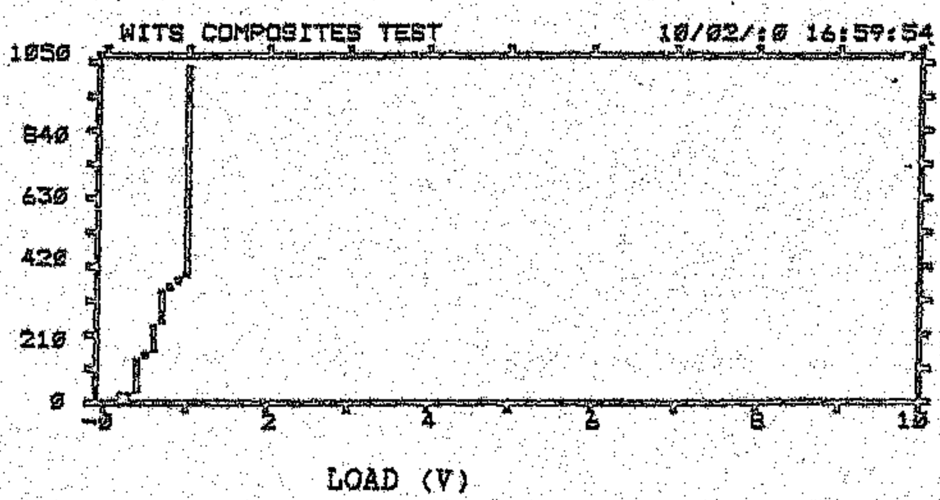

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GRAPH 5 OF 5

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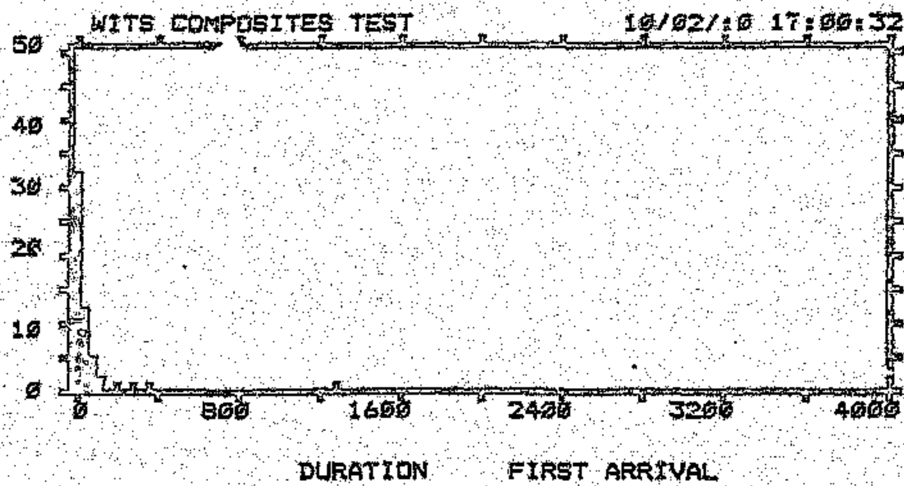

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GRAPH 1 OF 5

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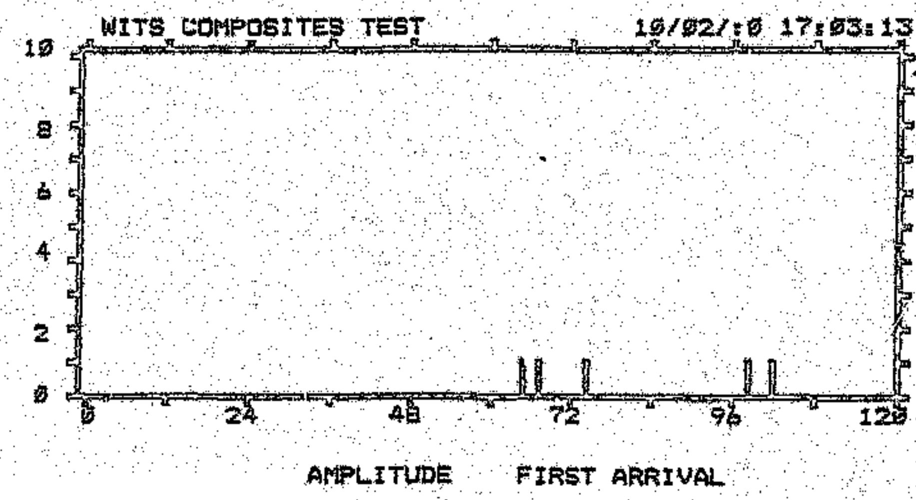

specimen 2

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HITS

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GRAPH 1 OF 5

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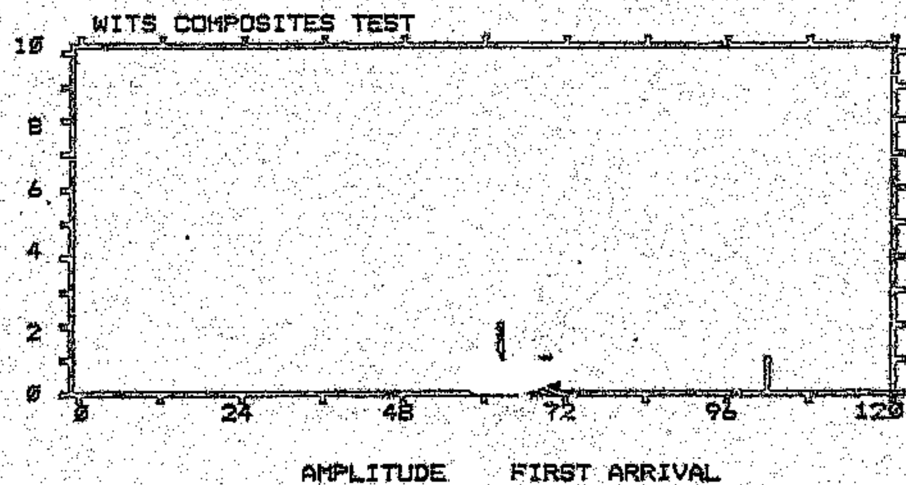

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HITS

FIRST ARRIVAL

GRAPH 2 OF 5

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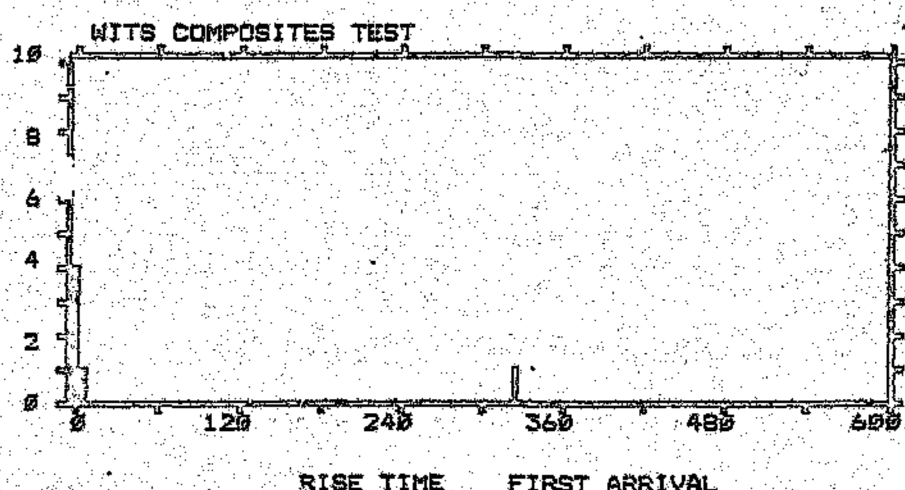

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AMPLITUDE

FIRST ARRIVAL

GRAPH 3 OF 5

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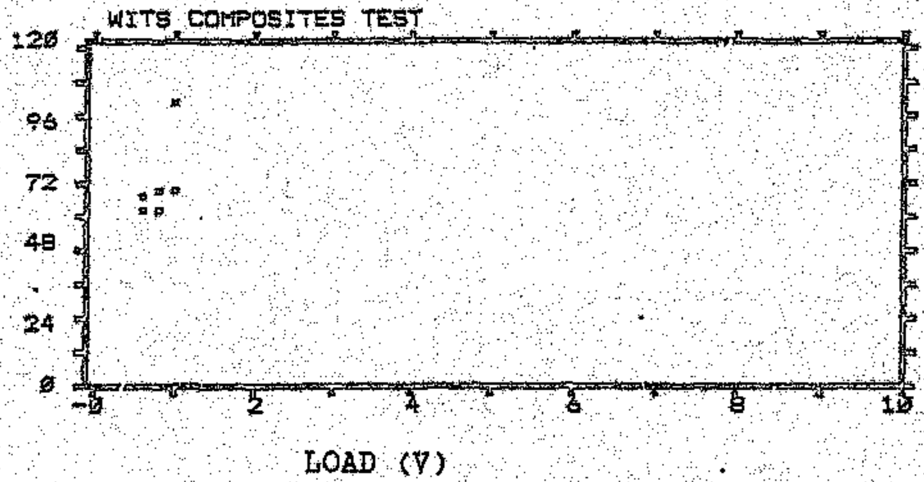

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COUNTS

FIRST ARRIVAL

GRAPH 4 OF 5

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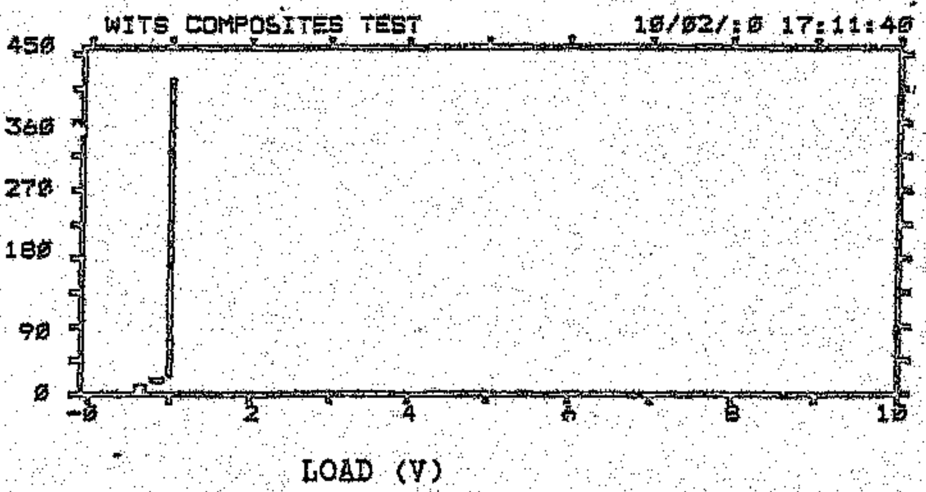

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FIRST ARRIVAL

GRAPH 5 OF 5

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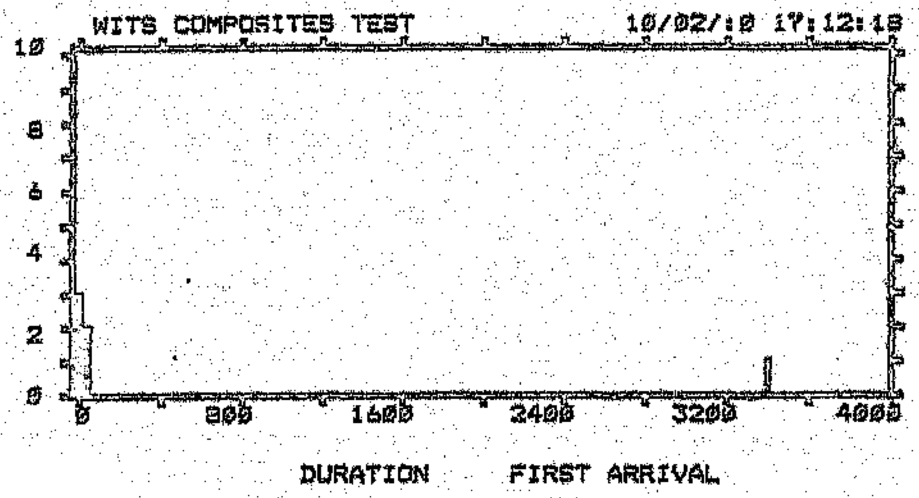

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FIRST ARRIVAL

GRAPH 1 OF 5

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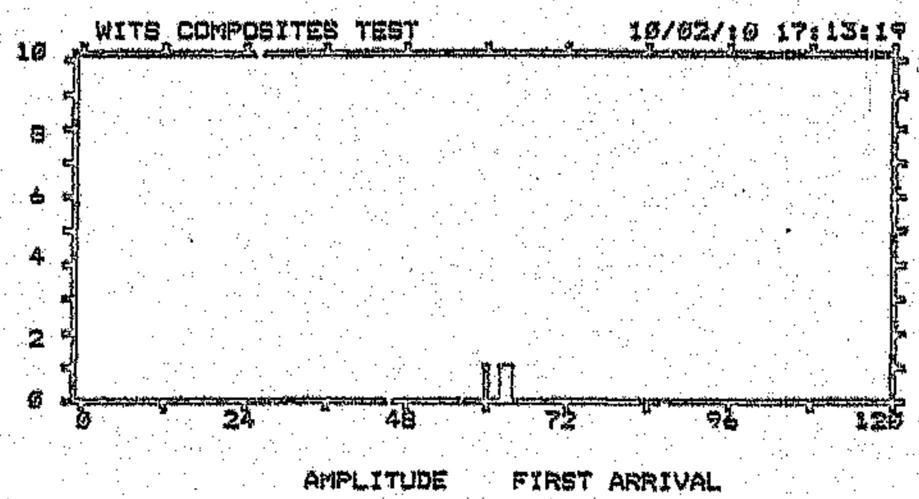

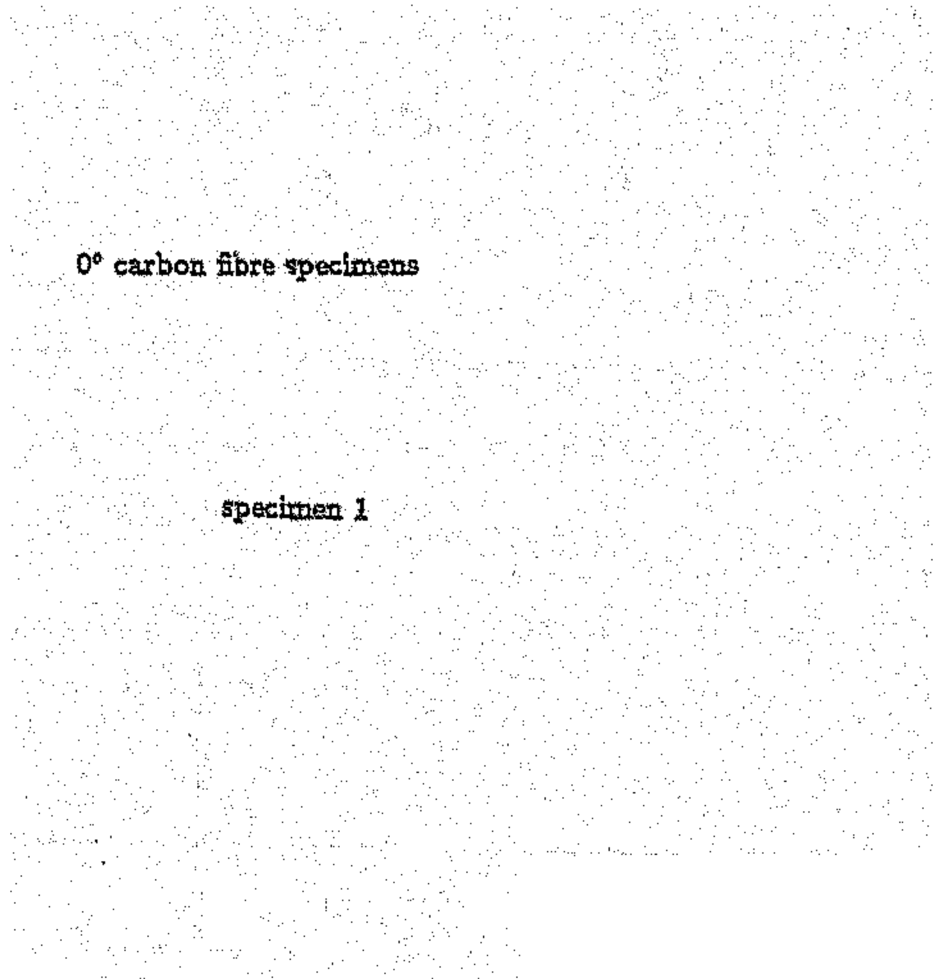
0° carbon fibre specimens
specimen 1

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HITS

FIRST ARRIVAL

GRAPH 1 OF 5

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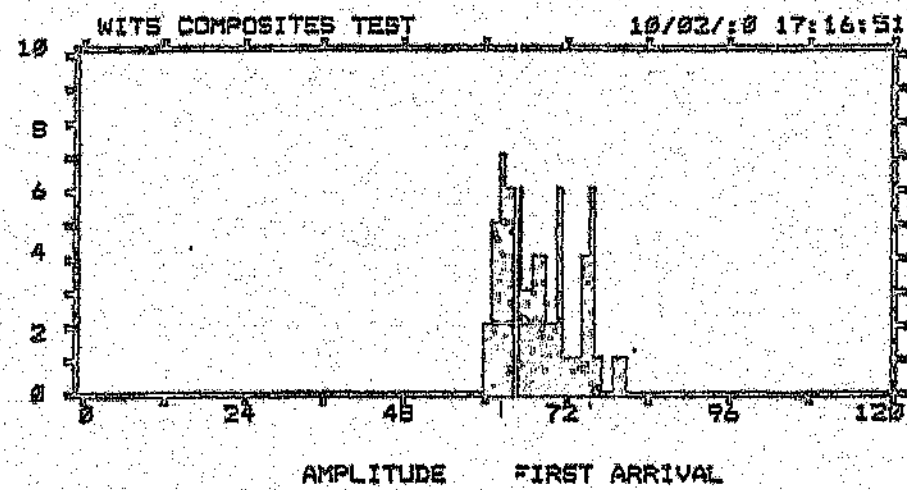

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FIRST ARRIVAL

GRAPH 2 OF 5

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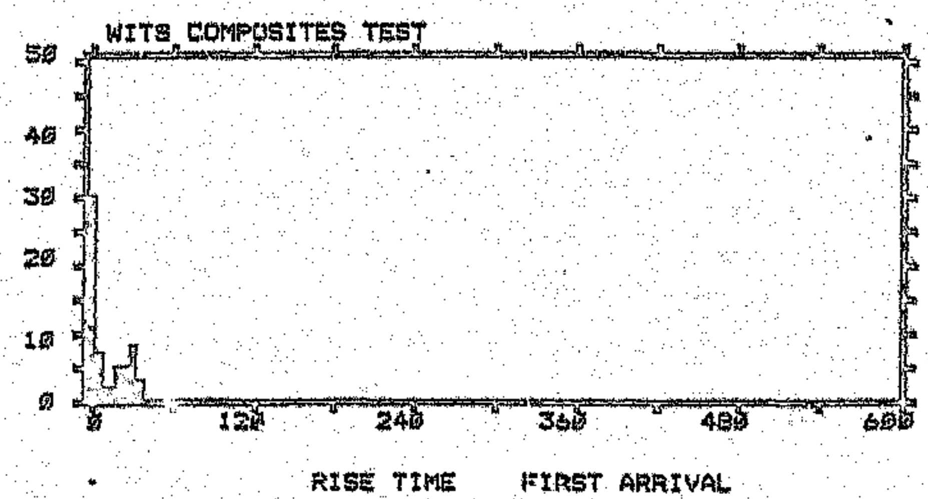

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AMPLITUDE

FIRST ARRIVAL

GRAPH 3 OF 5

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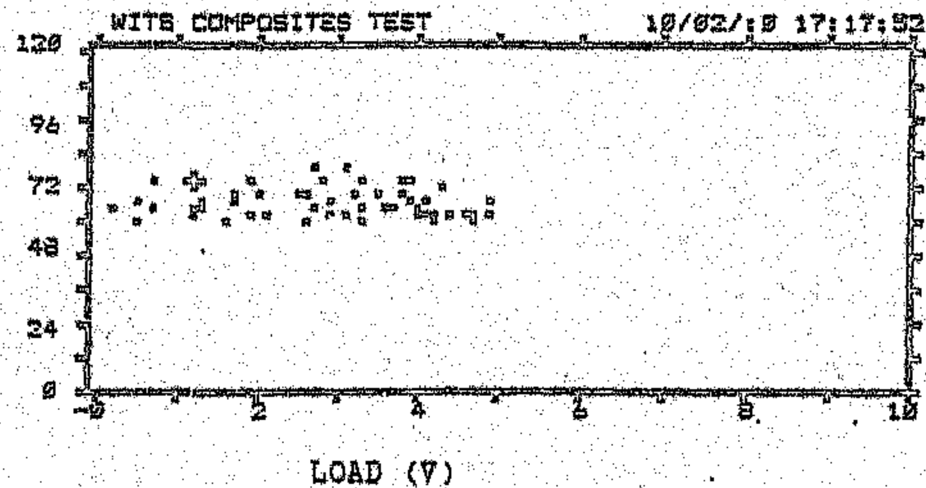

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FIRST ARRIVAL

GRAPH 4 OF 5

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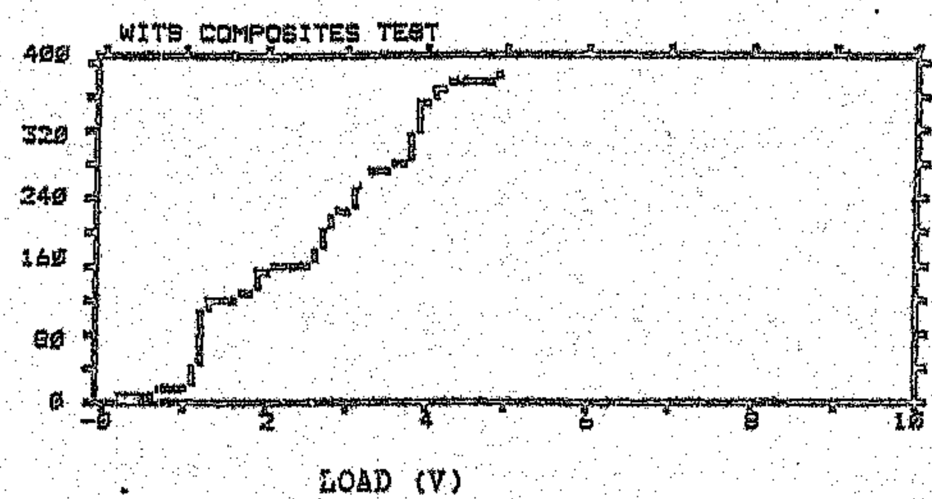

<: 1 CH. A-Dump is ON

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GRAPH 5 OF 5

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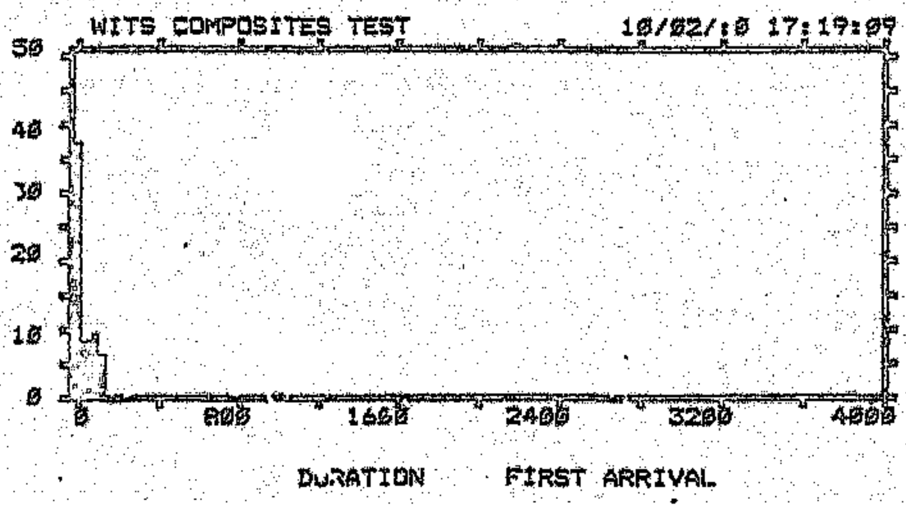

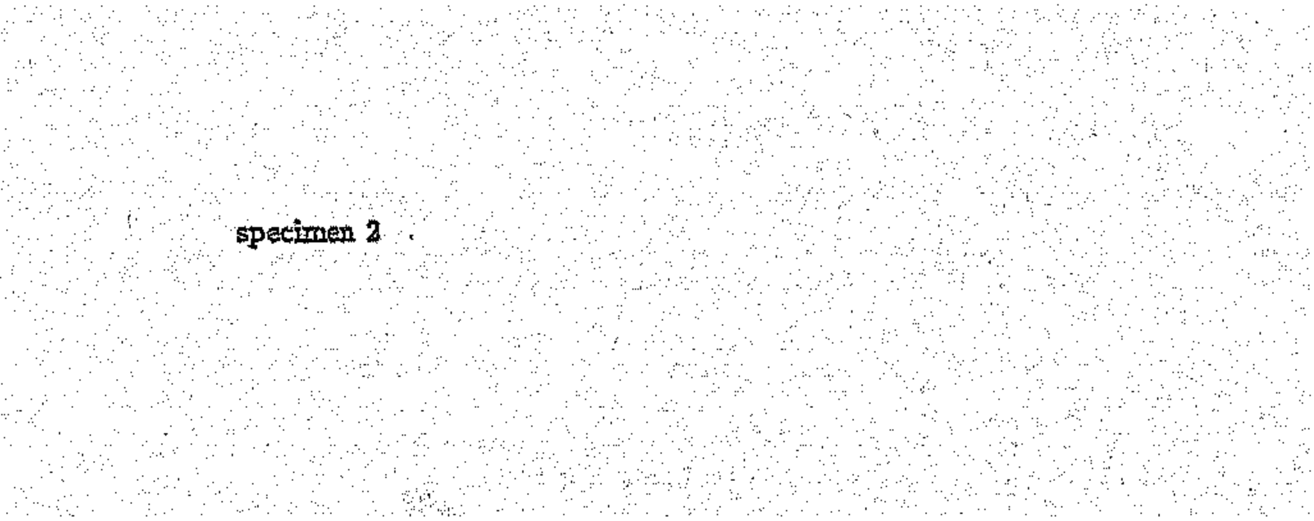
specimen 2

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FIRST ARRIVAL

GRAPH 1 OF 5

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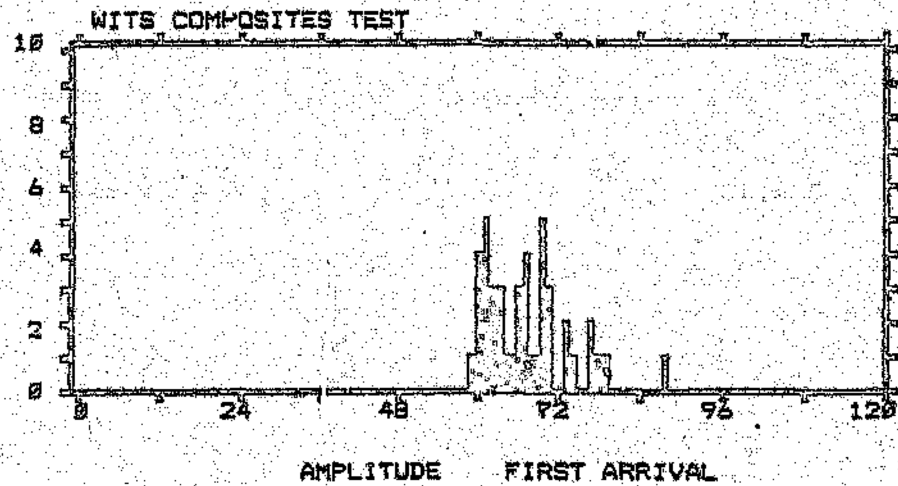

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FIRST ARRIVAL

GRAPH 2 OF 5

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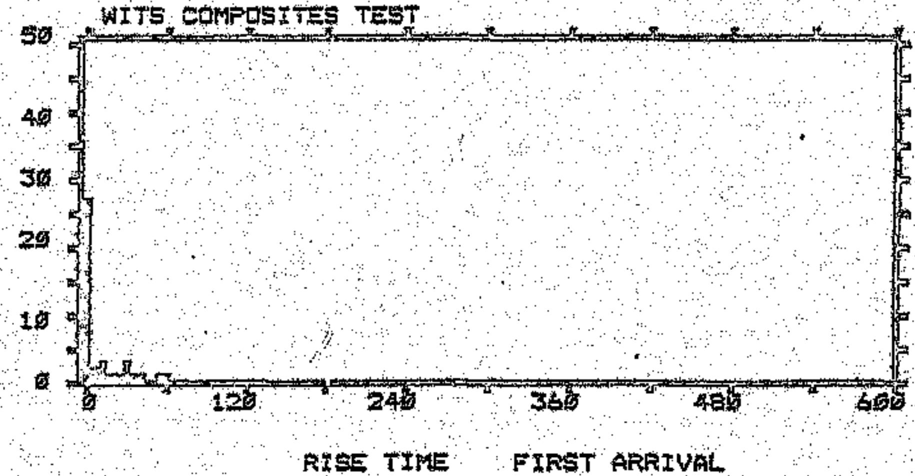

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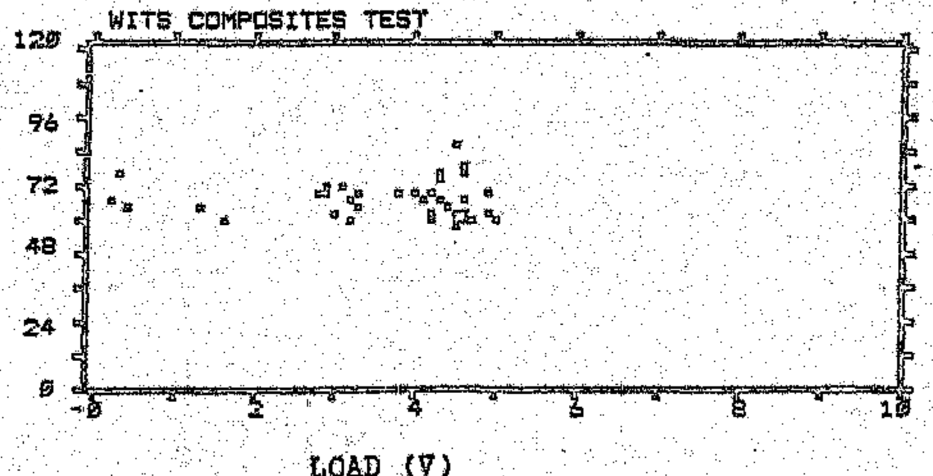

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GRAPH 4 OF 5

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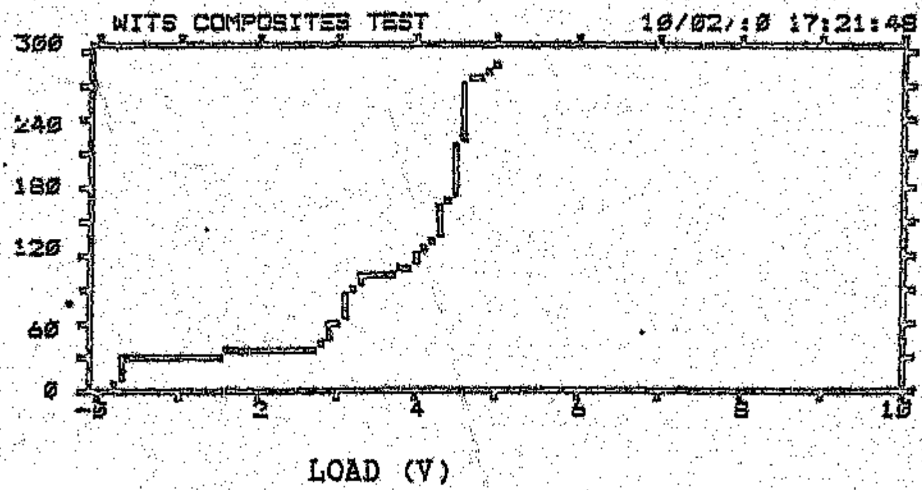

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GRAPH 5 OF 5

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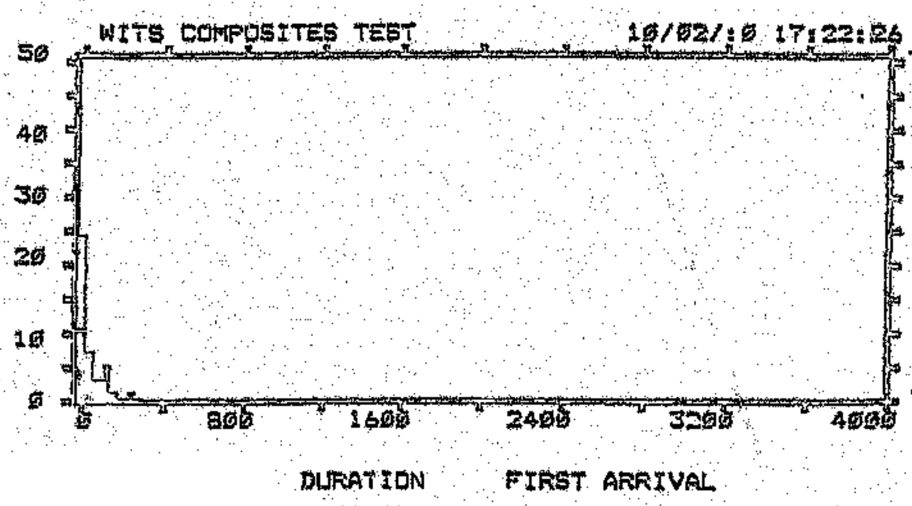

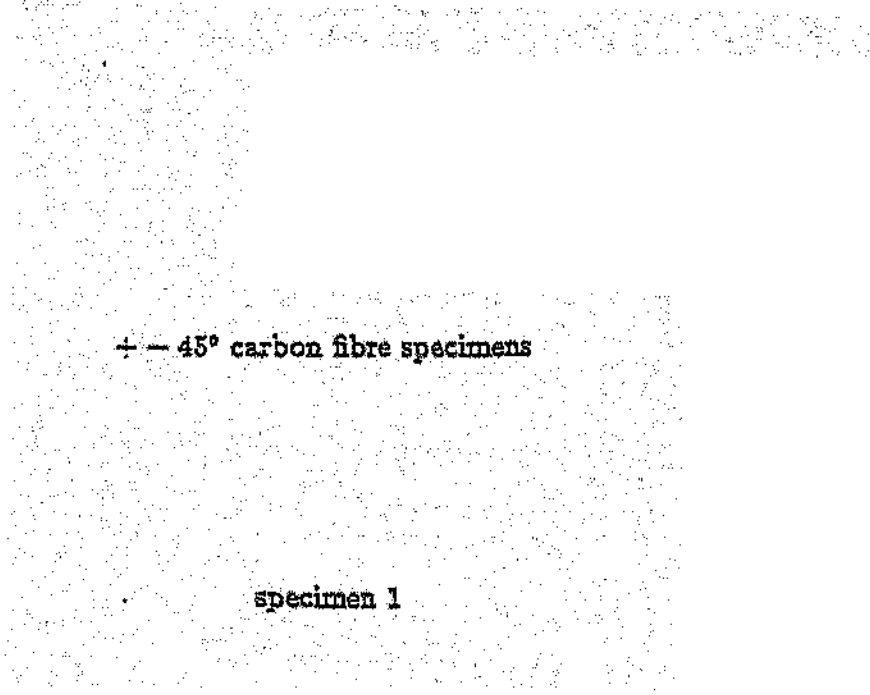
+ − 45° carbon fibre specimens
specimen 1

1 CH. A-Dump is ON

HITS

FIRST ARRIVAL

GRAPH 1 OF 5

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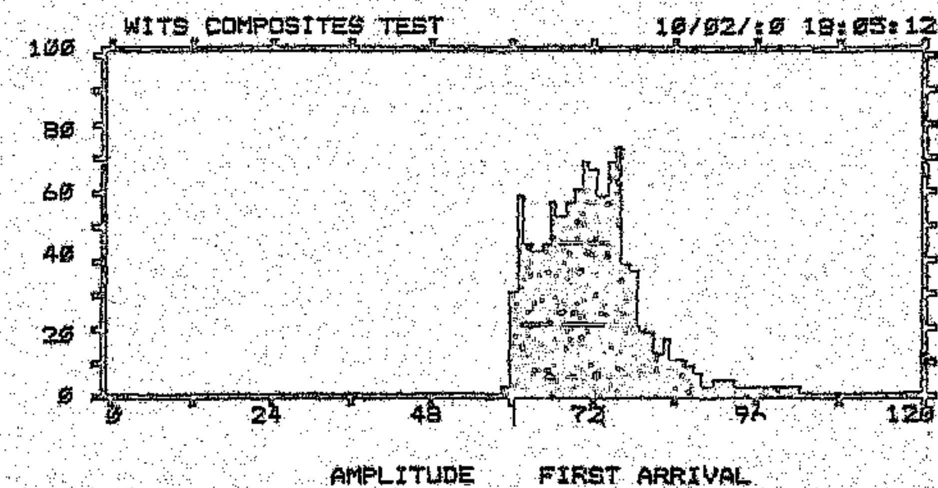

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FIRST ARRIVAL

GRAPH 2 OF 5

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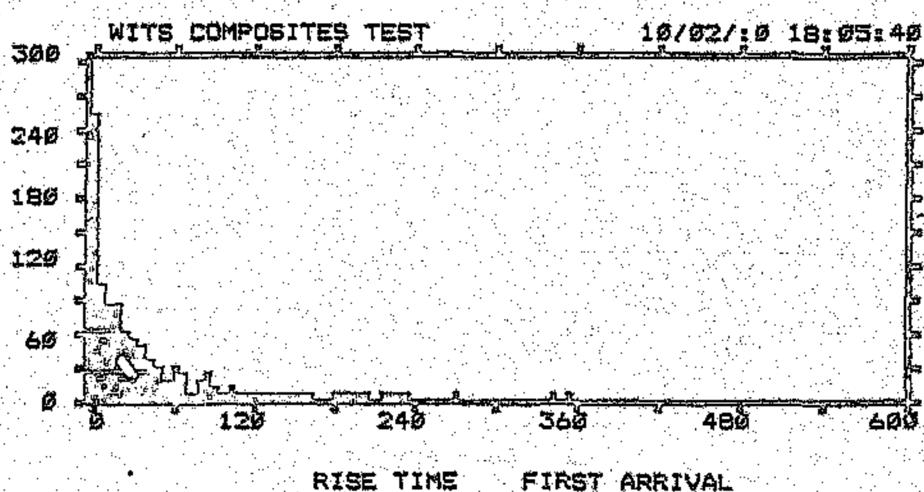

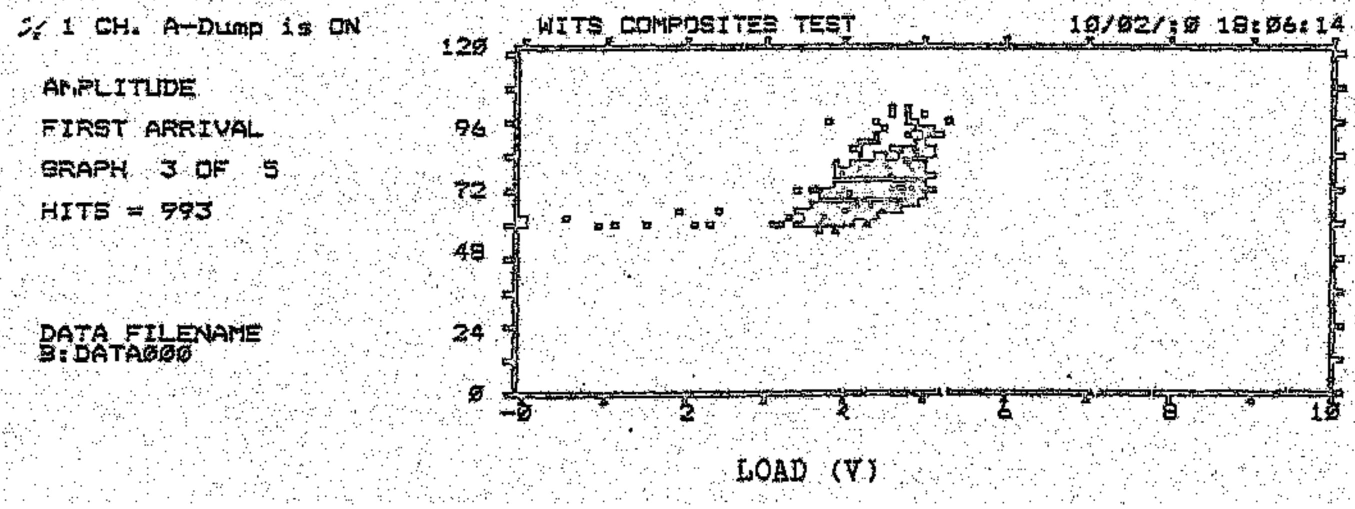
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WITS COMPOSITES TEST
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AMPLITUDE
FIRST ARRIVAL
GRAPH 3 OF 5
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B:DATA000
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96
72
48
24
0
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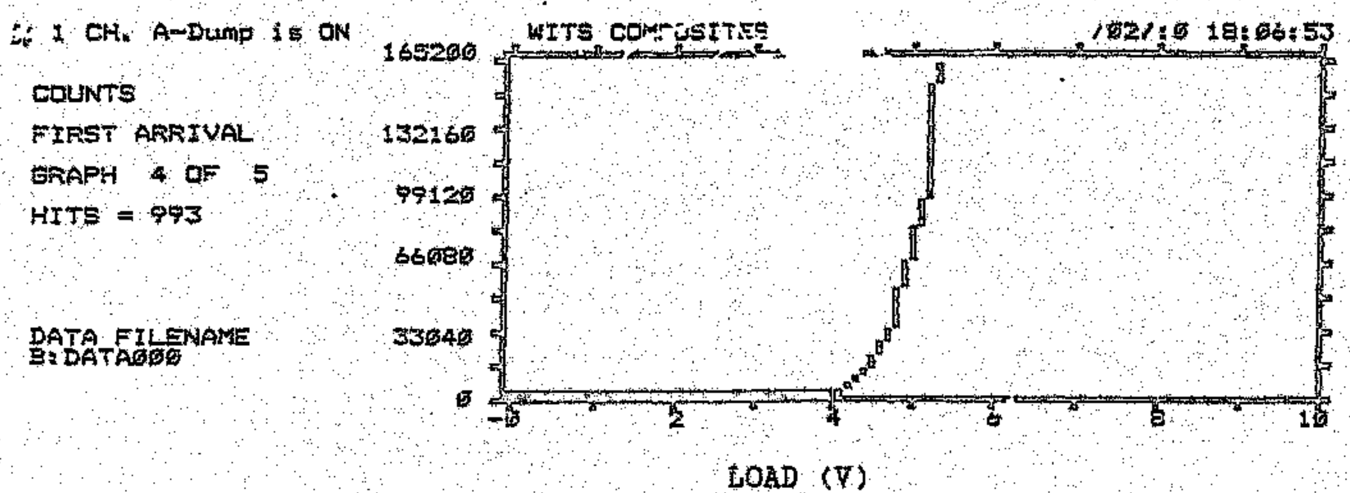
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
WITS COMPOSITES
/02/:0 18:06:53
COUNTS
FIRST ARRIVAL
GRAPH 4 OF 5
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66080
33040
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2
4
6
8
10
LOAD (V)

1 CH. A-Dump is ON

HITS

FIRST ARRIVAL

GRAPH 5 OF 5

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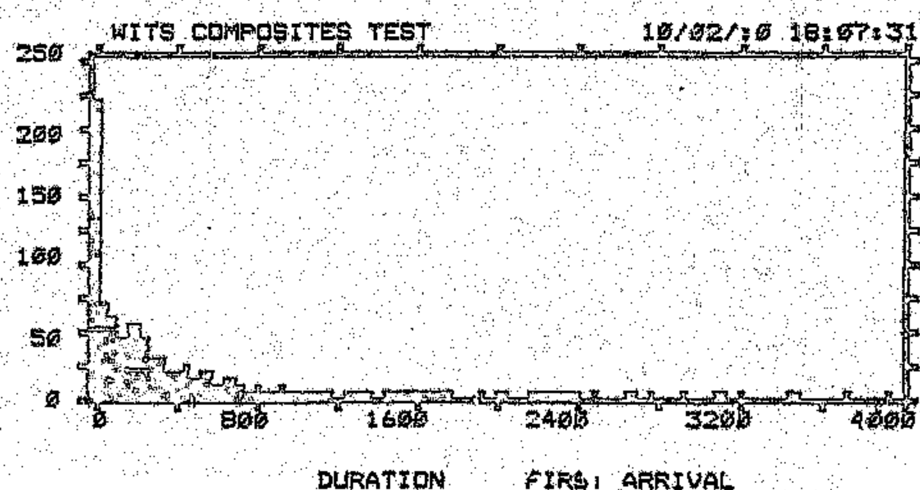

Specimen 2

1 CH. A-Dump is ON

HITS

FIRST ARRIVAL

GRAPH 1 OF 5

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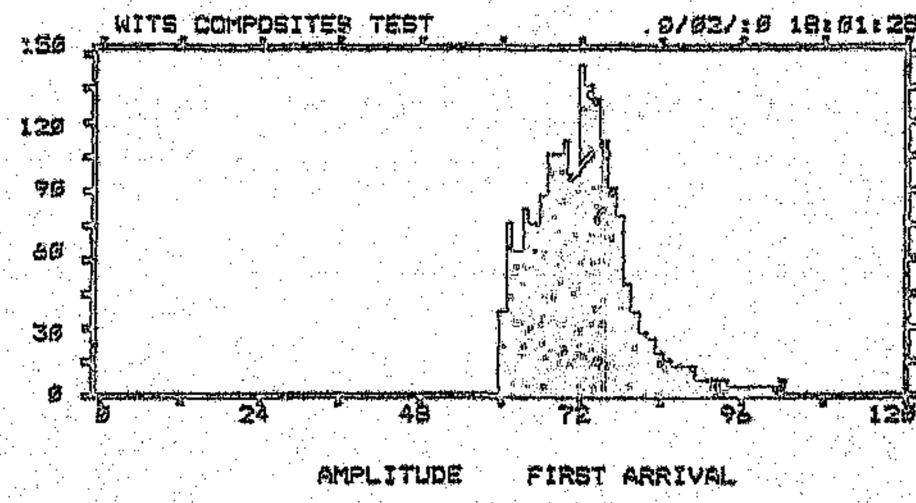

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GRAPH 2 OF 5

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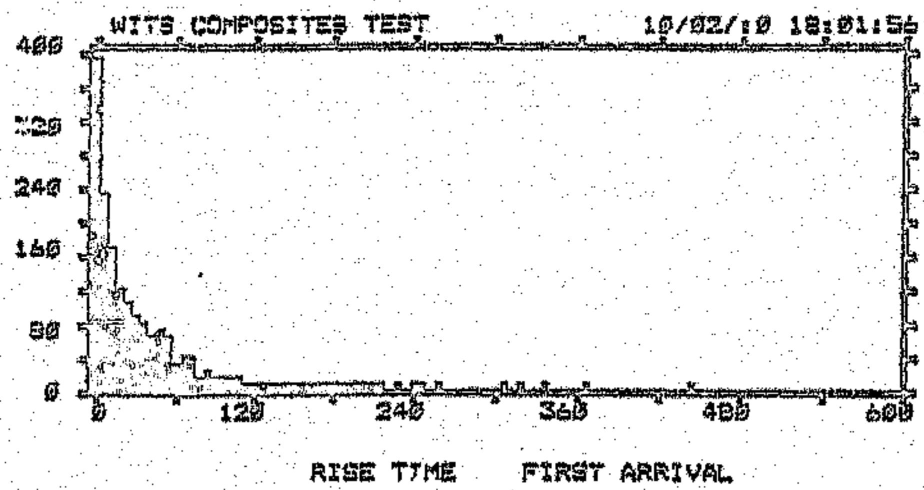

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AMPLITUDE

FIRST ARRIVAL

GRAPH 3 OF 5

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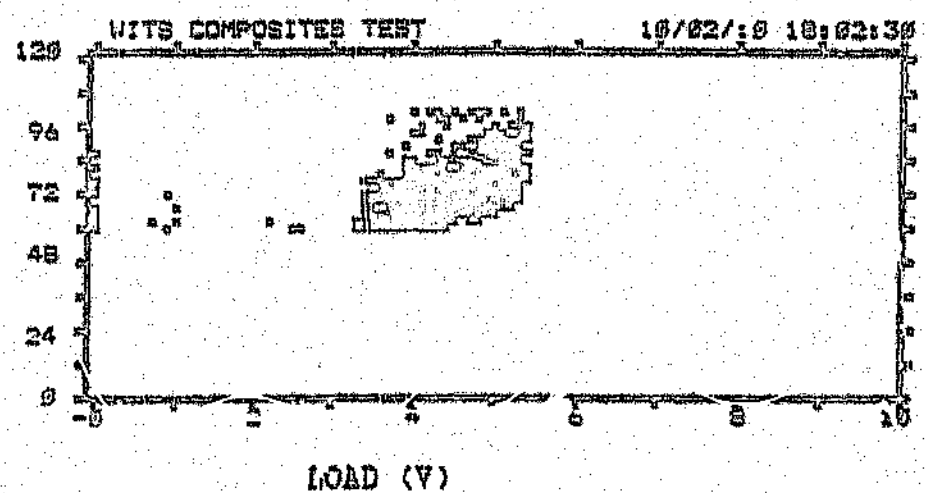

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FIRST ARRIVAL

GRAPH 4 OF 5

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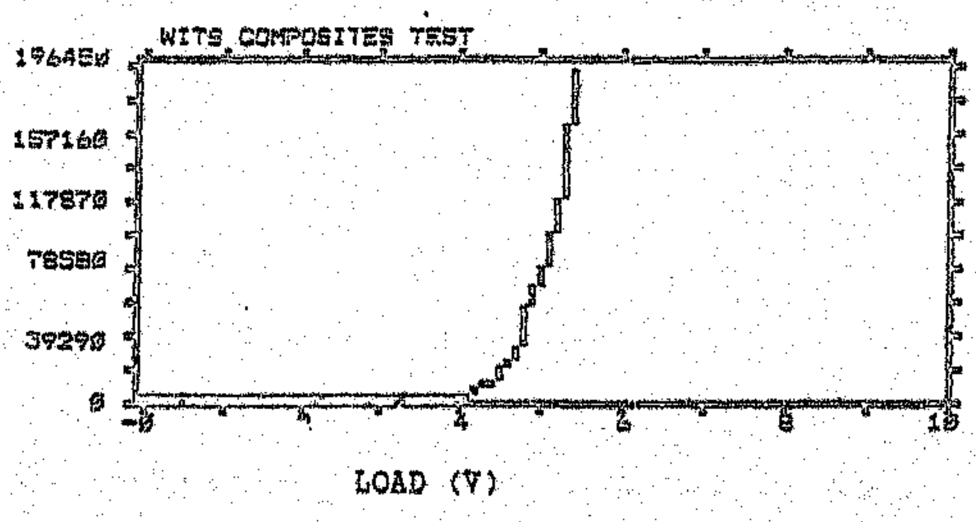

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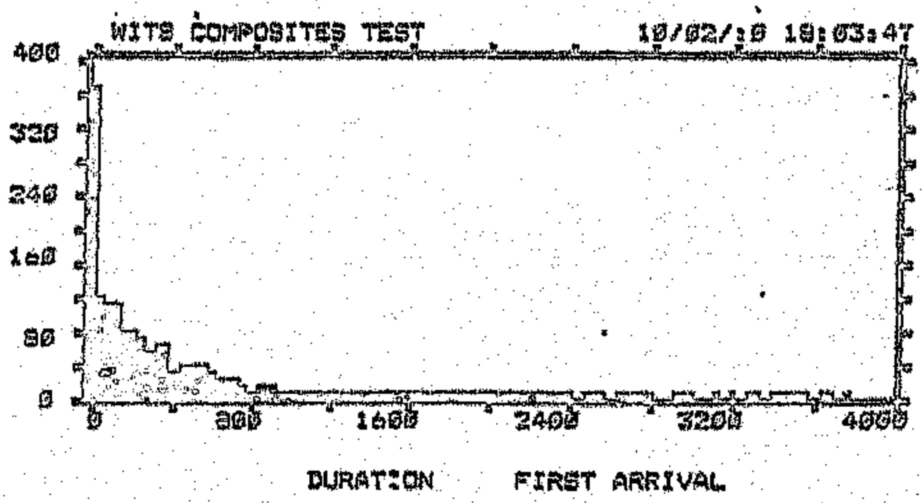

0/90° carbon fibre specimens

specimen 1

1 CH. A-Dump is ON

HITS

FIRST ARRIVAL

GRAPH 1 OF 5

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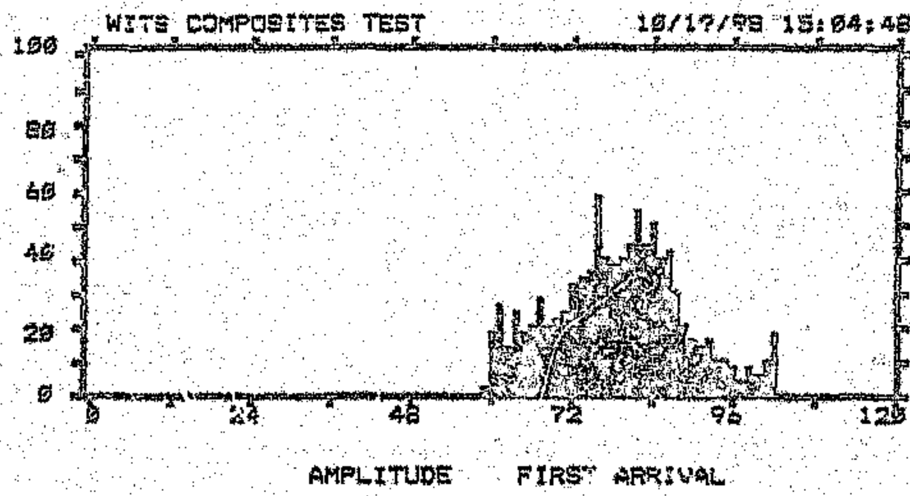

. 1 CH. A-Dump is ON

HITS

FIRST ARRIVAL

.APH 2 OF 5

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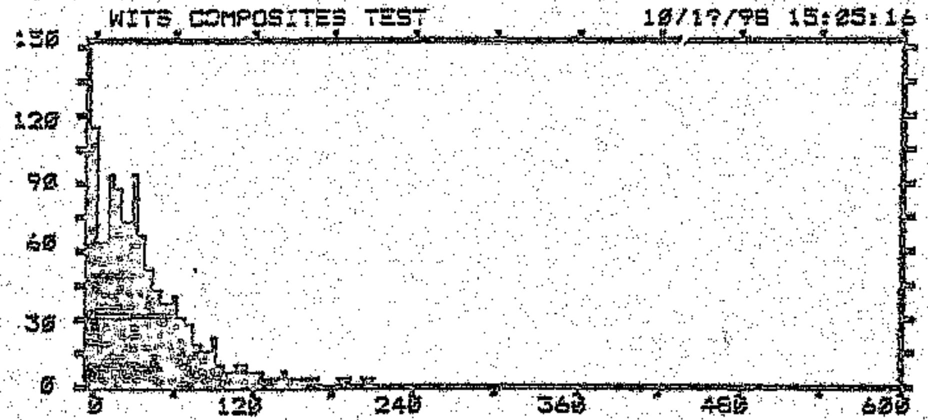
DATA FILENAME
B:DATA001



. 1 CH. A-Dump is ON

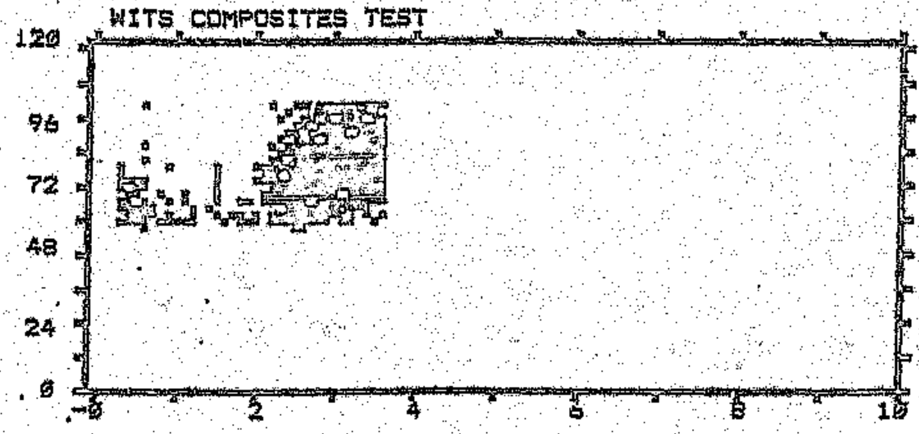
AMPLITUDE

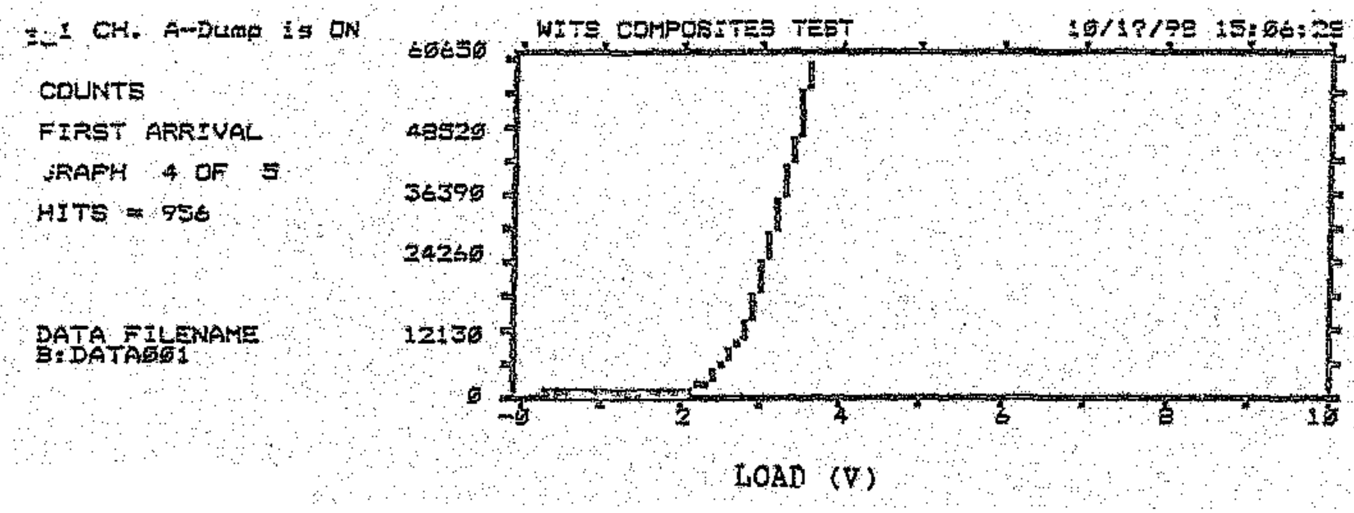
FIRST ARRIVAL

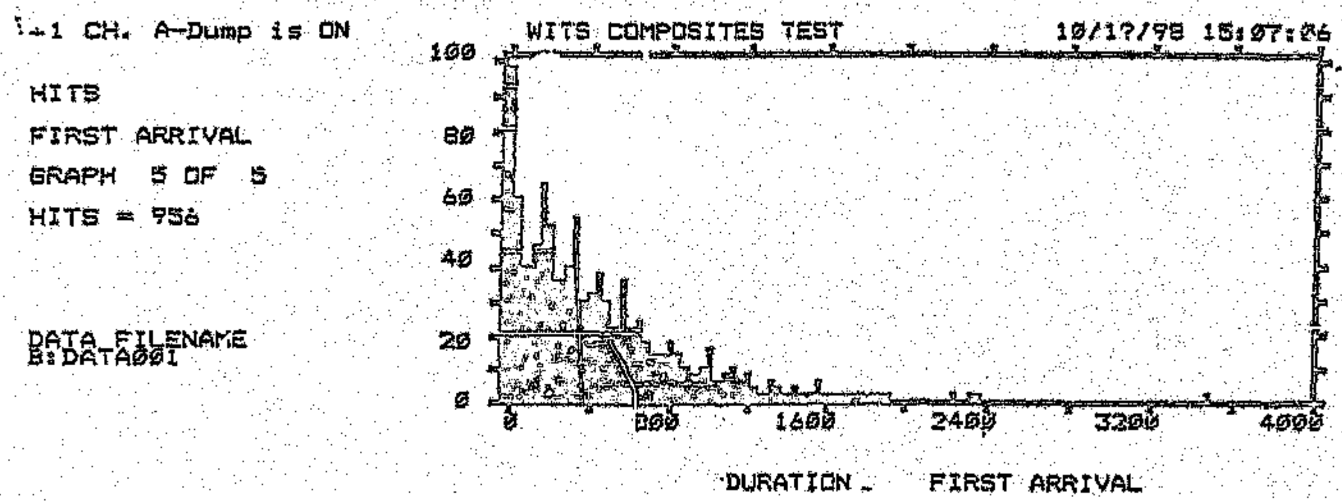
GRAPH 3 OF 5

HITS = 956

D... FILENAME
B.. .A001




1 CH. A-Dump is ON
COUNTS
FIRST ARRIVAL
GRAPH 4 OF 5
HITS = 956
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
10/17/98 15:06:29
60650
48520
36390
24260
12130
0
0
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 5 OF 5
HITS = 956
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
10/17/98 15:07:06
100
80
60
40
20
0
0
800
1600
2400
3200
4000
DURATION - FIRST ARRIVAL

specimen 2

#1 CH. A-Dump is ON

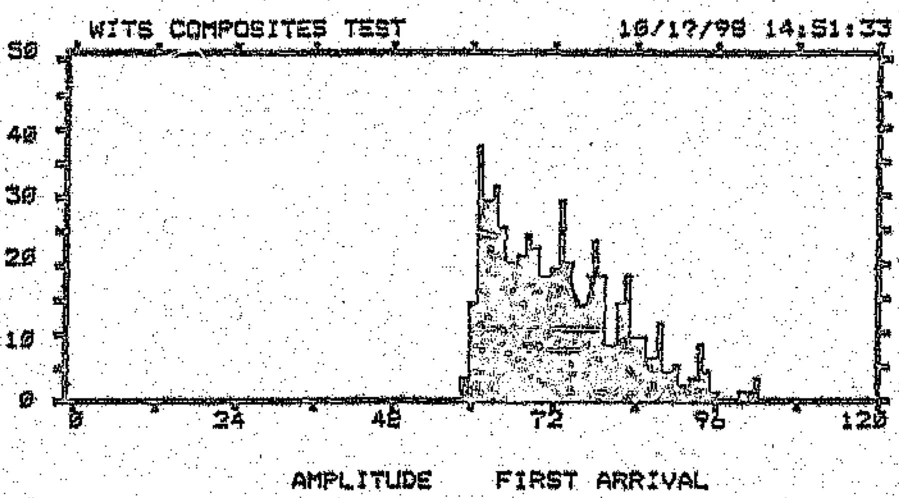
HITS

FIRST ARRIVAL

GRAPH 1 OF 5

HITS = 495

DATA FILENAME
B:DATA001



1 CH. A-Dump is ON

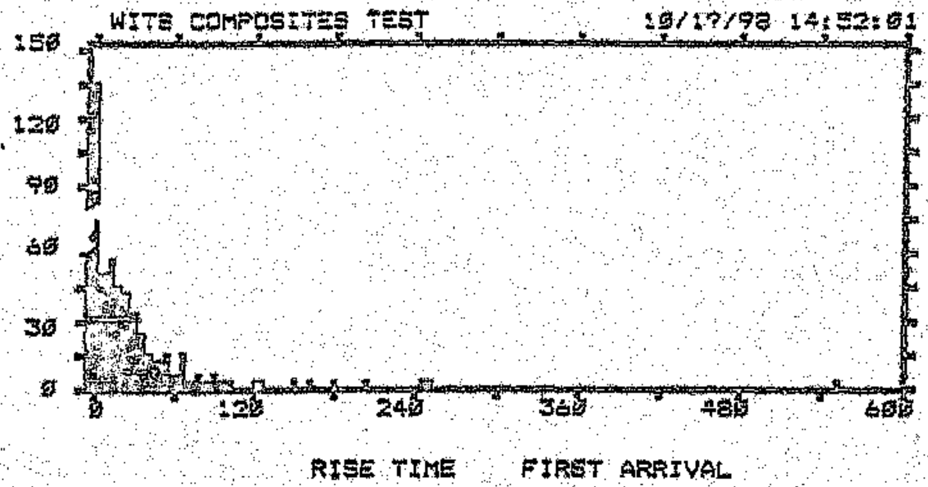
HITS

RST ARRIVAL

GRAPH 2 OF 5

HITS = 495

DATA FILENAME
B:DATA001



1 CH. A-Dump is ON

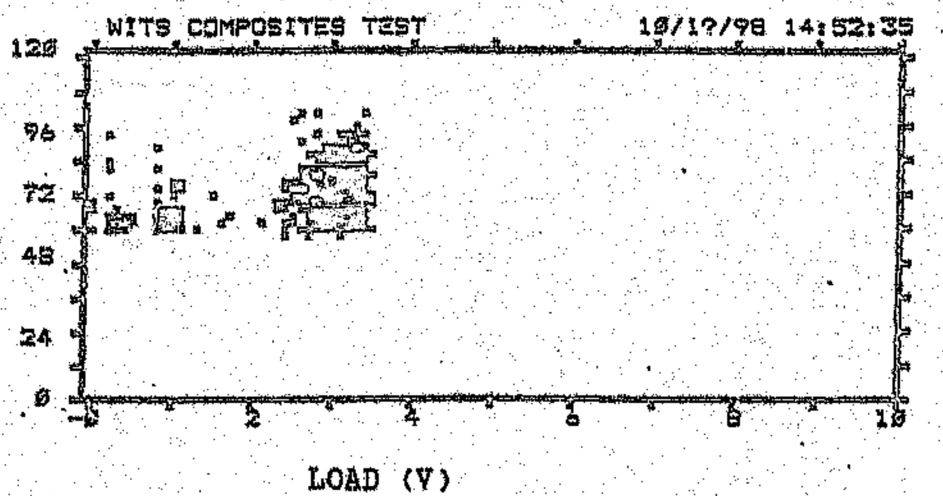
AMPLITUDE

FIRST ARRIVAL

GRAPH 3 OF 5

HITS = 495

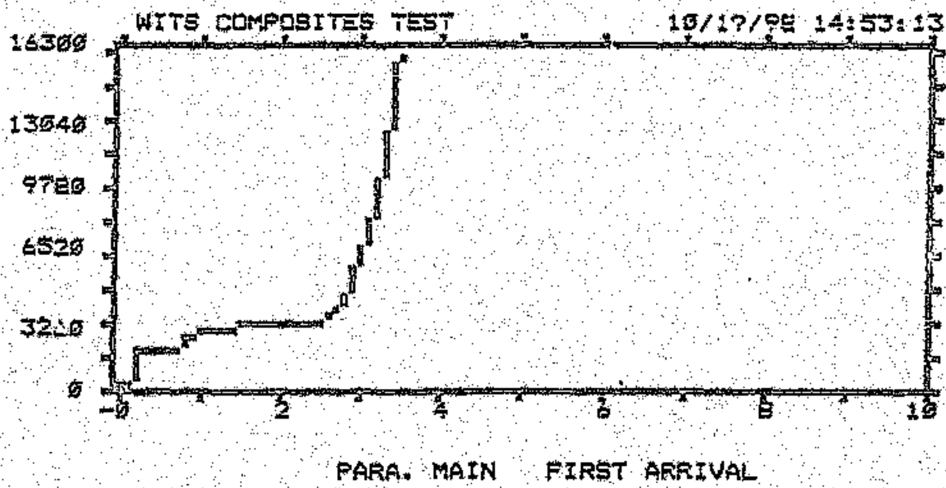
DATA FILENAME
B:DATA001



#1 CH. A-Dump is ON

COUNTS
FIRST ARRIVAL
GRAPH 4 OF 5
HITS = 495

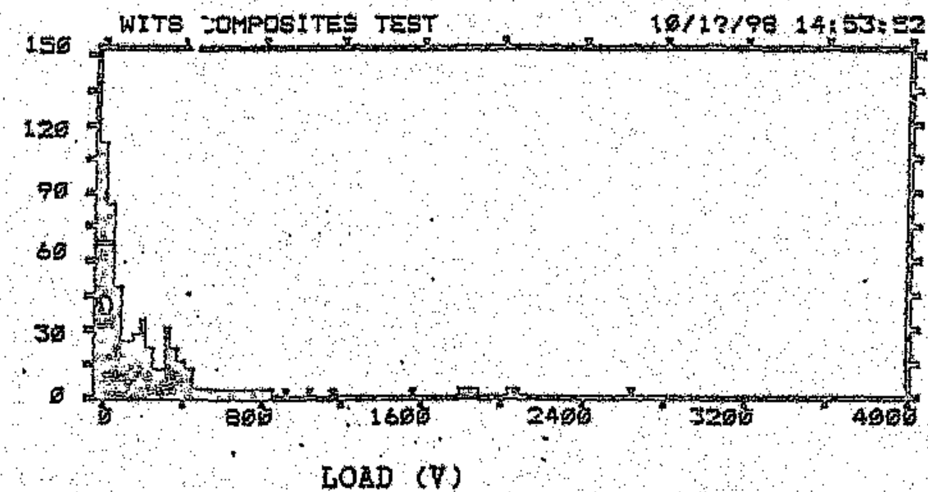
DATA FILENAME
B:DATA001

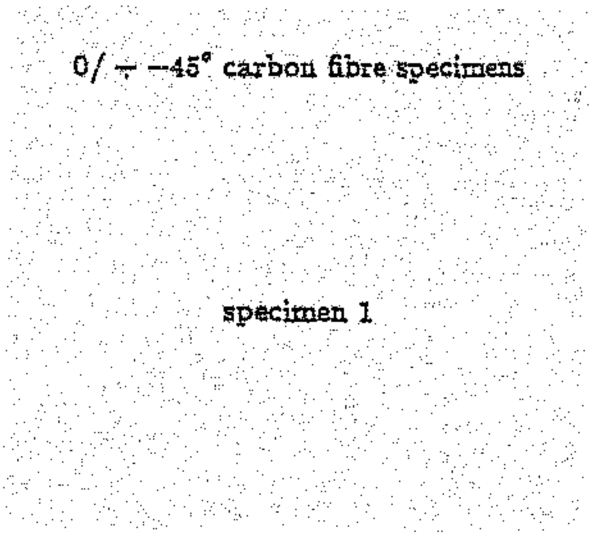


#1 CH. A-Dump is ON

HITS
FIRST ARRIVAL
GRAPH 5 OF 5
HITS = 495

DATA FILENAME
B:DATA001




0/ ∓ −45° carbon fibre specimens
specimen 1

-, 1 CH. A-Dump is ON

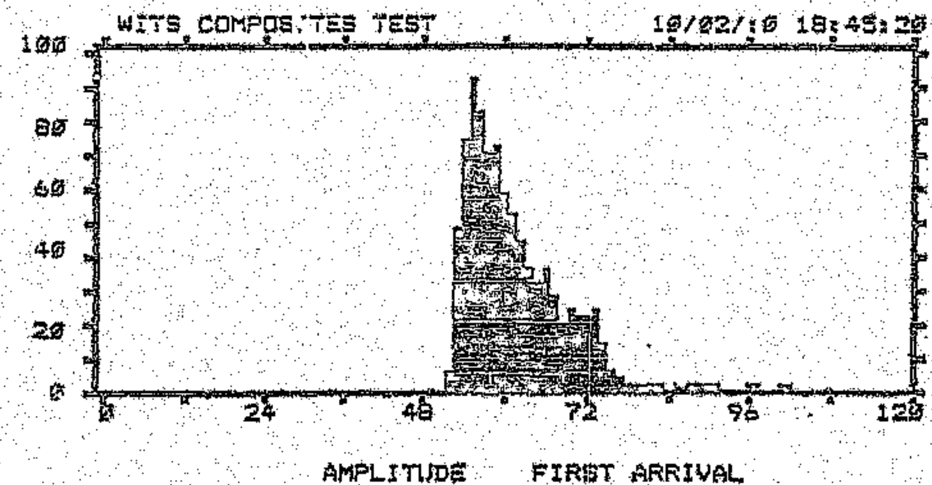
HITS

IRST ARRIVAL

GRAPH 1 OF 5

HITS = 899

DATA FILENAME
B:DATA000



4;1 CH. A-Dump is ON

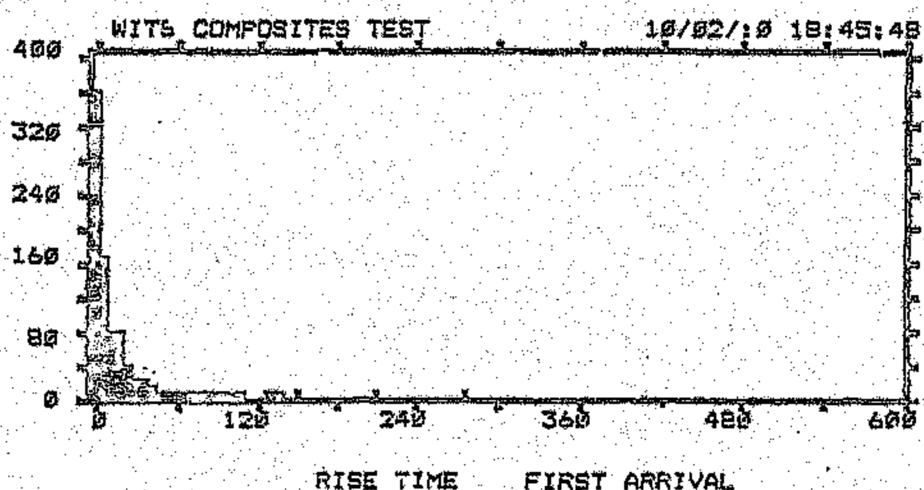
HITS

FIRST ARRIVAL

GRAPH 2 OF 5

HITS = 899

DATA FILENAME
B:DATA000



4.1 CH. A-Dump is ON

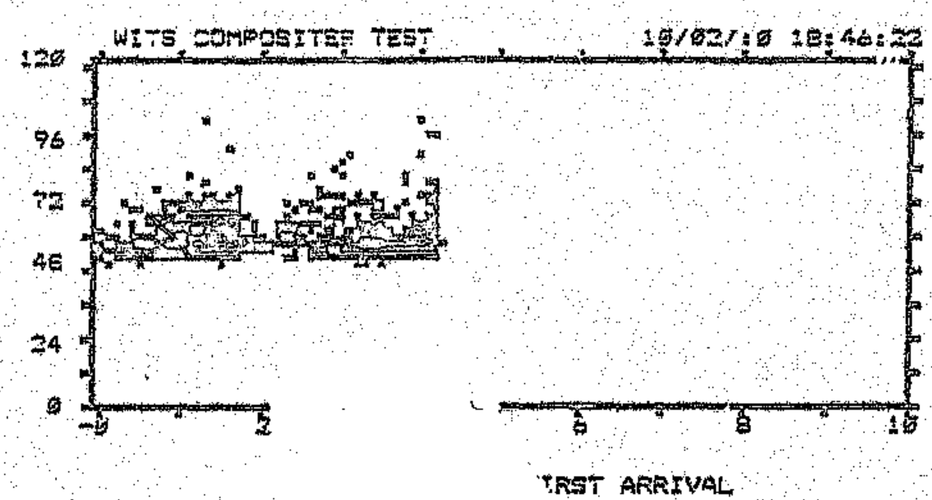
AMPLITUD3

'IRST ARRIVAL

GRAPH 3 OF 5

HITZ = 899

DATA FILENAME
B:DATA000



4.1 CH. A-Dump is ON

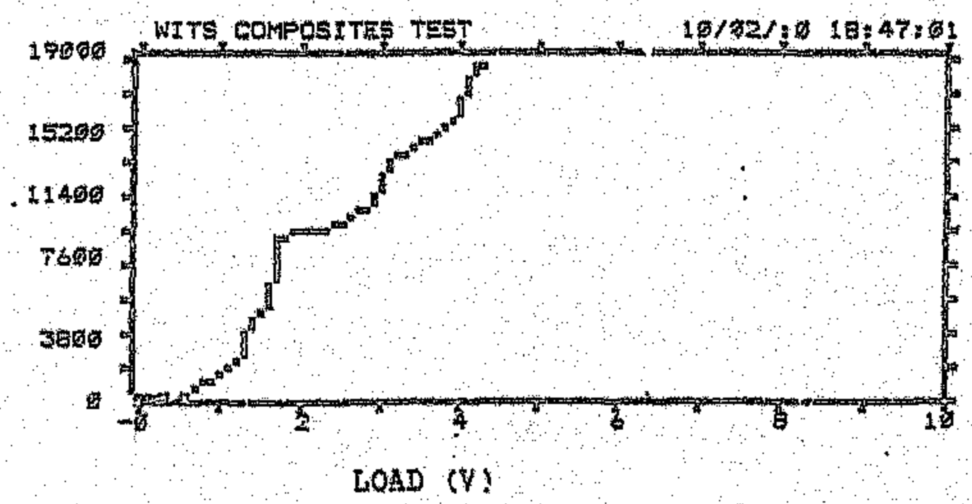
COUNTS

FIRST ARRIVAL

GRAPH 4 OF 5

HITS = 899

DATA FILENAME
B:DATA000



/; 1 CH. A-Dump is ON

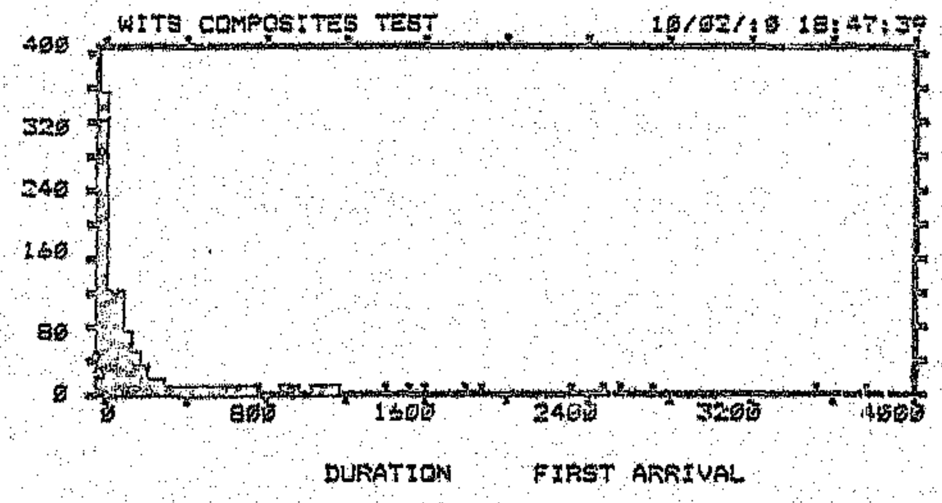
HITS

FIRST ARRIVAL

GRAPH 5 OF 5

HITS = 899

DATA FILENAME
B:DATA000



specimen 2

CH. A-Dump is ON

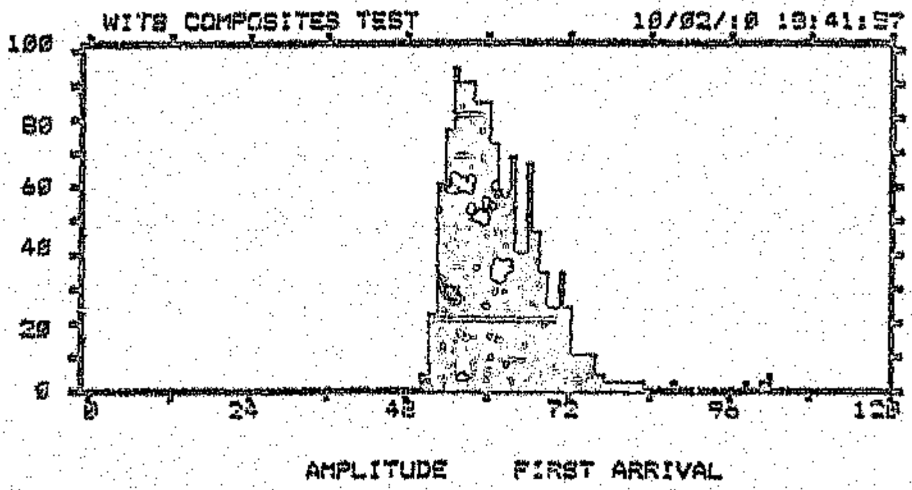
HITS

FIRST ARRIVAL

GRAPH 1 OF 5

HITS = 1129

DATA_FILENAME
B:DATA001



1 CH. A-Dump is ON

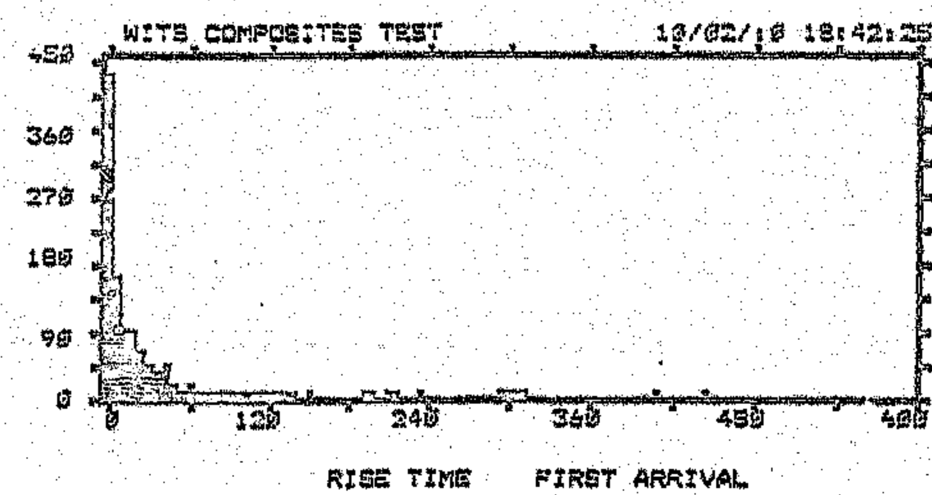
HITS

FIRST ARRIVAL

GRAPH 2 OF 5

HITS = 1129

DATA FILENAME
B:DATA001



1 CH. A-Dump is ON

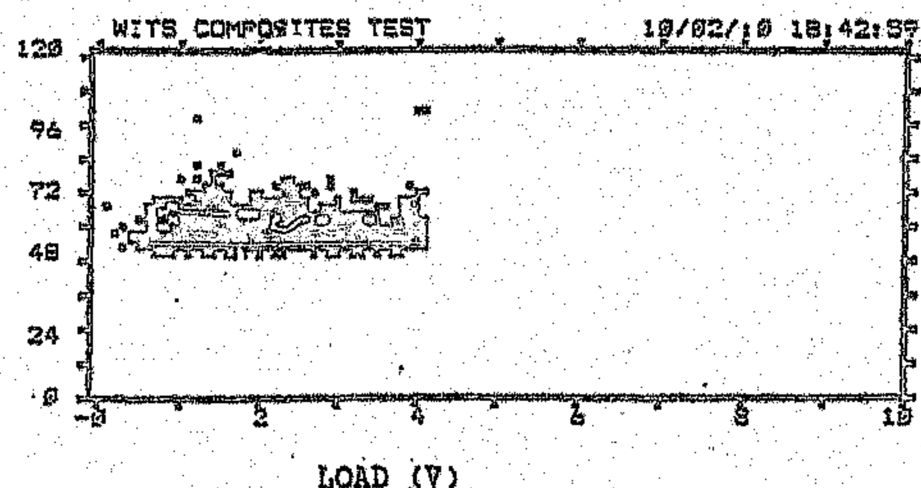
AMPLITUDE

FIRST ARRIVAL

GRAPH 3 OF 5

HITS = 1129

DATA FILENAME
B.DATA001



*:1 CH. A-Dump is ON

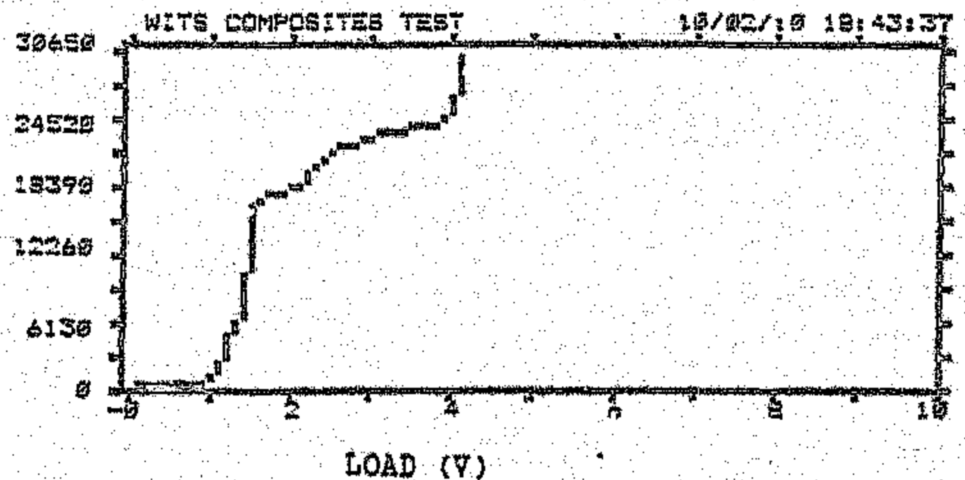
COUNTS

'IRST ARRIVAL

GRAPH 4 OF 5

HITS = 1129

DATA FILENAME
B:DATA001



*:1 CH. A-Dump is ON

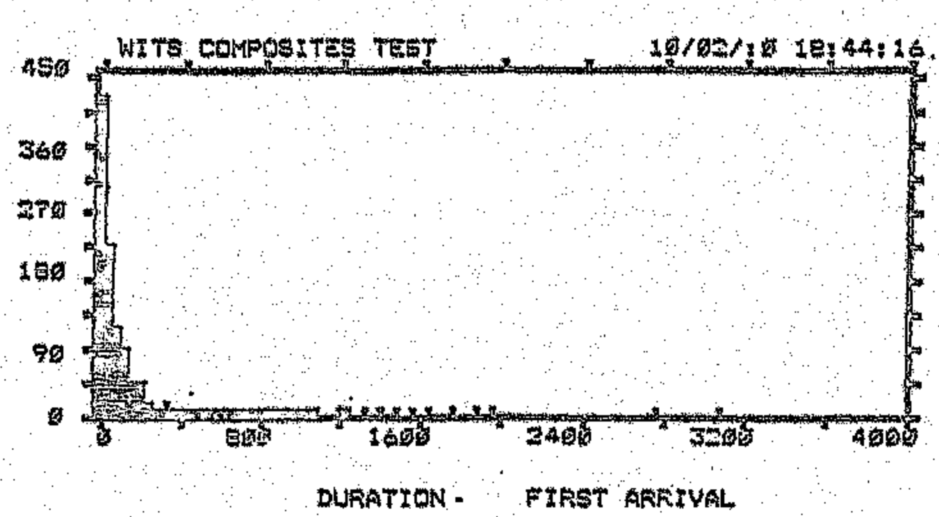
HITS

FIRST ARRIVAL

GRAPH 5 OF 5

HITS = 1129

DATA FILENAME
B:DATA001



0/90/ $+-45^{\circ}$ carbon fibre specimens

specimen 1

2> 1 CH. A-Dump is ON

HITS

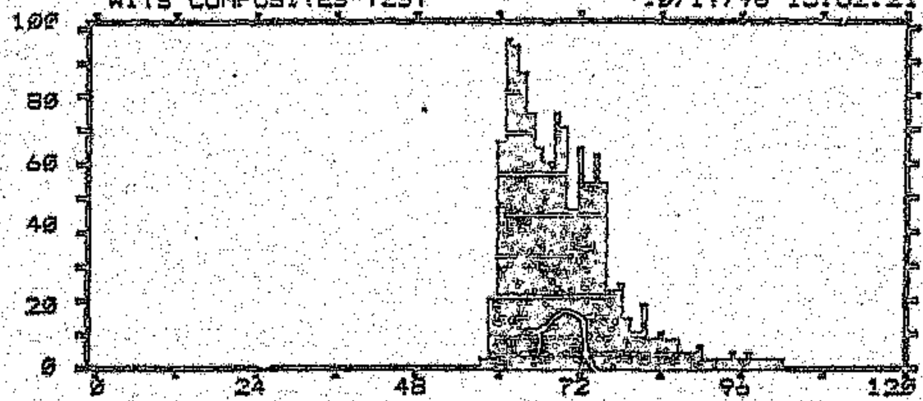
FIRST ARRIVAL

GRAPH 1 OF 5

HITS = 1161

DATA FILENAME
B:DATA000

WITS COMPOSITES TEST 10/19/98 15:32:21



AMPLITUDE FIRST ARRIVAL

2> 1 CH. A-Dump is ON

HITS

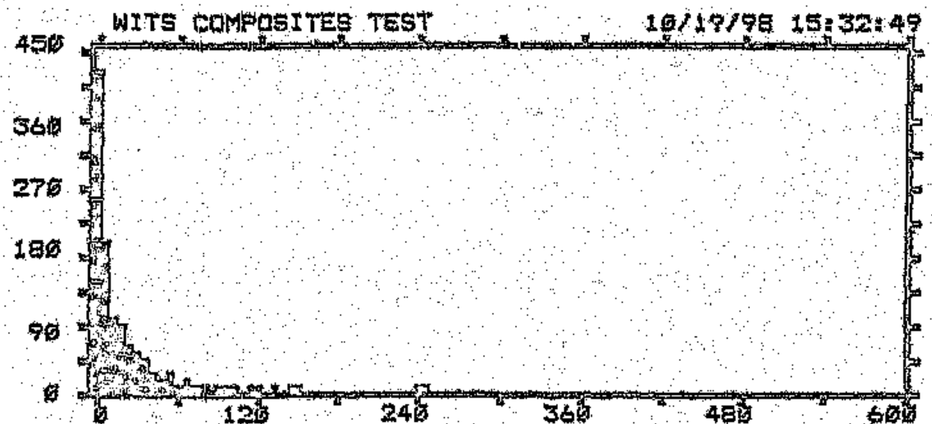
FIRST ARRIVAL

GRAPH 2 OF 5

HITS = 1161

DATA FILENAME
B:DATA000

WITS COMPOSITES TEST 10/19/98 15:32:49



RISE TIME FIRST ARRIVAL

1 CH. A-Dump is ON

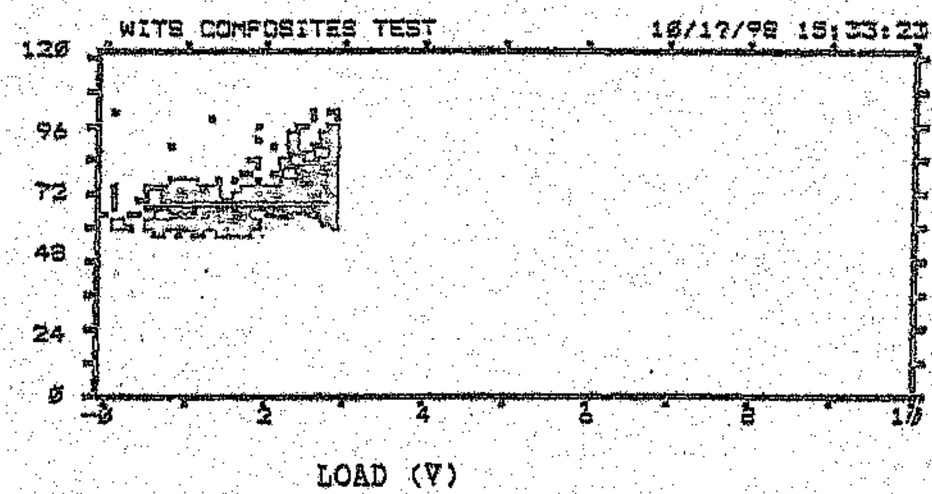
AMPLITUDE

FIRST ARRIVAL

GRAPH 3 OF 5

HITS = 1161

DATA FILENAME
B:DATA000



1 CH. A-Dump is ON

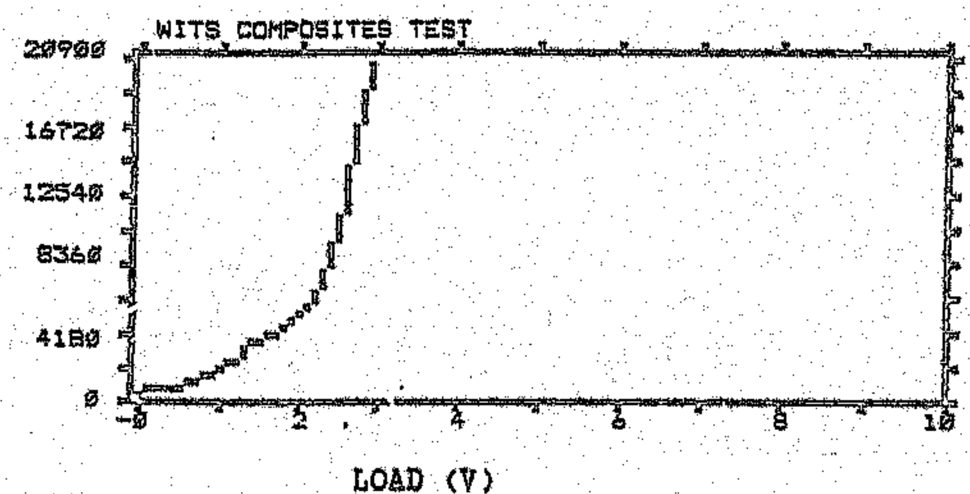
COUNTS

FIRST ARRIVAL

GRAPH 4 OF 5

HITS = 1161

DATA FILENAME
B:DATA000



1 CH. A-Dump is ON

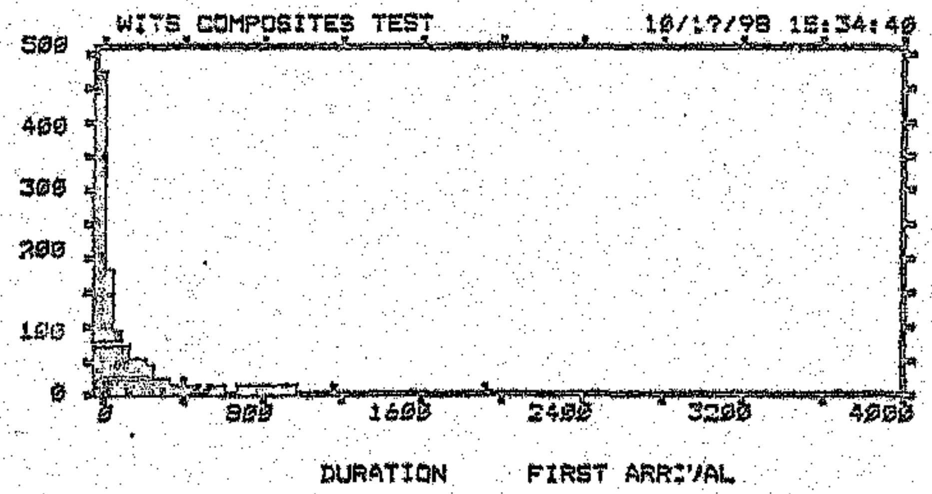
HITS

FIRST ARRIVAL

GRAPH 5 OF 5

HITS = 1161

DATA FILENAME
B:DATA000



specimen 2

1 CH. A–Dump is ON

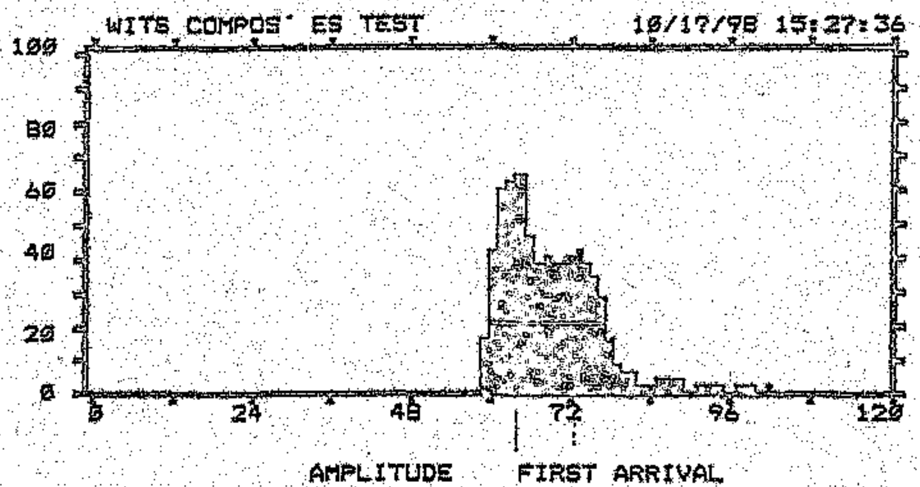
HITS

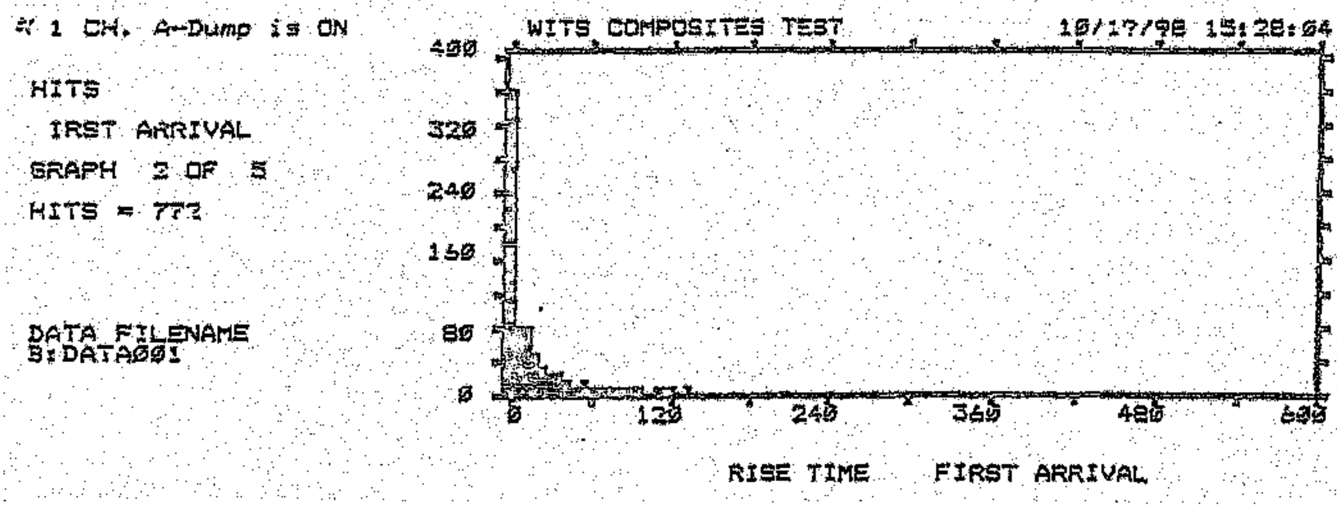
FIRST ARRIVAL

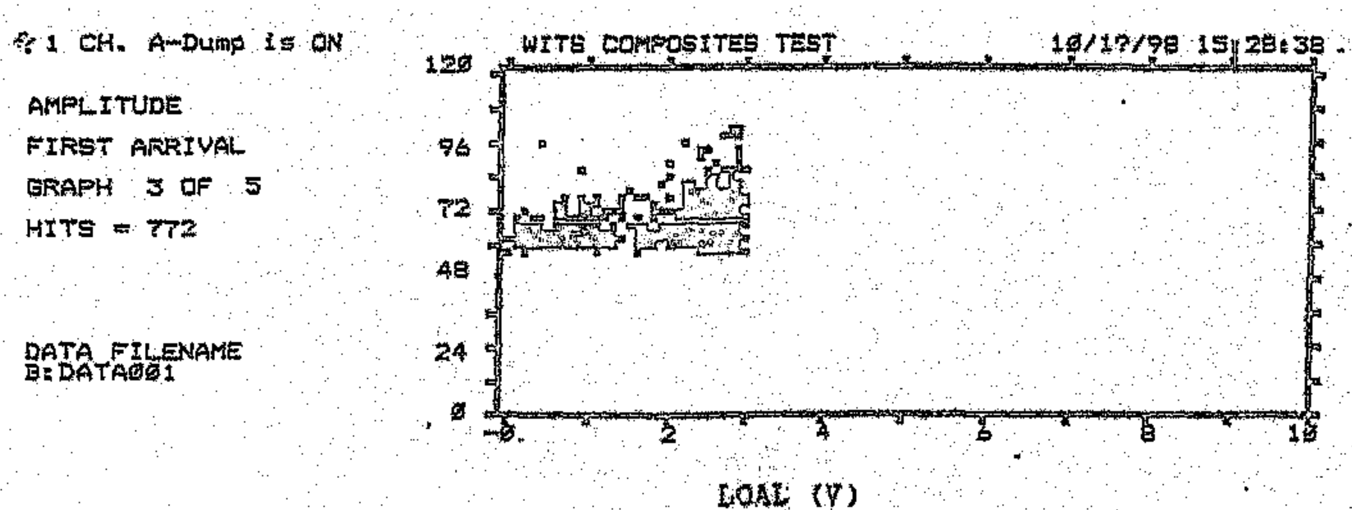
GRAPH 1 OF 5

HITS = 772

DATA FILENAME
B:DATA001




1 CH. A-Dump is ON
HITS
IRST ARRIVAL
GRAPH 2 OF 5
HITS = 773
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
10/17/98 15:28:04
400
320
240
160
80
0
0
120
240
360
480
600
RISE TIME FIRST ARRIVAL


1 CH. A-Dump is ON
AMPLITUDE
FIRST ARRIVAL
GRAPH 3 OF 5
HITS = 772
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
10/17/98 15:28:38
120
96
72
48
24
0
0.
2
4
6
8
10
LOAL (V)

:1 CH. A-Dump is ON

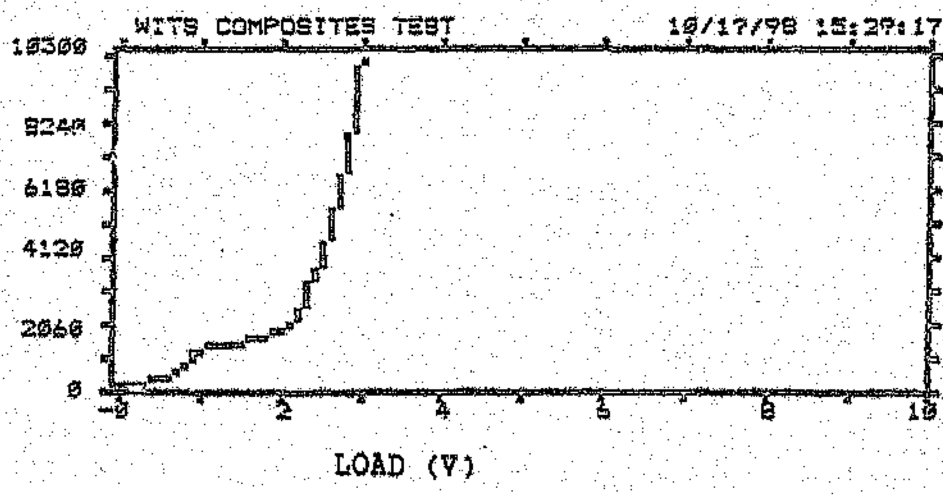
COUNTS

RST ARRIVAL

GRAPH 4 OF 5

HITS = 772

DATA FILENAME
B:DATA001



1 CH. A-Dump is ON

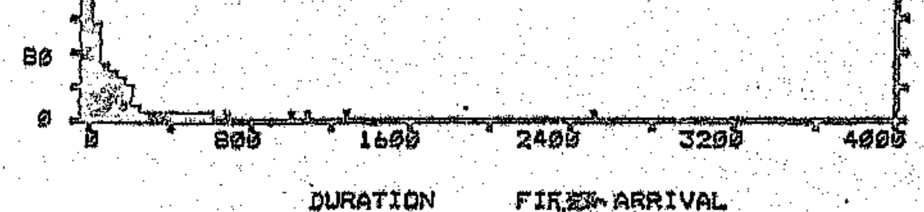
HITS

FIRST ARRIVAL

GRAPH 5 OF 5

HITS = 772

DATA FILENAME
B:DATA001



90/ + −45° carbon fibre specimens

specimen 1

#1 CH. A-Dump is ON

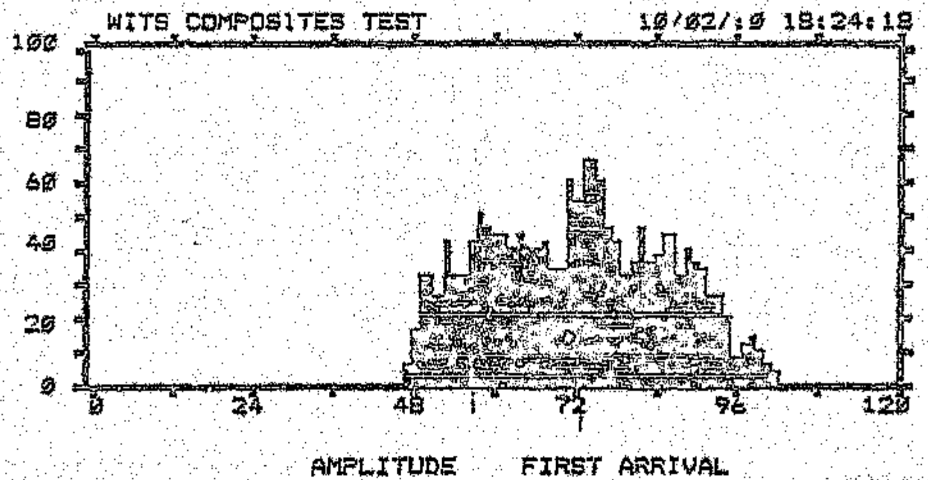
HITS

FIRST ARRIVAL

GRAPH 1 OF 5

HITS = 1680

DATA FILENAME
B:DATA000



#1 CH. A-Dump is ON

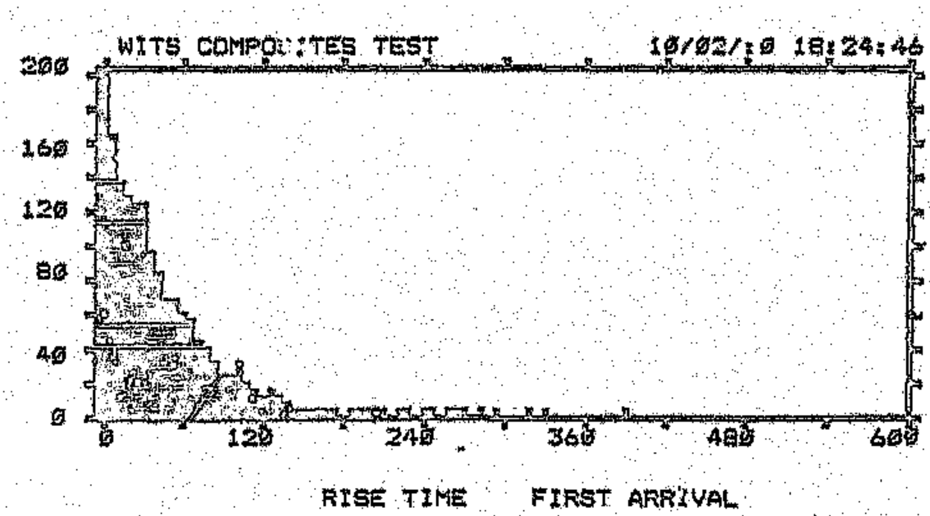
HITS

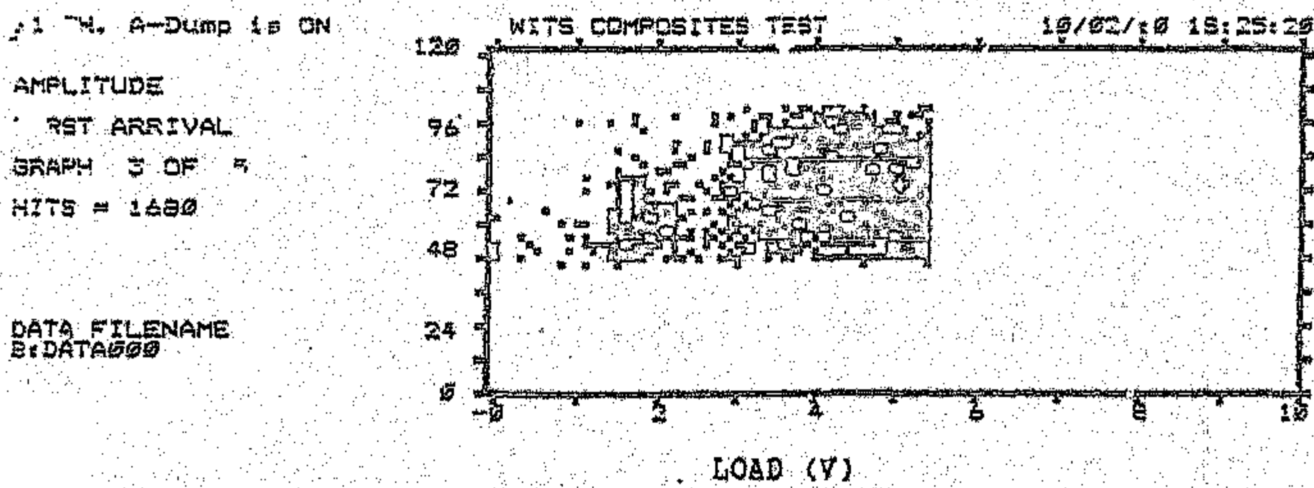
FIRST ARRIVAL

GRAPH 2 OF 5

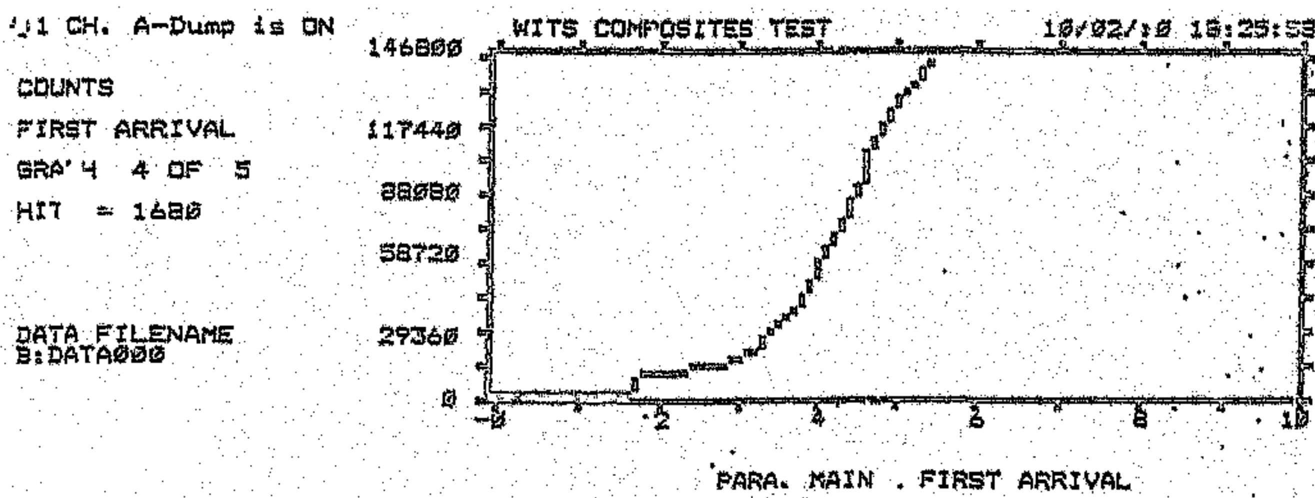
HITS = 1680

DATA FILENAME
B:DATA000





1 CH. A-Dump is ON
AMPLITUDE
RST ARRIVAL
GRAPH 3 OF 5
HITS = 1680
DATA FILENAME
B:DATA000
WITS COMPOSITES TEST
10/02/10 15:25:20
120
96
72
48
24
0
-0
2
4
6
8
10
LOAD (V)



1 CH. A-Dump is ON
COUNTS
FIRST ARRIVAL
GRAPH 4 OF 5
HIT = 1680
DATA FILENAME
B:DATA000
WITS COMPOSITES TEST
10/02/10 15:25:58
146800
117440
88080
58720
29360
0
-0
2
4
6
8
10
PARA. MAIN . FIRST ARRIVAL

#1 CH. A-Dump is ON

WITS COMPOSITES TEST 10/02/:0 18:26:37

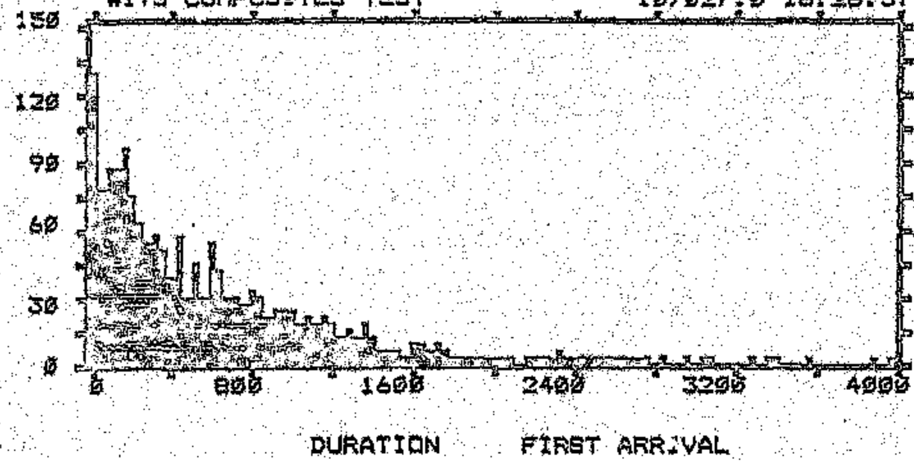
HITS

FIRST ARRIVAL

GRAPH 5 OF 5

HITS = 1690

DATA FILENAME
B:DATA000



specimen 2

#: 1 CH. A-Dump is ON

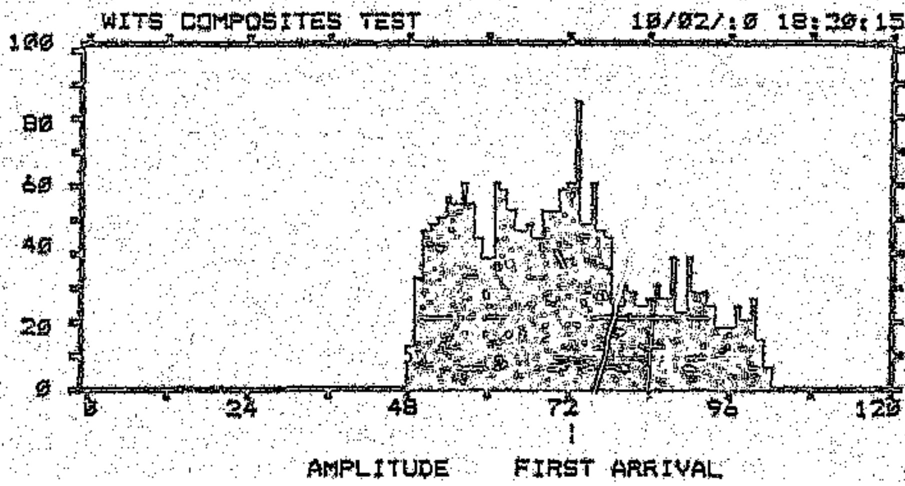
HITS

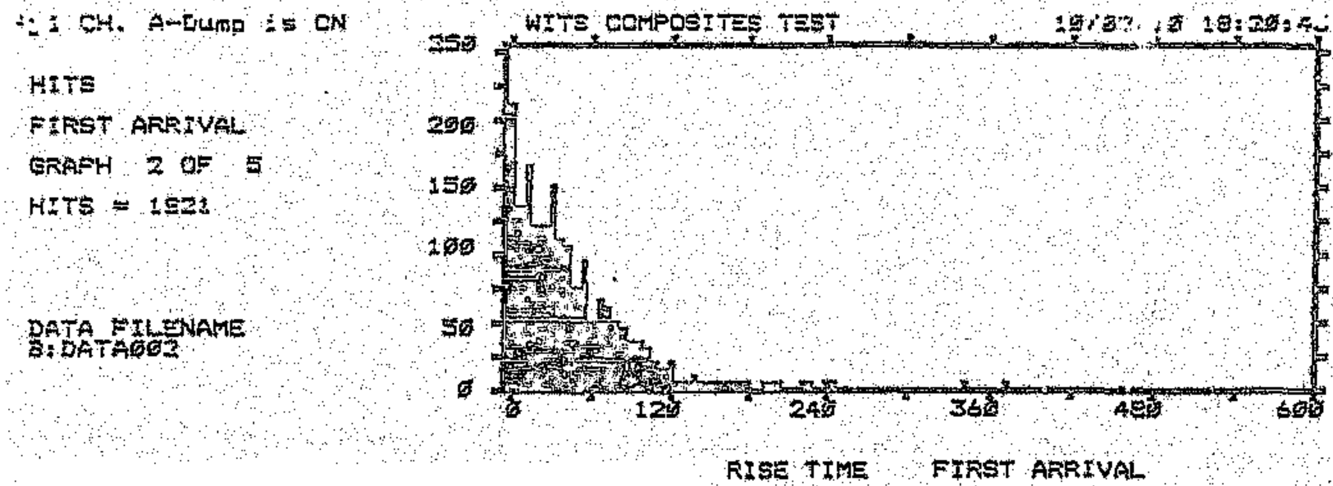
FIF T ARRIVAL

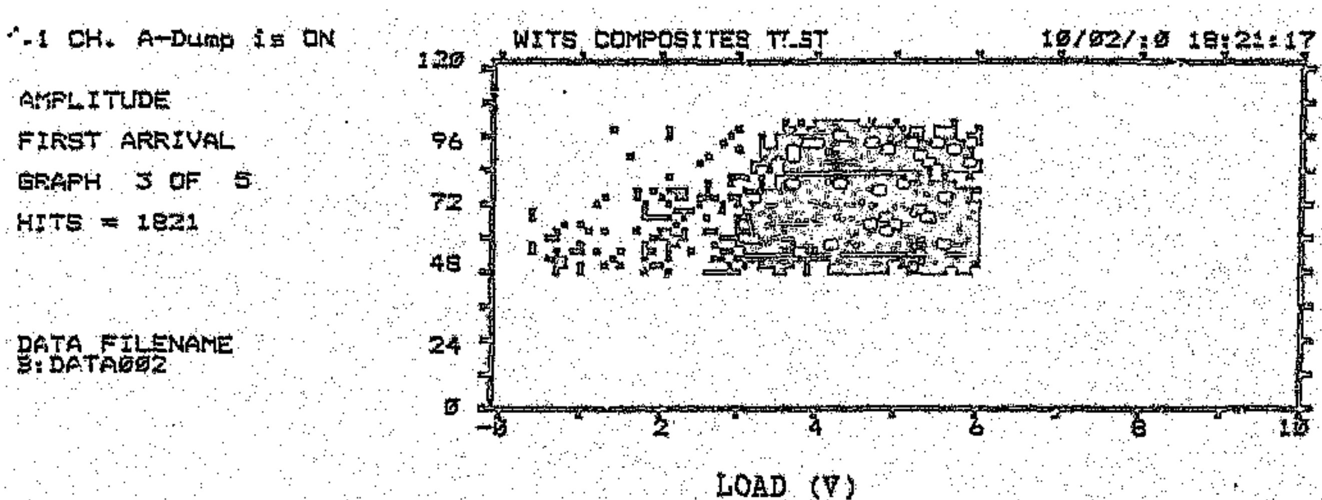
GRAPH 1 OF 5

HITS = 1621

DATA FILENAME
B:DATA002




CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 2 OF 5
DATA FILENAME
B:DATA003
WITS COMPOSITES TEST
350
200
150
100
50
0
120
240
360
480
600
RISE TIME FIRST ARRIVAL


CH. A-Dump is ON
AMPLITUDE
FIRST ARRIVAL
GRAPH 3 OF 5
HITS = 1821
DATA FILENAME
B:DATA002
WITS COMPOSITES
18:21:17
120
96
72
48
24
0
2
4
6
8
10
LOAD (V)

*1 CH. A-Dump is ON

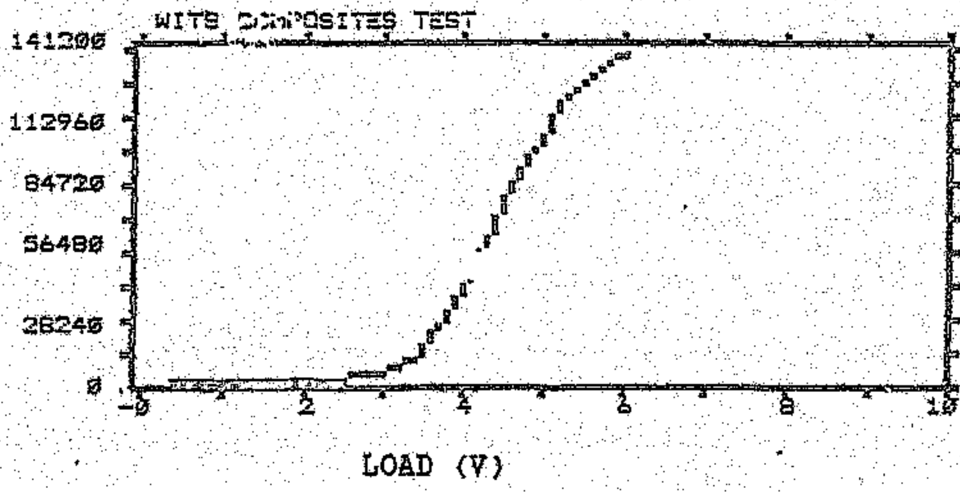
COUNTS

IRST ARRIVAL

GRAPH 4 OF 5

HITS = 1821

DATA FILENAME
B:DATA002



*1 CH. A-Dump is ON

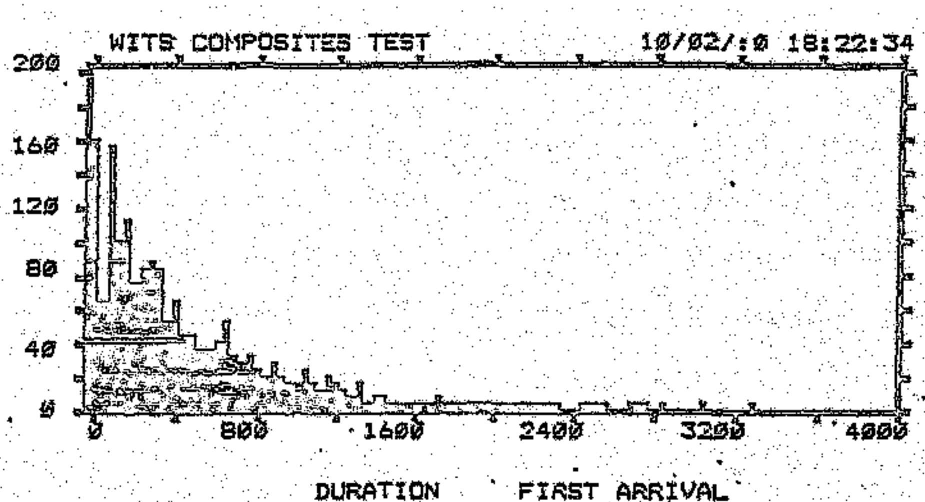
HITS

FIRST ARRIVAL

GRAPH 5 OF 5

HITS = 1821

DATA FILENAME
B:DATA002

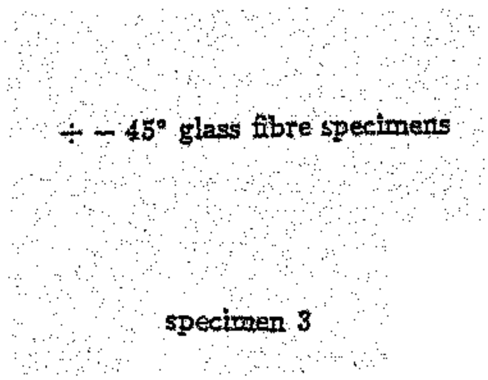


B.2 - Glass Fibre Reinforced Specimens

These specimens were loaded in steps, with the AE data from each step stored in seperate files. Seven plots were produced from each file:

1) non-cumulative events vs amplitude histogram
2) non-cumulative events vs rise time histogram
3) cumulative events vs load line graph
4) cumulative counts vs load line graph
5) non-cumulative events vs duration histogram
6) non-cumulative amplitude vs load point plot
7) non-cumulative events vs load histogram

Examples of all the plots from one specimen of each lay-up type are included.


+ − 45° glass fibre specimens
specimen 3

1 CH. A-Dump is ON

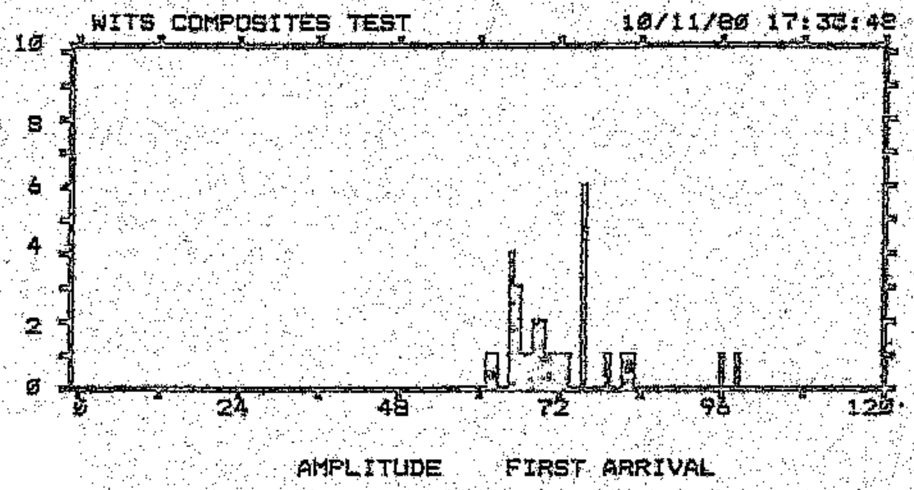
HITS

FIRST ARRIVAL

GRAPH 1 OF 7

HITS = 28

DATA FILENAME
B:DATA000



1 CH. A-Dump is ON

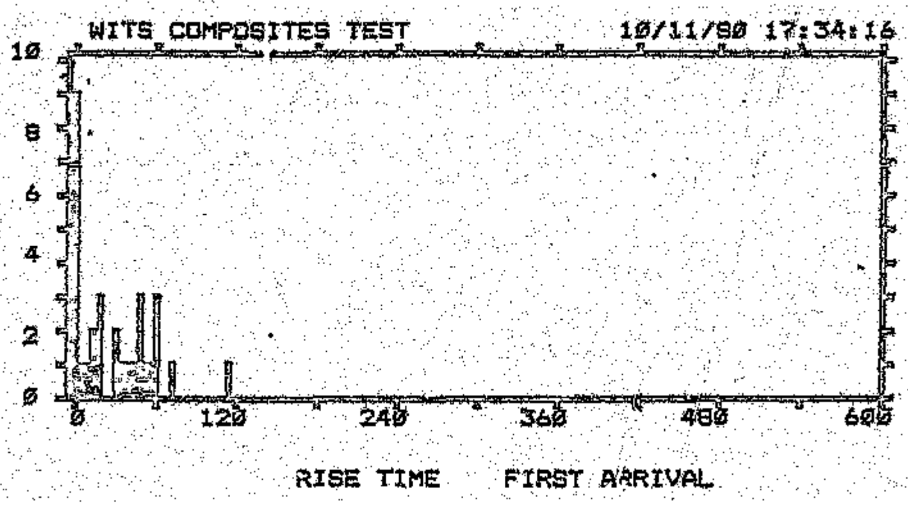
HITS

FIRST ARRIVAL

GRAPH 2 OF 7

HITS = 28

DATA FILENAME
B:DATA000



1 CH. A-Dump is ON

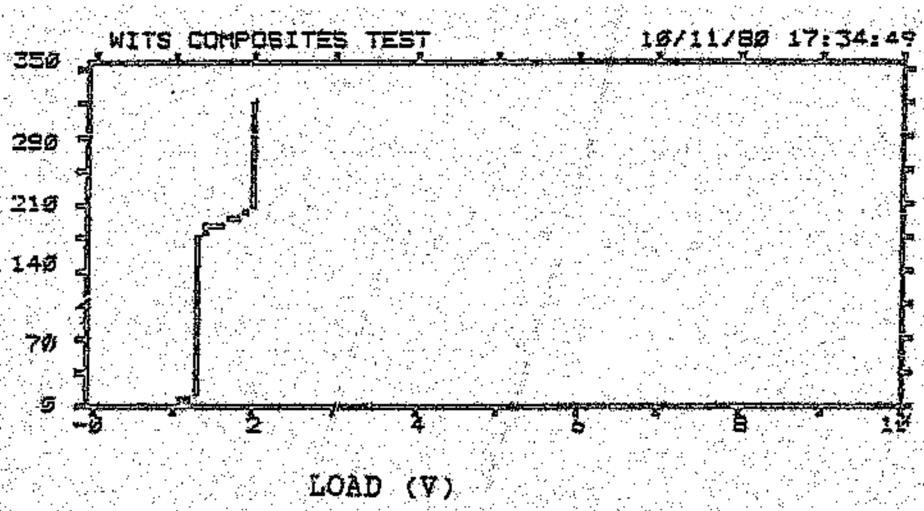
ENERGY

FIRST ARRIVAL

GRAPH 3 OF 7

HITS = 29

DATA FILENAME
B:DATA000



1 CH. A-Dump is ON

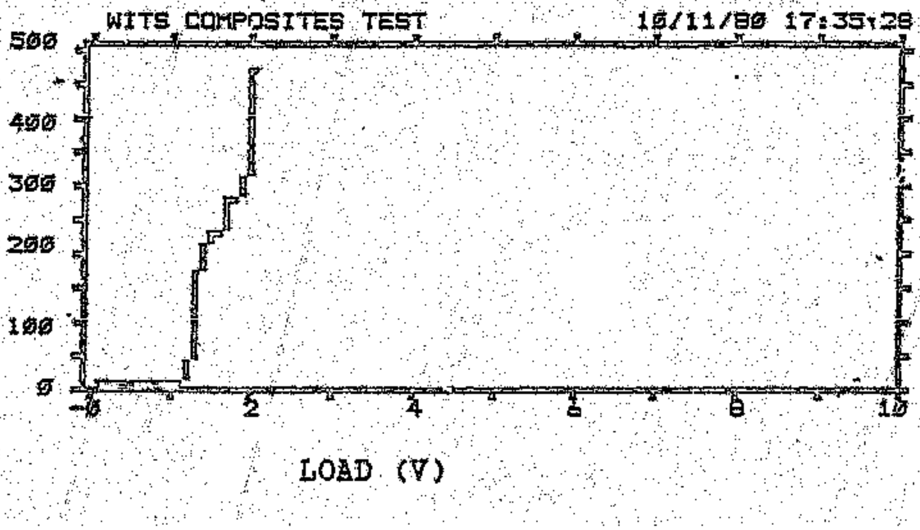
COUNTS

FIRST ARRIVAL

GRAPH 4 OF 7

HITS = 29

DATA FILENAME
B:DATA000



1 CH. A-Dump is ON

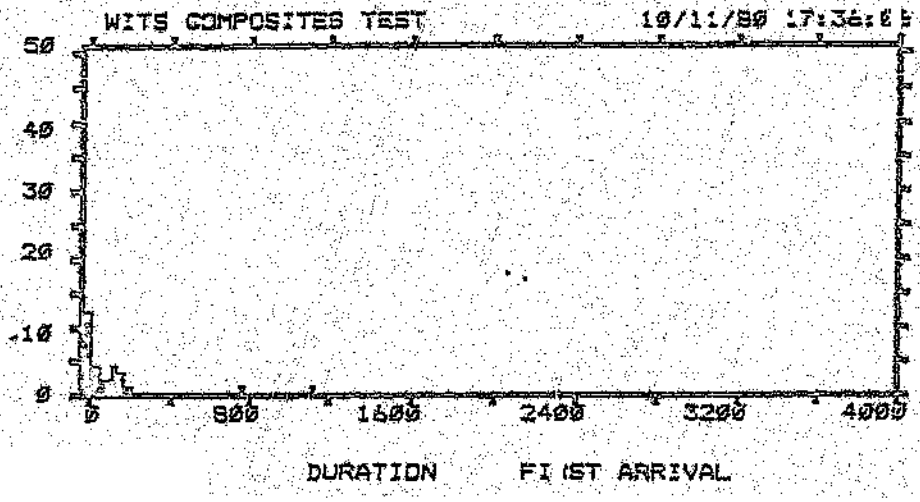
HITS

FIRST ARRIVAL

GRAPH 5 OF 7

HITS = 28

DATA FILENAME
B:DATA000



1 CH. A-Dump is ON

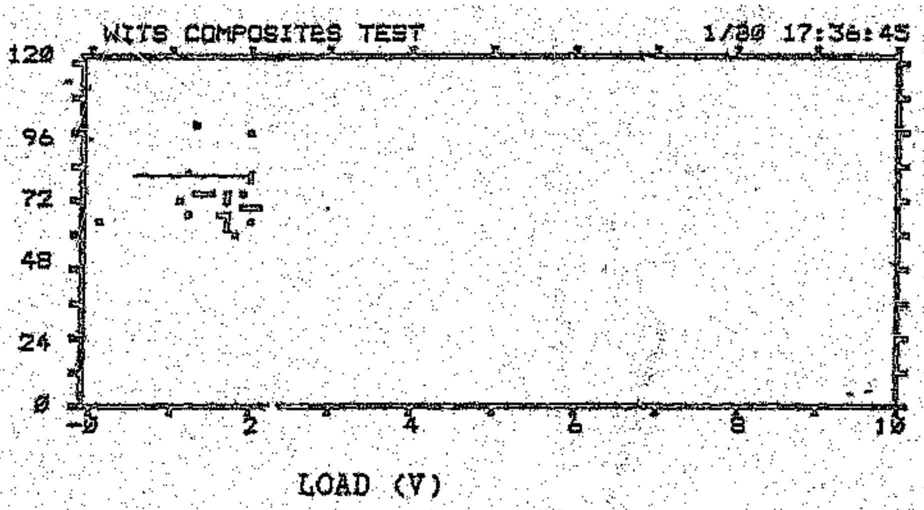
AMPLITUDE

FIRST ARRIVAL

GRAPH 6 OF 7

HITS = 28

DATA FILENAME
B:DATA000



>1 CH. A-Dump is ON

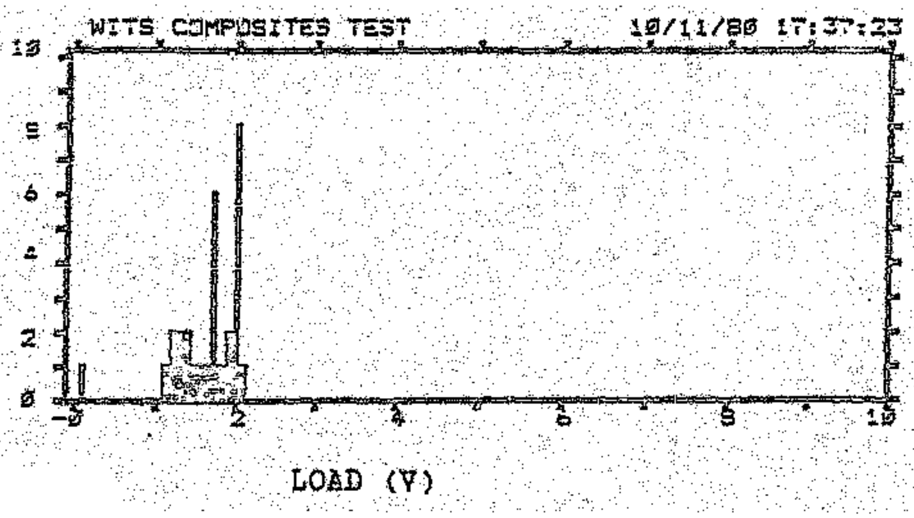
HITS

FIRST ARRIVAL

GRAPH 7 OF 7

HITS = 28

DATA FILENAME
B:DATA000



>1 CH. A-Dump is ON

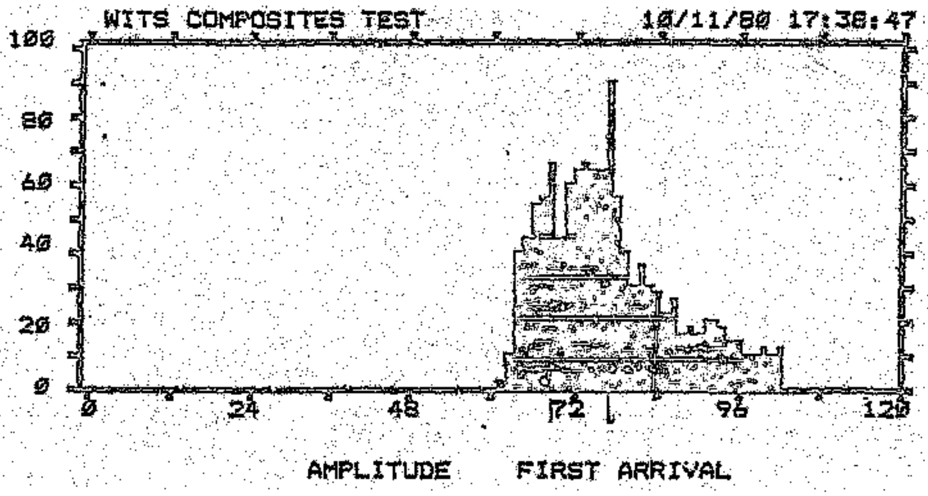
HITS

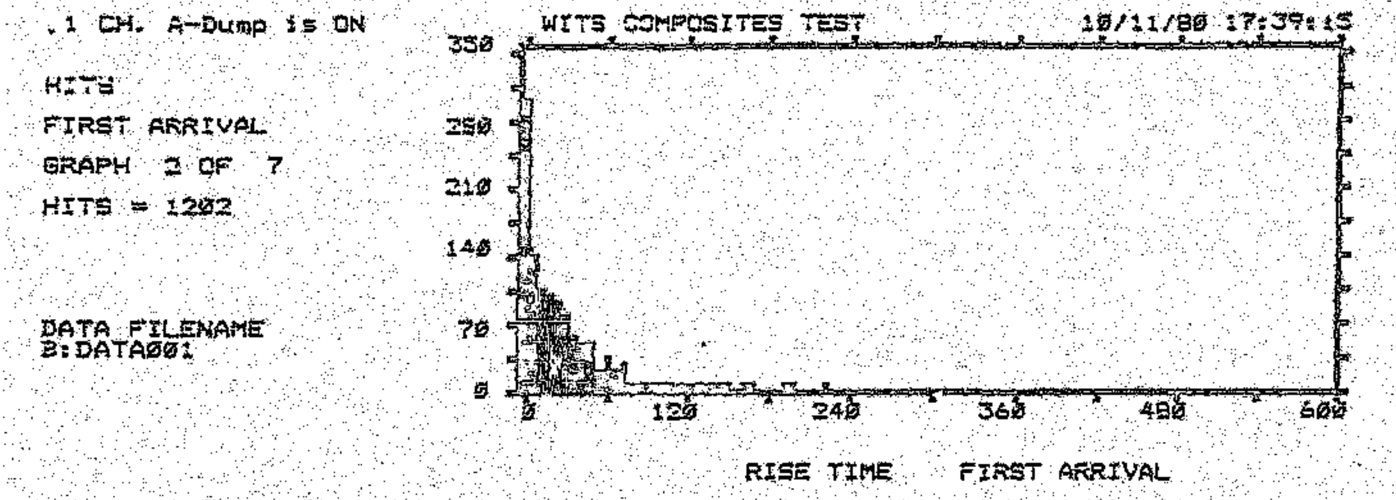
FIRST ARRIVAL

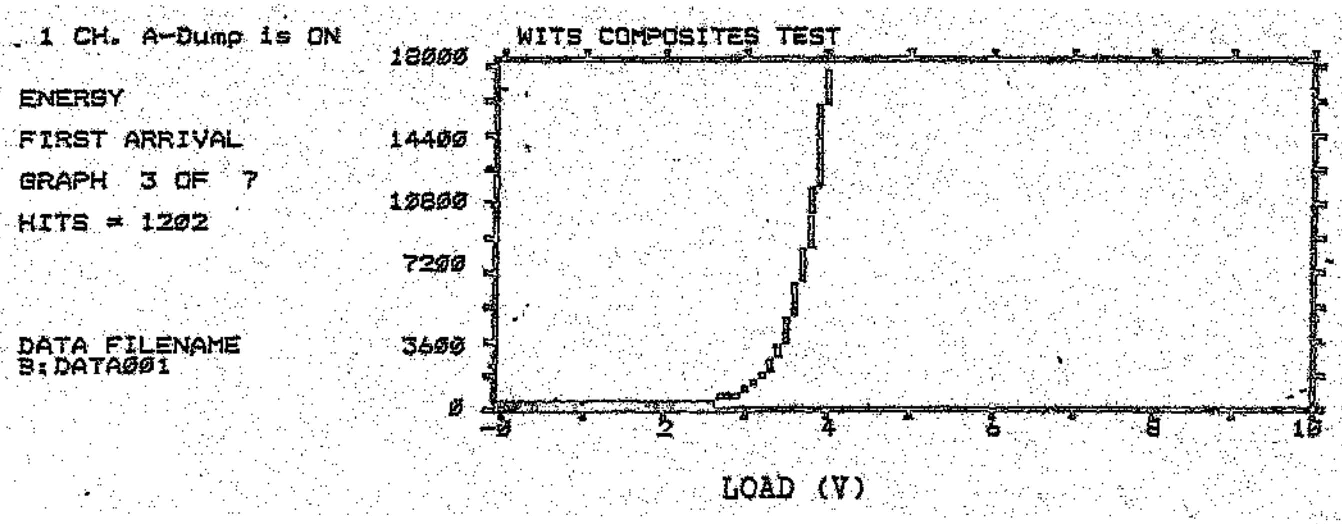
GRAPH 1 OF 7

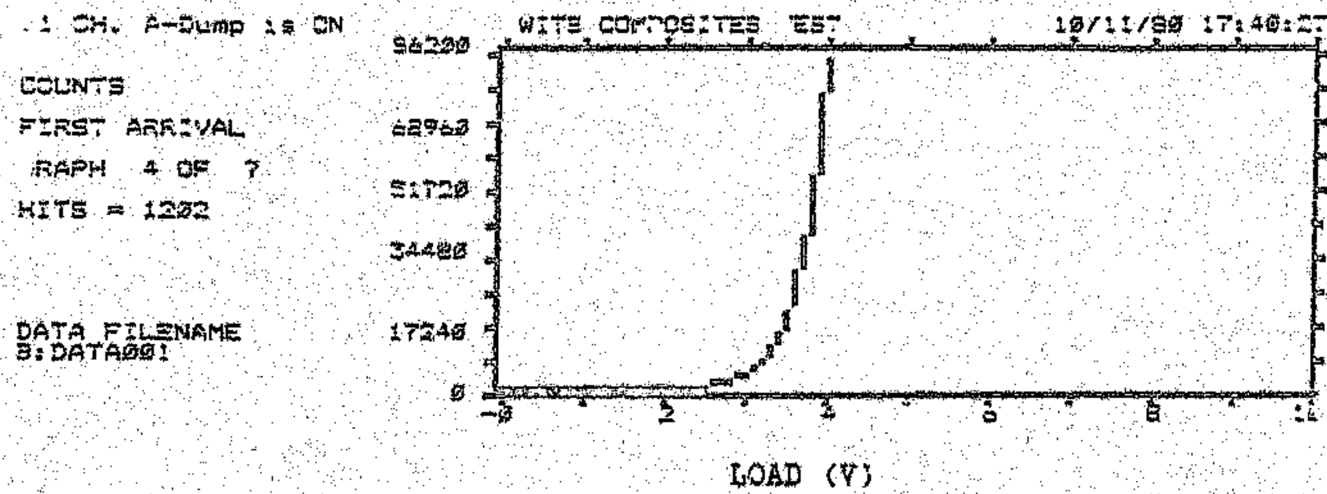
HITS = 1202

DATA FILENAME
B:DATA001

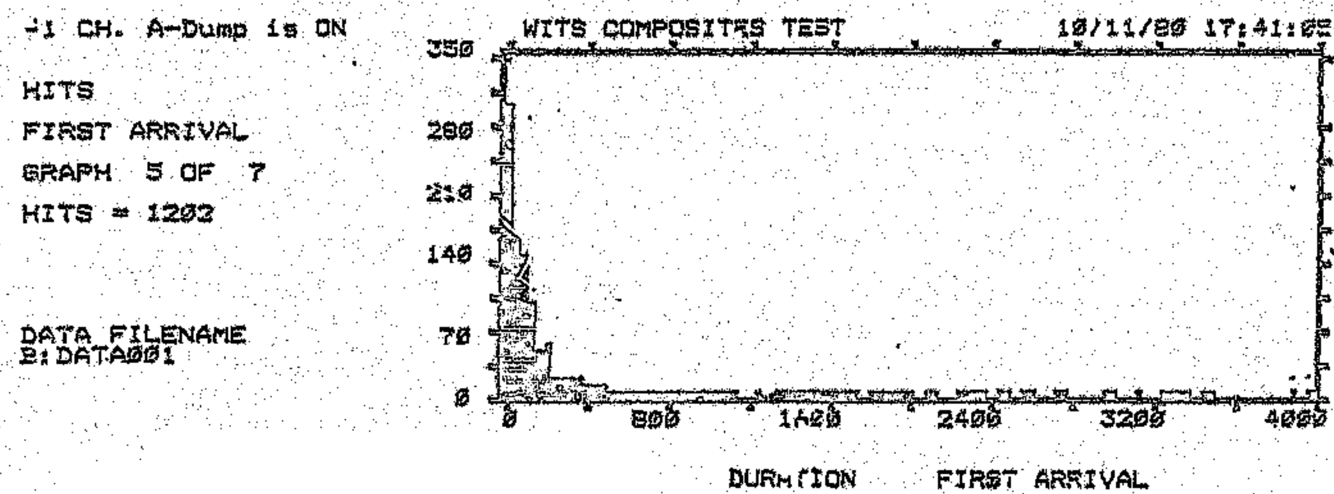



.1 CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 2 OF 7
HITS = 1202
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
10/11/80 17:39:15
350
280
210
140
70
0
0
120
240
360
480
600
RISE TIME FIRST ARRIVAL


.1 CH. A-Dump is ON
ENERGY
FIRST ARRIVAL
GRAPH 3 OF 7
HITS = 1202
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
18000
14400
10800
7200
3600
0
0
2
4
6
8
10
LOAD (V)



1 CH. A-Dump is ON
COUNTS
FIRST ARRIVAL
GRAPH 4 OF 7
HITS = 1202
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
10/11/80
86200
68960
51720
34480
17240
0
LOAD (V)



-1 CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 5 OF 7
HITS = 1203
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
10/11/80
350
280
210
140
70
0
0
800
1600
2400
3200
4000
DURATION FIRST ARRIVAL

1 CH. A-Dump is ON

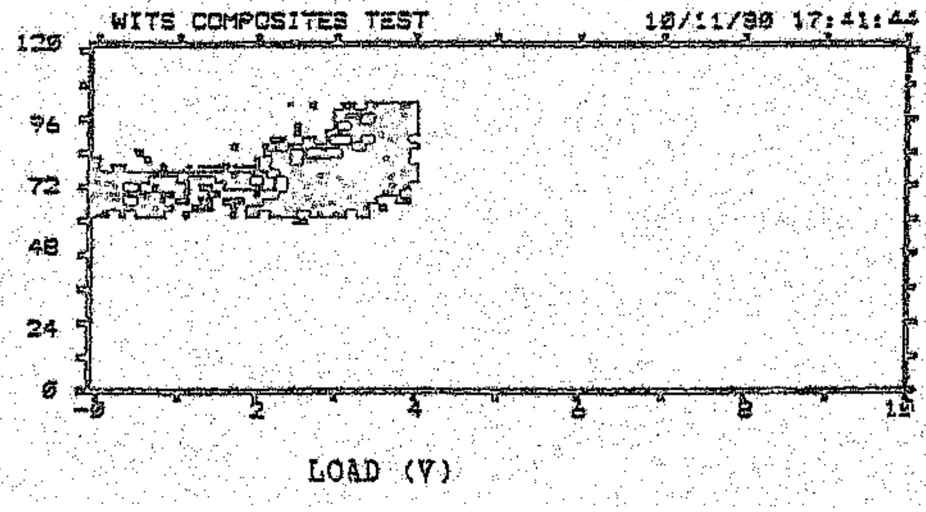
AMPLITUDE

FIRST ARRIVAL

GRAPH 6 OF 7

HITS = 1202

DATA FILENAME
B:DATA001



1 CH. A-Dump is ON

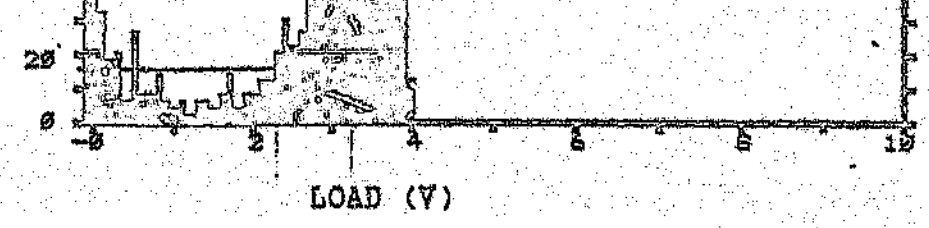
HITS

FIRST ARRIVAL

GRAPH 7 OF 7

HITS = 1202

DATA FILENAME
B:DATA001



; 1 CH. A-Dump is ON

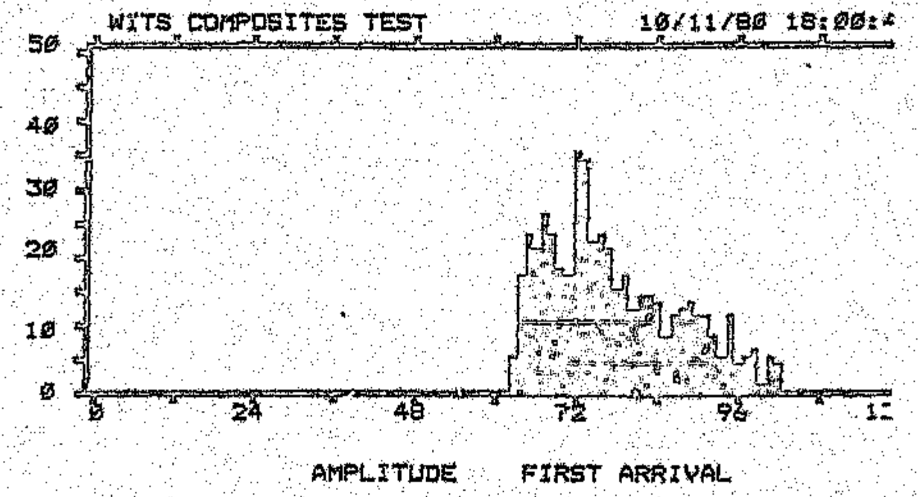
HITS

FIRST ARRIVAL

GRAPH 1 OF 7

HITS = 485

DATA FILENAME
B:DATA002



; 1 CH. A-Dump is ON

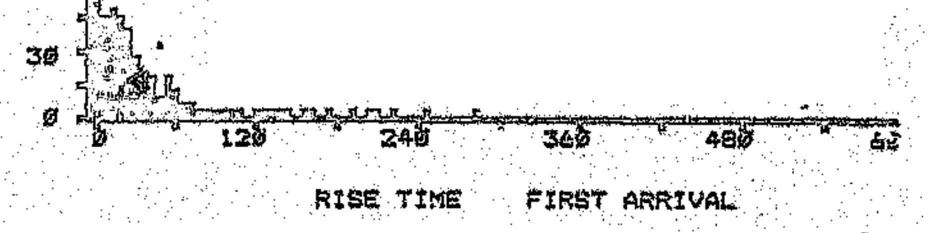
HITS

FIRST ARRIVAL

GRAPH 2 OF 7

HITS = 485

DATA FILENAME
B:DATA002



; 1 CH. A-Dump is ON

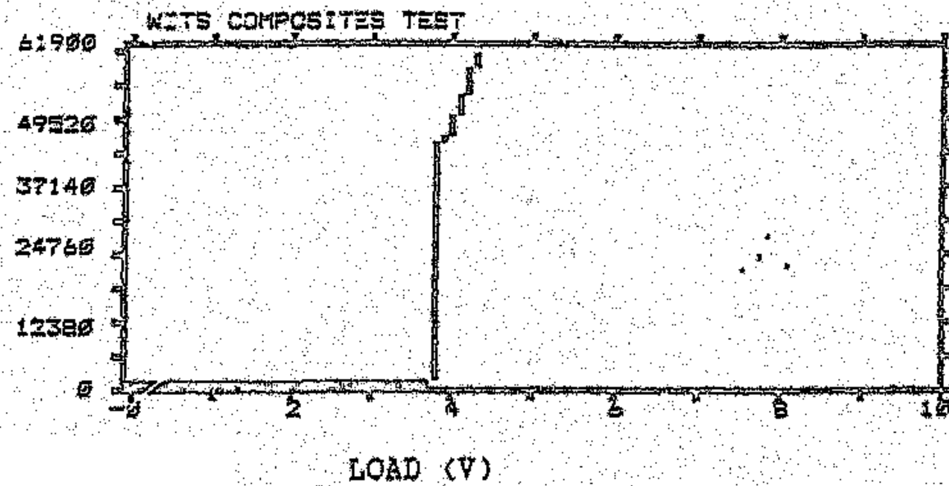
ENERGY

FIRST ARRIVAL

GRAPH 3 OF 7

HITS = 485

DATA FILENAME
B:DATA002



;1 CH. A-Dump is ON

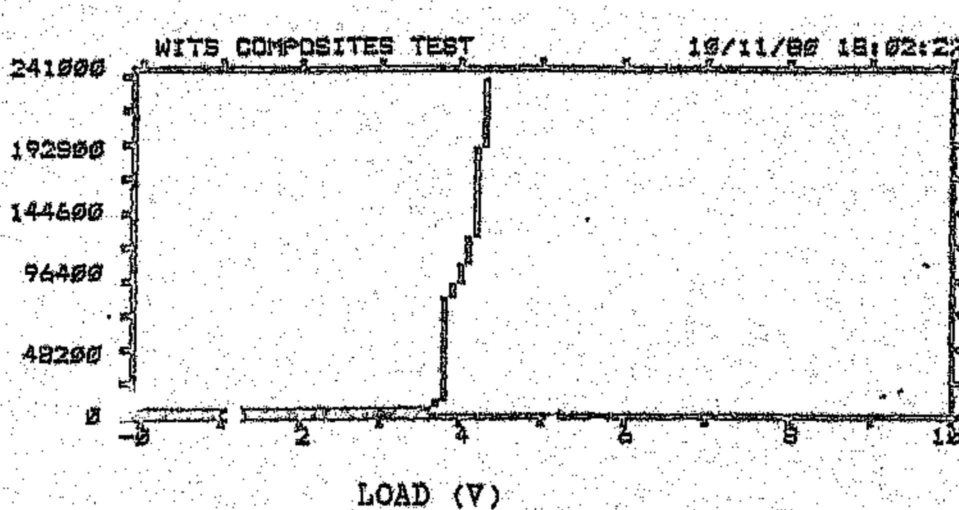
COUNTS

FIRST ARRIVAL

GRAPH 4 OF 7

HITS = 485

DATA FILENAME
B:DATA002



1 CH. A-Dump is ON

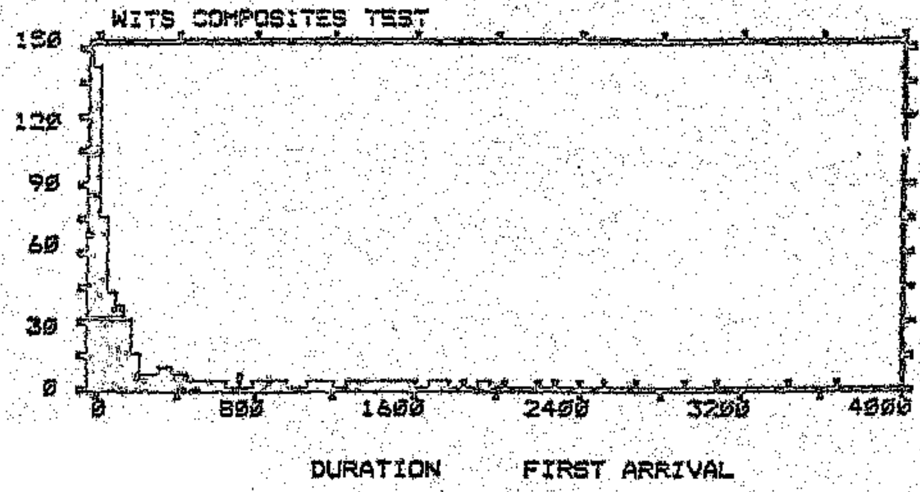
HITS

FIRST ARRIVAL

GRAPH 5 OF 7

HITS = 485

DATA FILENAME
B:DATA002



1 CH. A-Dump is ON

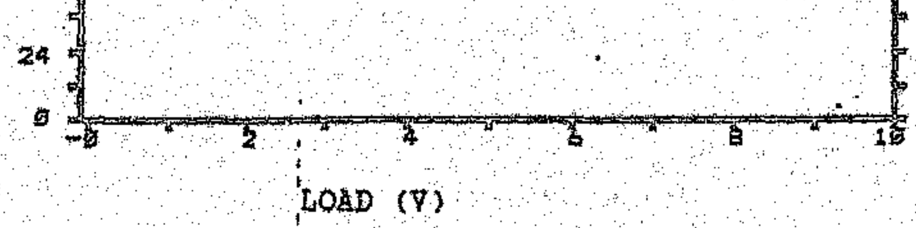
AMPLITUDE

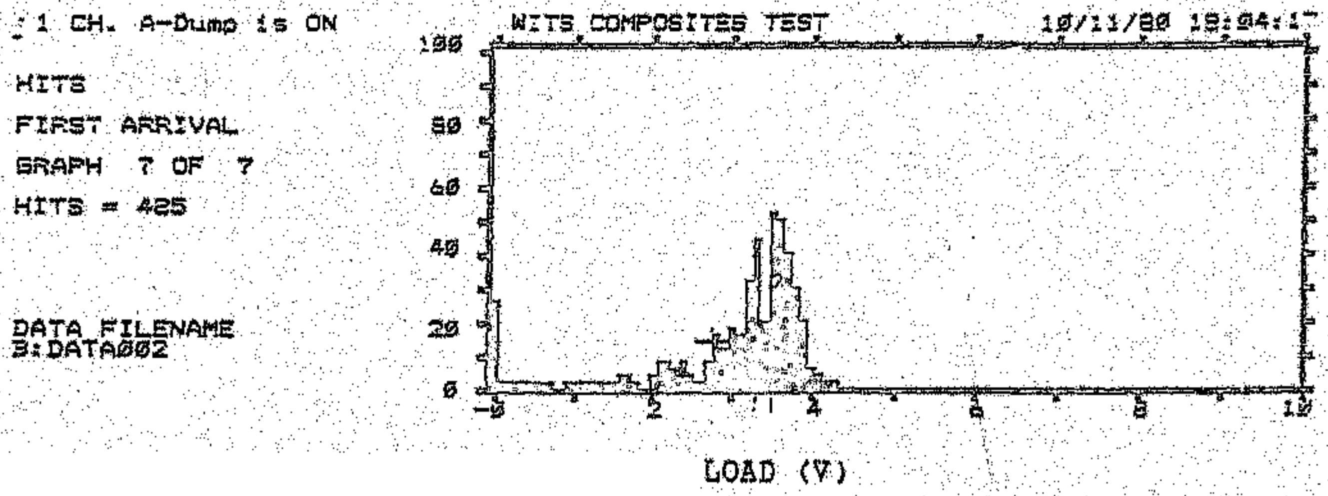
FIRST ARRIVAL

GRAPH 6 OF 7

HITS = 485

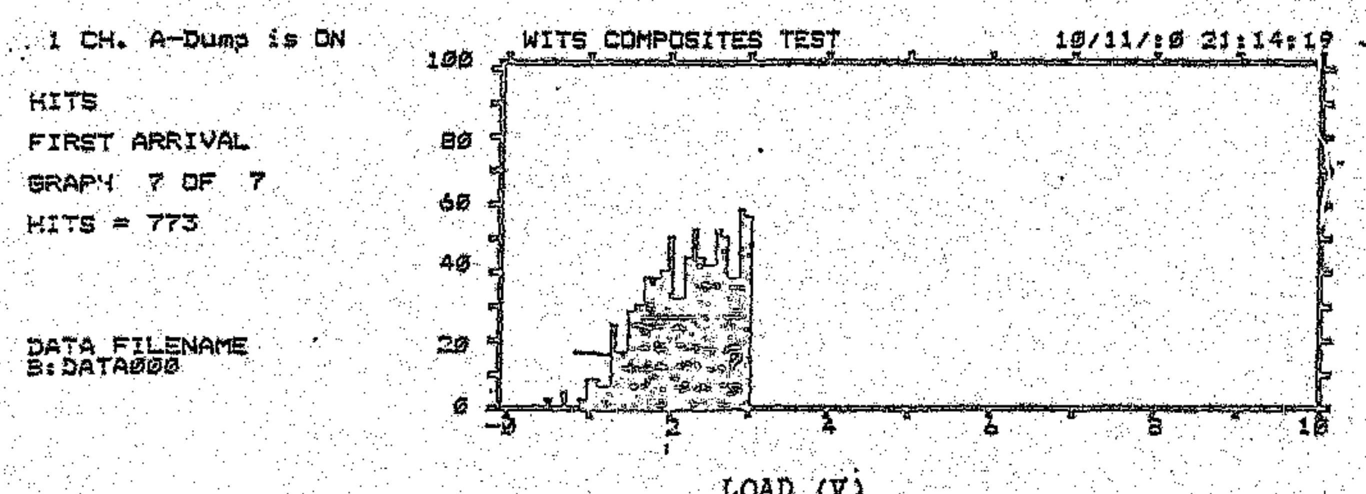
DATA FILENAME
B:DATA002

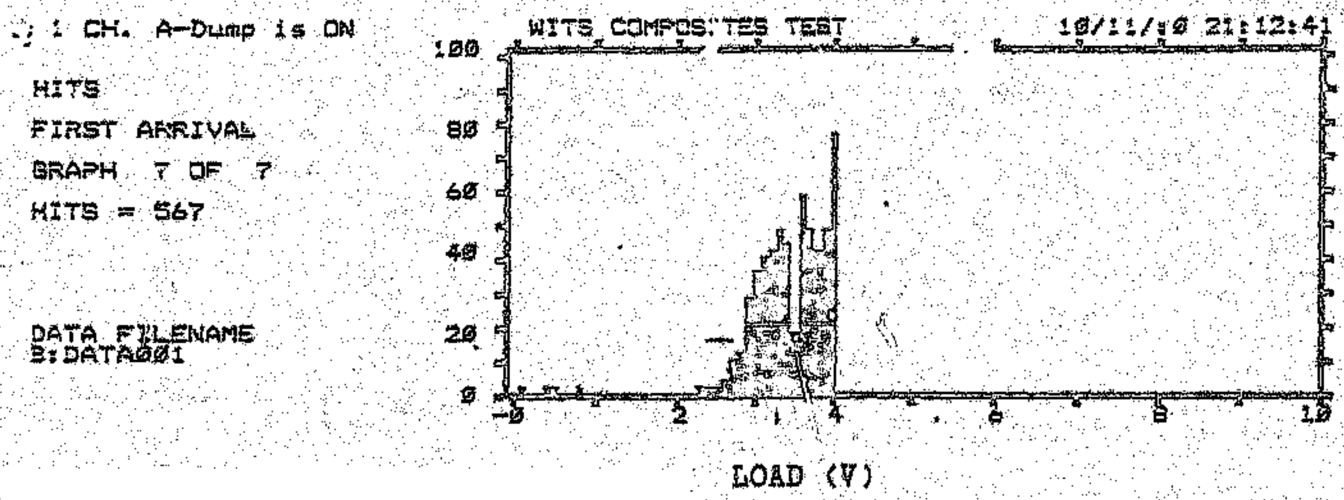


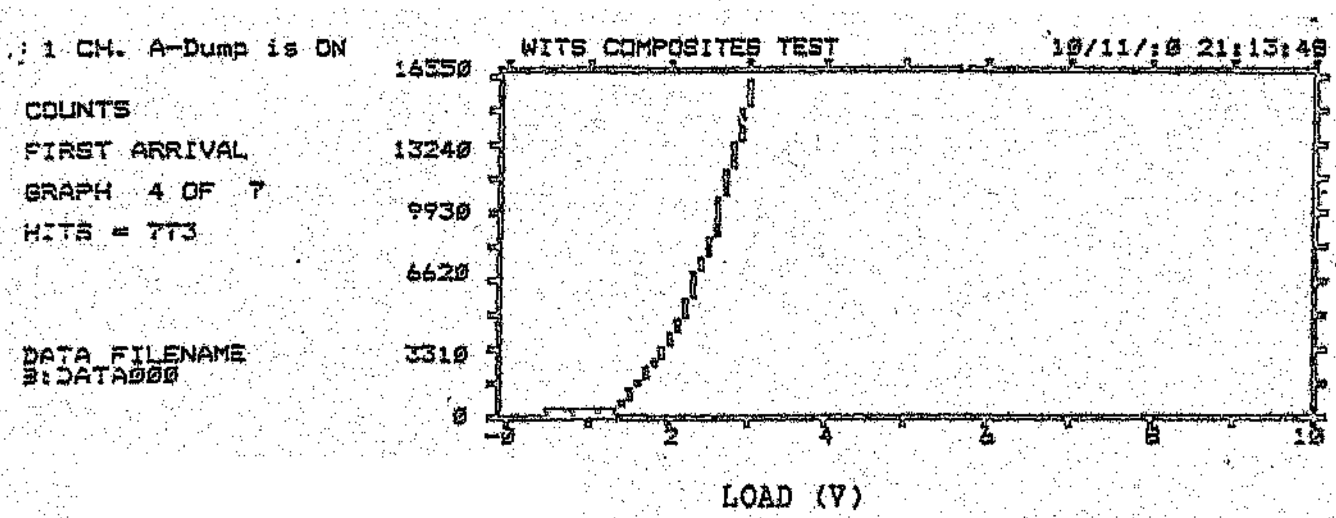

1 CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 7 OF 7
HITS = 425
DATA FILENAME
B:DATA002
WITS COMPOSITES TEST
10/11/80 19:04:17
LOAD (V)

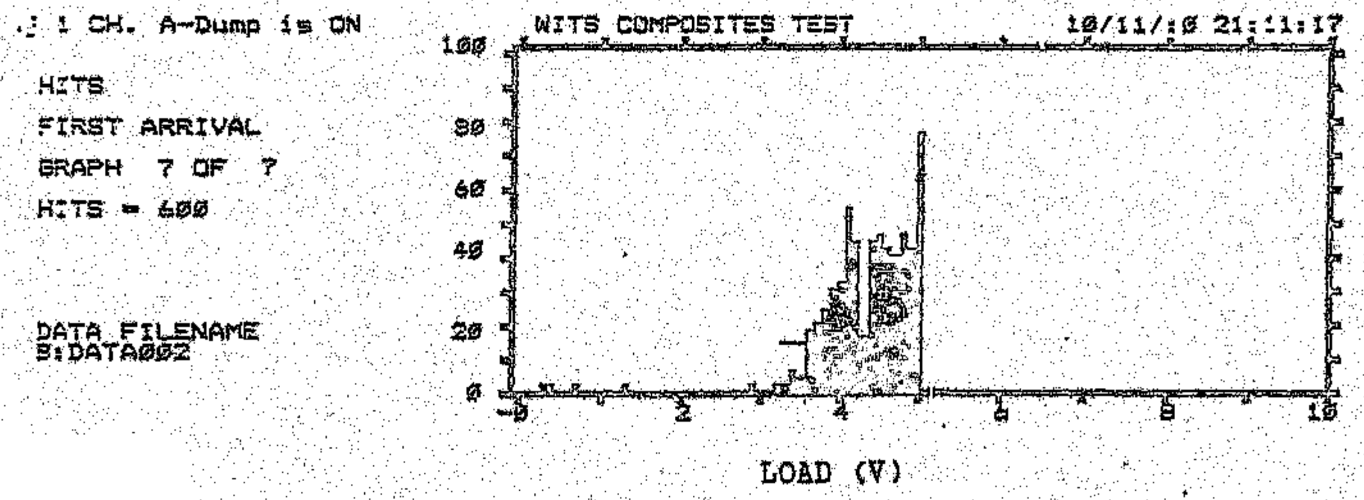
0/90° glass fibre specimens

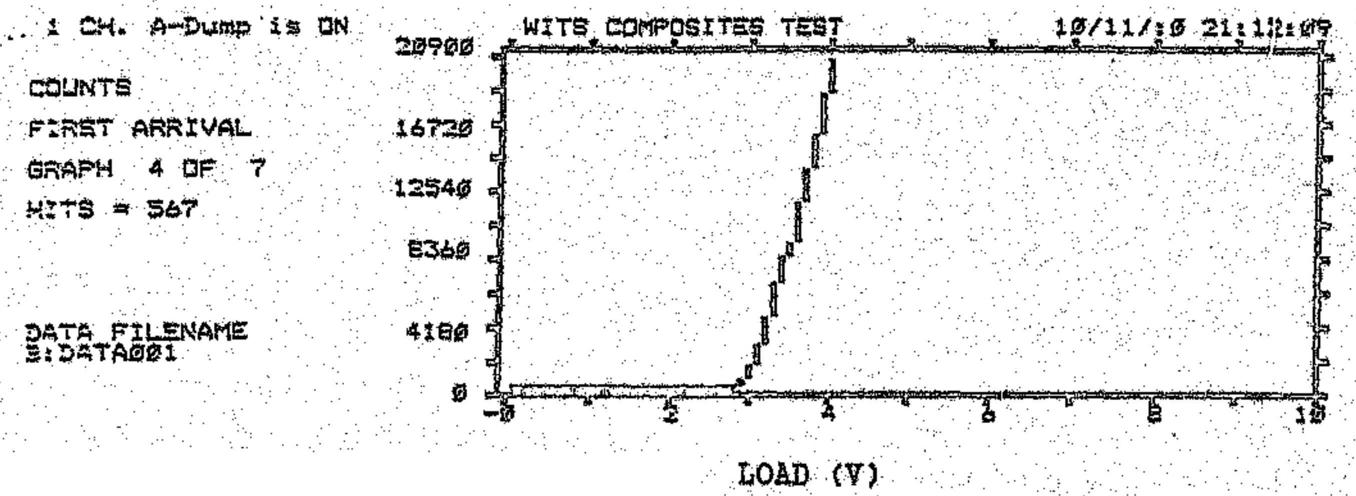
specimen 23


1 CH. A-Dump is ON
WITS COMPOSITES TEST
10/11/:0 21:14:19
HITS
FIRST ARRIVAL
GRAPH 7 OF 7
HITS = 773
DATA FILENAME
B:DATA000
100
80
60
40
20
0
0
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 7 OF 7
HITS = 567
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
100
80
60
40
20
0
0
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
COUNTS
FIRST ARRIVAL
GRAPH 4 OF 7
HITS = 773
DATA FILENAME
B:DATA000
WITS COMPOSITES TEST
16550
13240
9930
6620
3310
0
0
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 7 OF 7
HITS = 600
DATA FILENAME
B:DATA002
WITS COMPOSITES TEST
100
80
60
40
20
0
0
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
COUNTS
FIRST ARRIVAL
GRAPH 4 OF 7
HITS = 567
DATA FILENAME
B:DATA001
WITS COMPOSITES TEST
20900
16720
12540
8360
4180
0
0
2
4
6
8
10
LOAD (V)

1 CH. A-Dump is ON

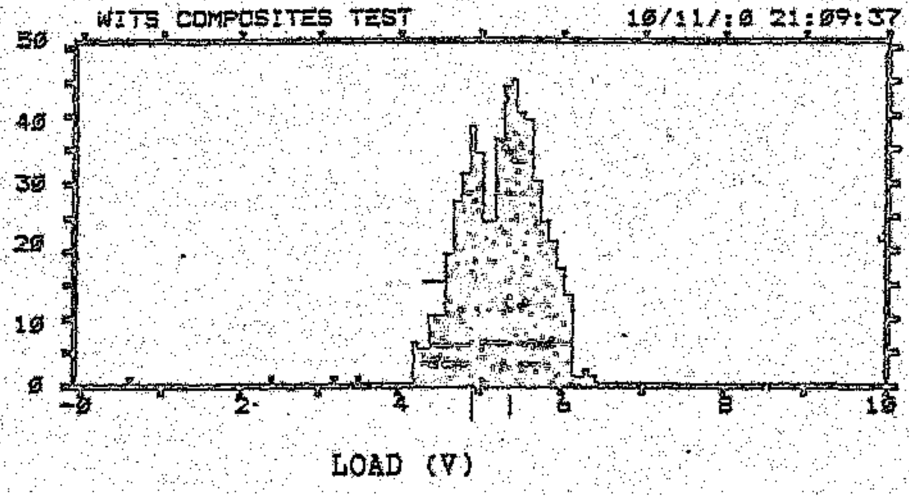
HITS

FIRST ARRIVAL

GRAPH 7 OF 7

HITS = 7864841

DATA FILENAME
B:POST003



1 CH. A-Dump is ON

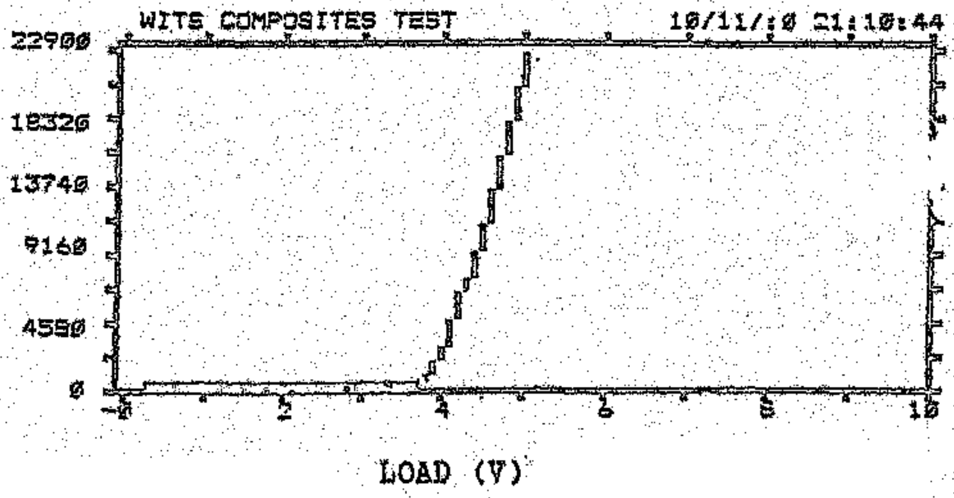
COUNTS

FIRST ARRIVAL

GRAPH 4 OF 7

HITS = 600

DATA FILENAME
B:DATA002



1 CH. A-Dump is ON

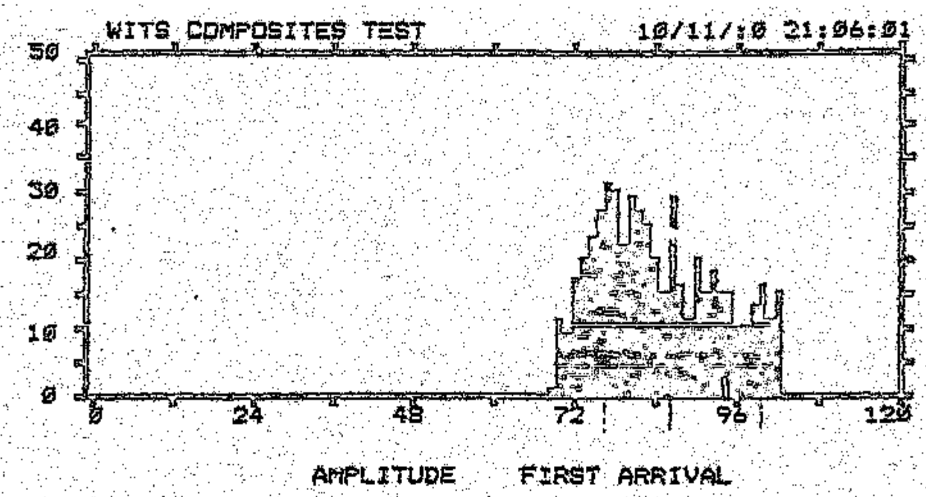
HITS

FIRST ARRIVAL

GRAPH 1 OF 7

HITS = 7864841

DATA FILENAME
B:POST003



1 CH. A-Dump is ON

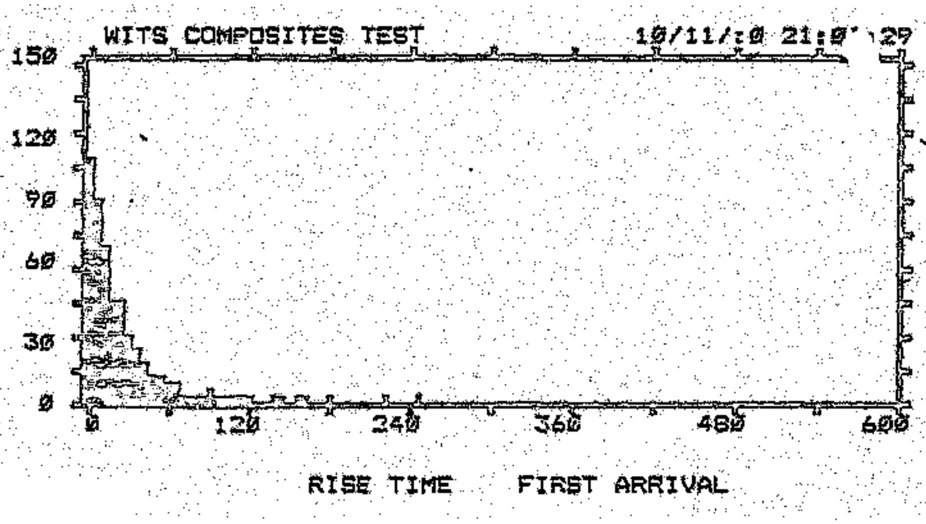
HITS

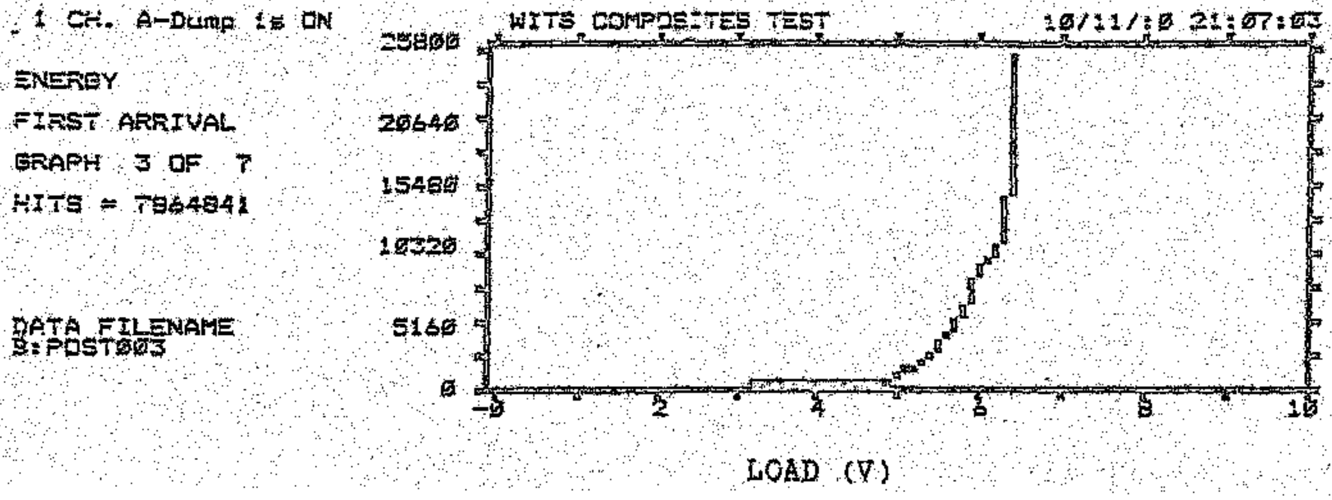
FIRST ARRIVAL

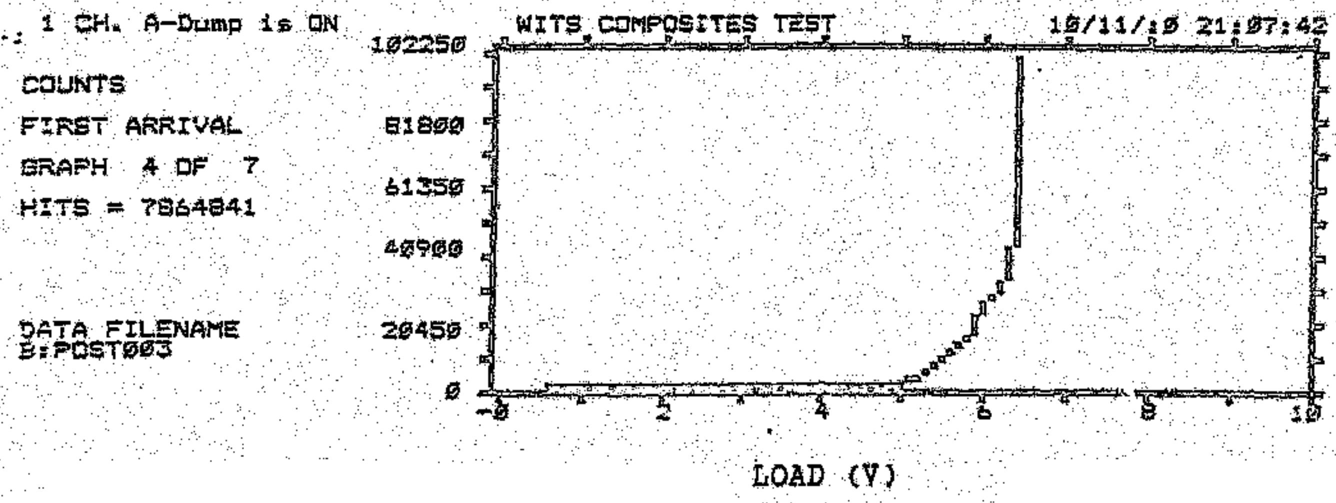
GRAPH 2 OF 7

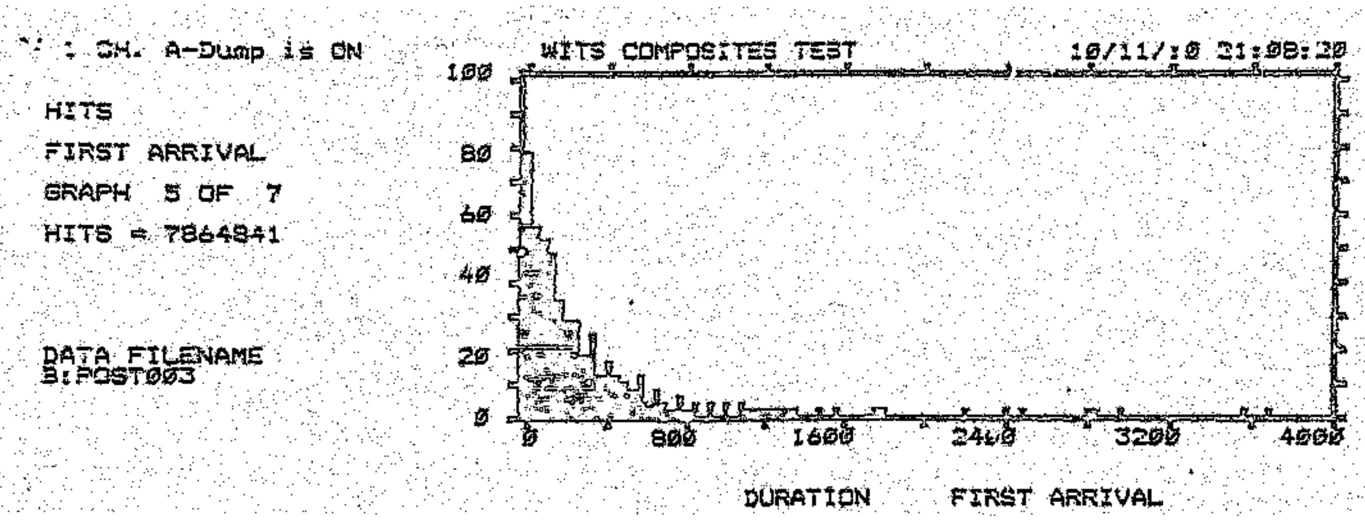
HITS = 7864841

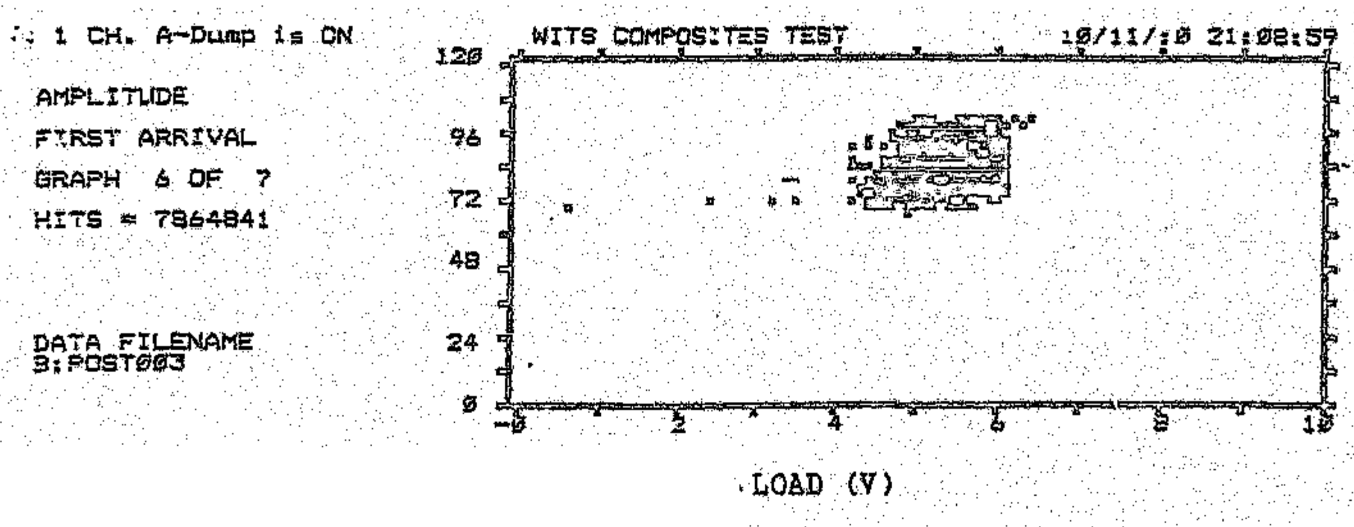
DATA FILENAME
B:POST003




1 CH. A-Dump is ON
ENERGY
FIRST ARRIVAL
GRAPH 3 OF 7
HITS = 7864841
DATA FILENAME
B:POST003
WITS COMPOSITES TEST
10/11/:0 21:07:03
25800
20640
15480
10320
5160
0
-0
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
COUNTS
FIRST ARRIVAL
GRAPH 4 OF 7
HITS = 7864841
DATA FILENAME
B:POST003
WITS COMPOSITES TEST
10/11/:0 21:07:42
102250
81800
61350
40900
20450
0
-0
2
4
6
8
10
LOAD (V)


1 CH. A-Dump is ON
HITS
FIRST ARRIVAL
GRAPH 5 OF 7
HITS = 7864841
DATA FILENAME
B:POST003
WITS COMPOSITES TEST
10/11/:0 21:08:20
100
80
60
40
20
0
0
800
1600
2400
3200
4000
DURATION
FIRST ARRIVAL


1 CH. A-Dump is ON
AMPLITUDE
FIRST ARRIVAL
GRAPH 6 OF 7
HITS = 7864841
DATA FILENAME
B:POST003
WITS COMPOSITES TEST
10/11/:0 21:08:59
120
96
72
48
24
0
-0
2
4
6
8
10
LOAD (V)

APPENDIX C - Results from IBM Computer

2nd Set of Glass Fibre Reinforced Specimens

These plots were used to obtain ply failure information. Three or four specimens are plotted on each set of axes, and there are two similarly labelled graphs for each laminate type. Three different parameters were plotted:

1) duration time vs load
2) event rate vs load
3) energy vs load

All the parameters are non-cumulative.

Figure C.1 +-45 Laminate

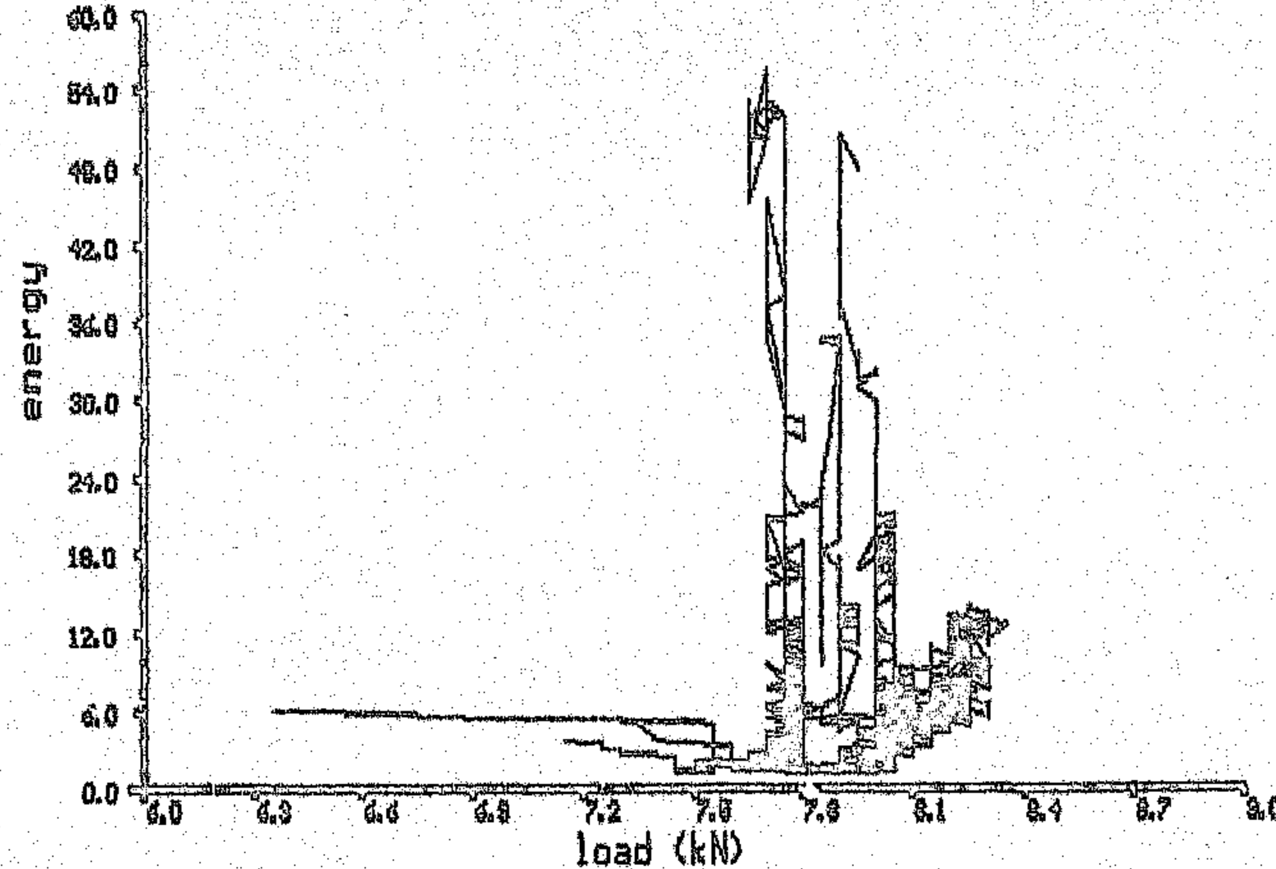


Figure C.2 +-45 Laminate

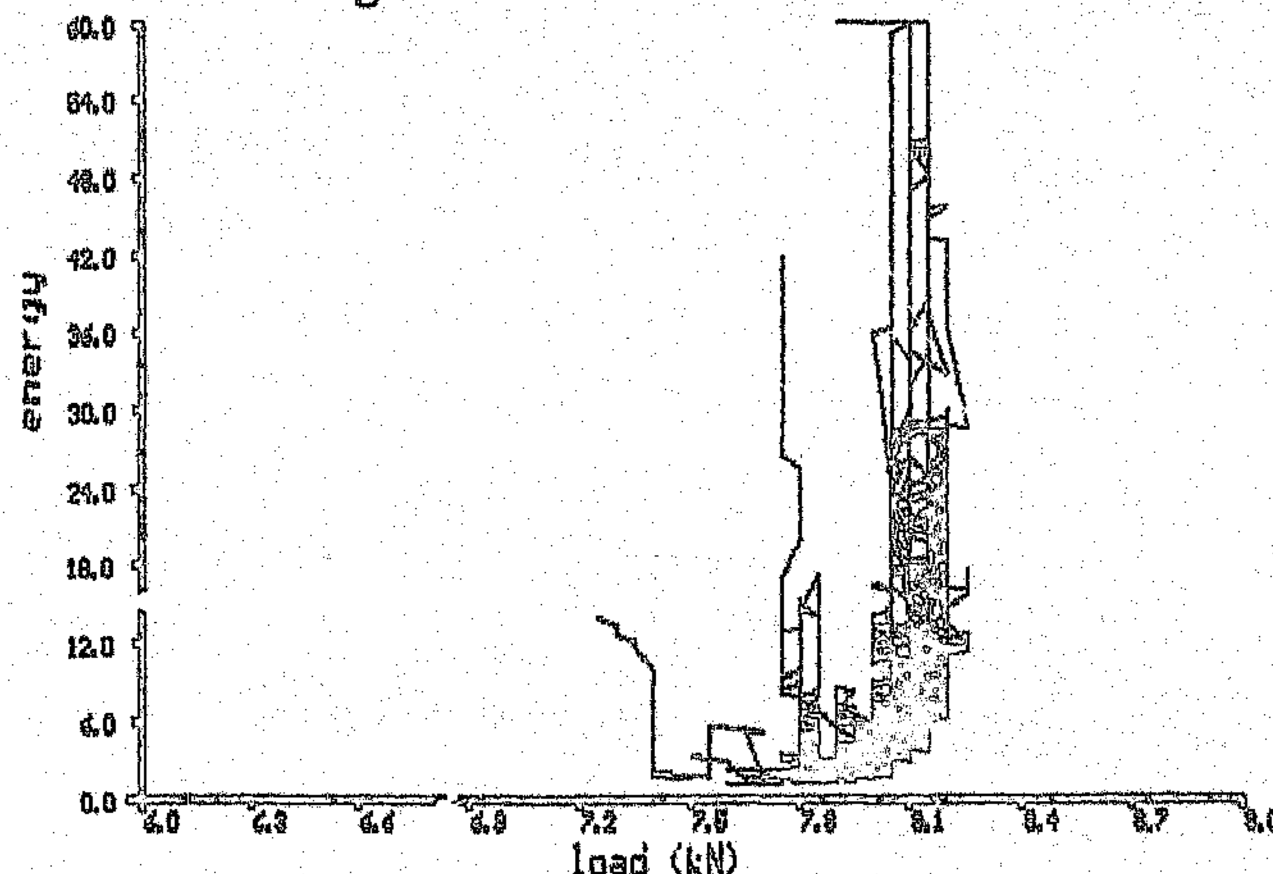


Figure C.3 0/90 Laminate

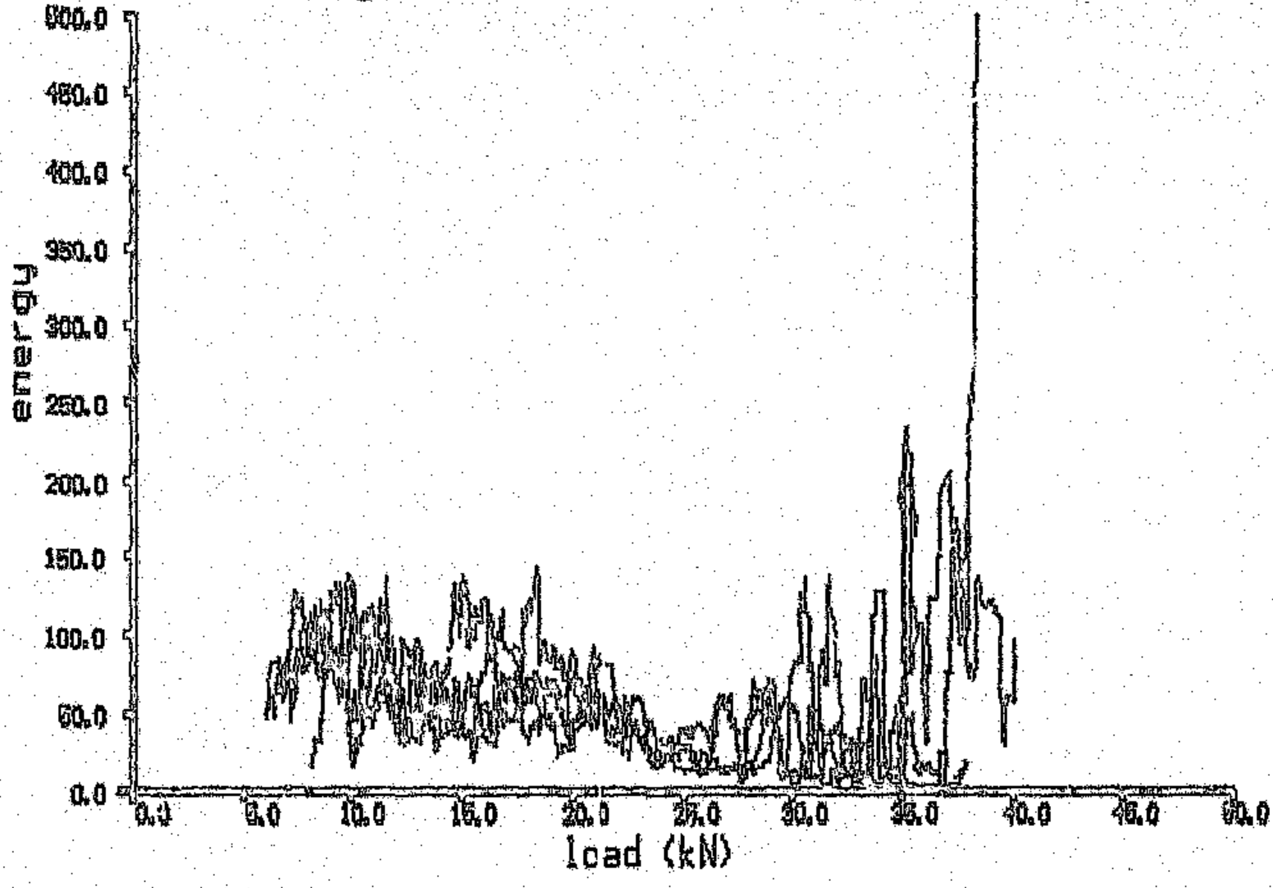


Figure C.4 0/90 Laminate

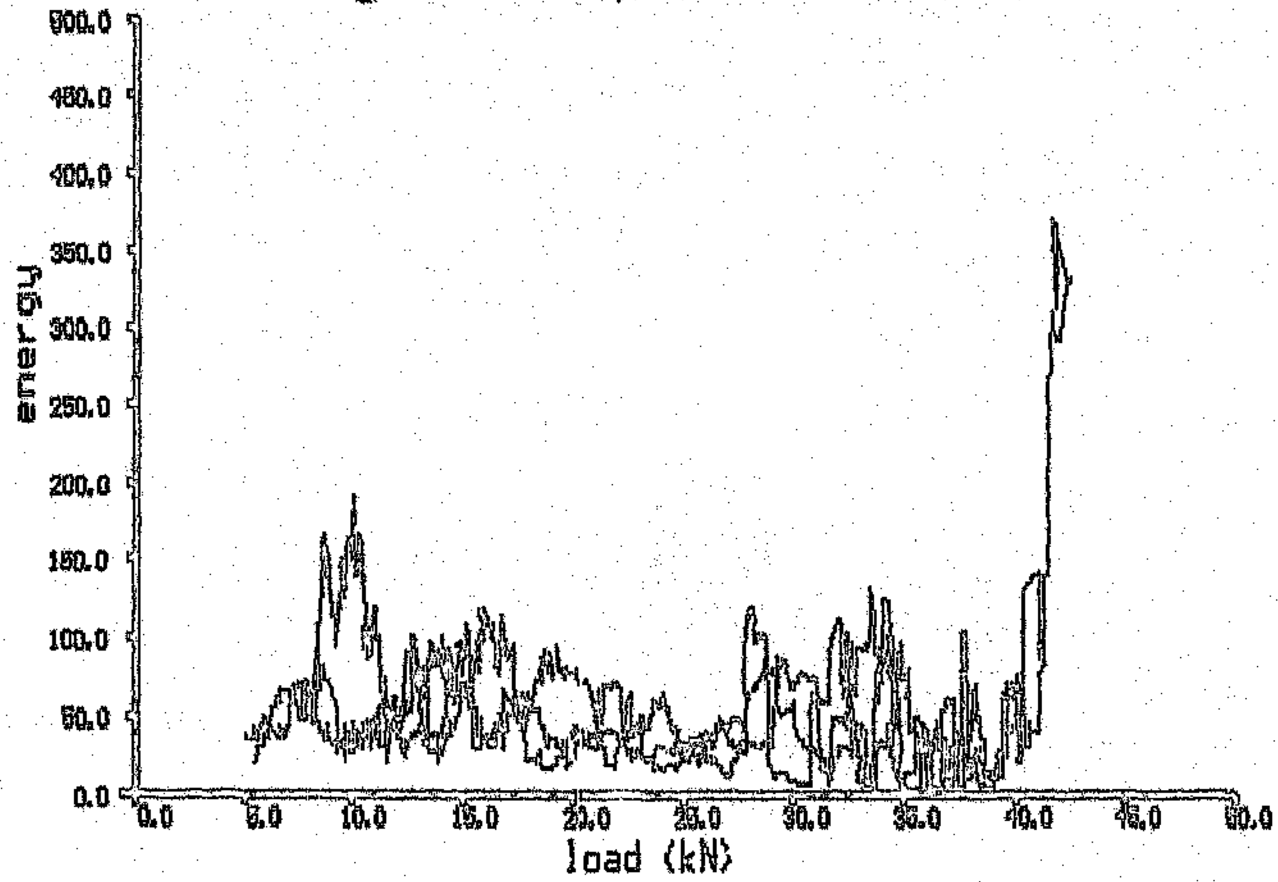


Figure C.5 90/+-45 Laminate

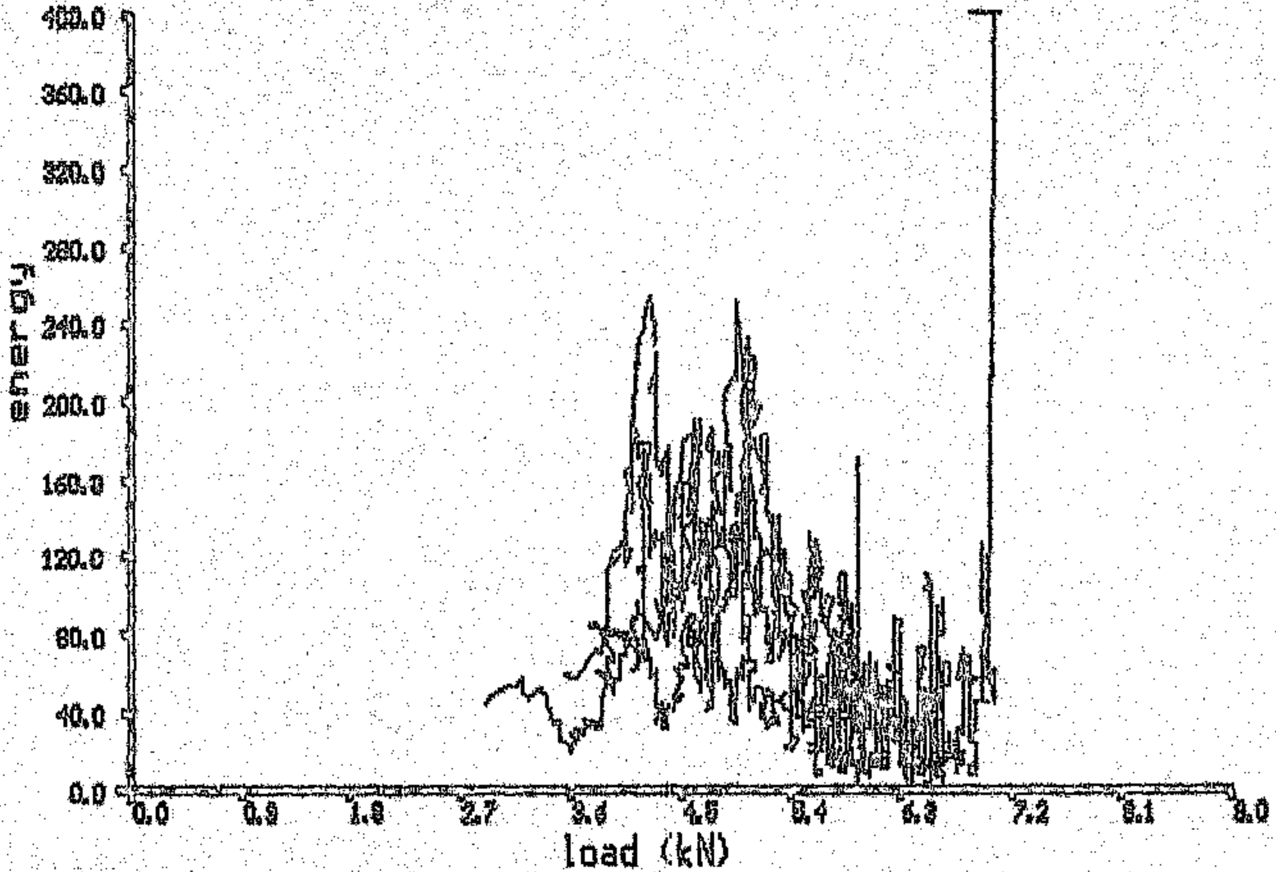


Figure C.6 90/+-45 Laminate

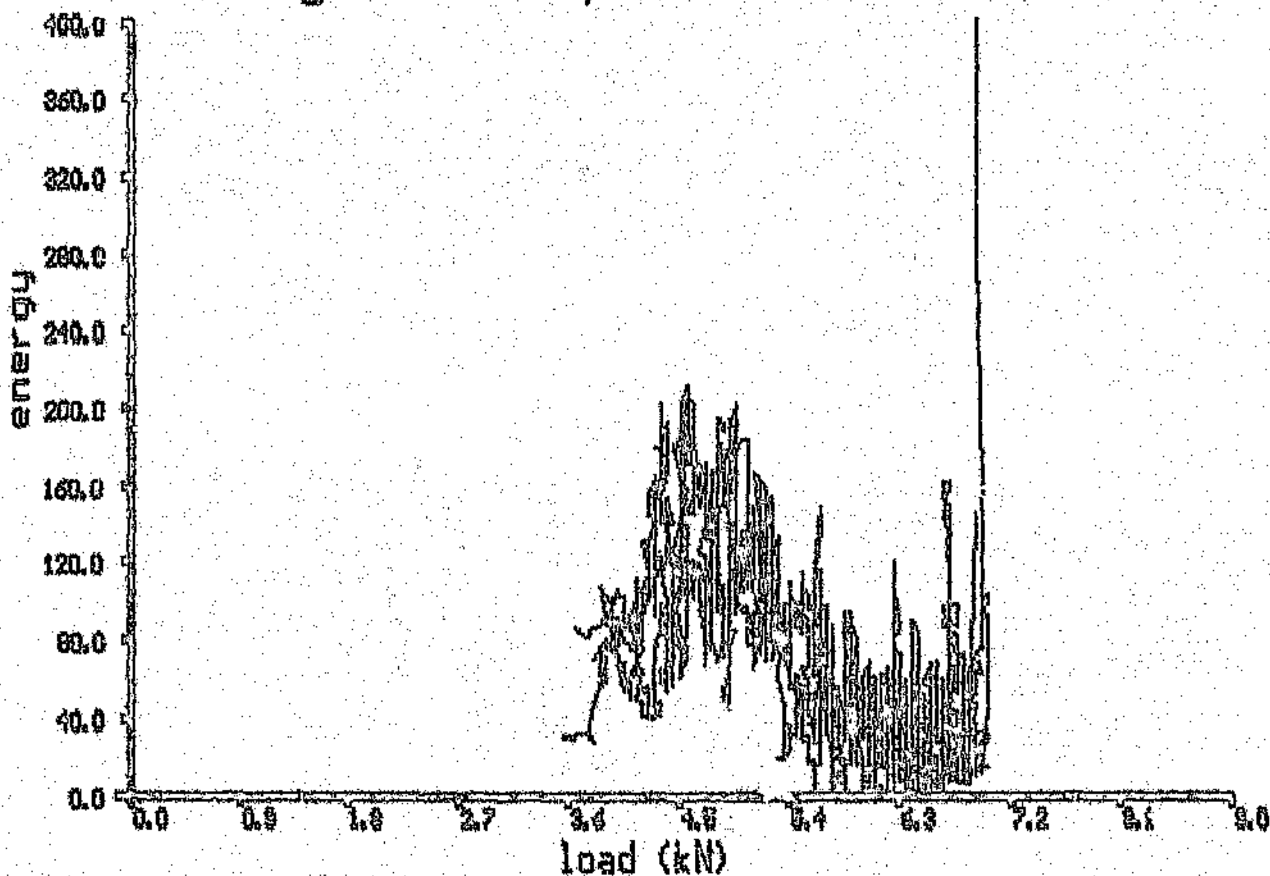


Figure C.7 0/90/+-45 Laminate

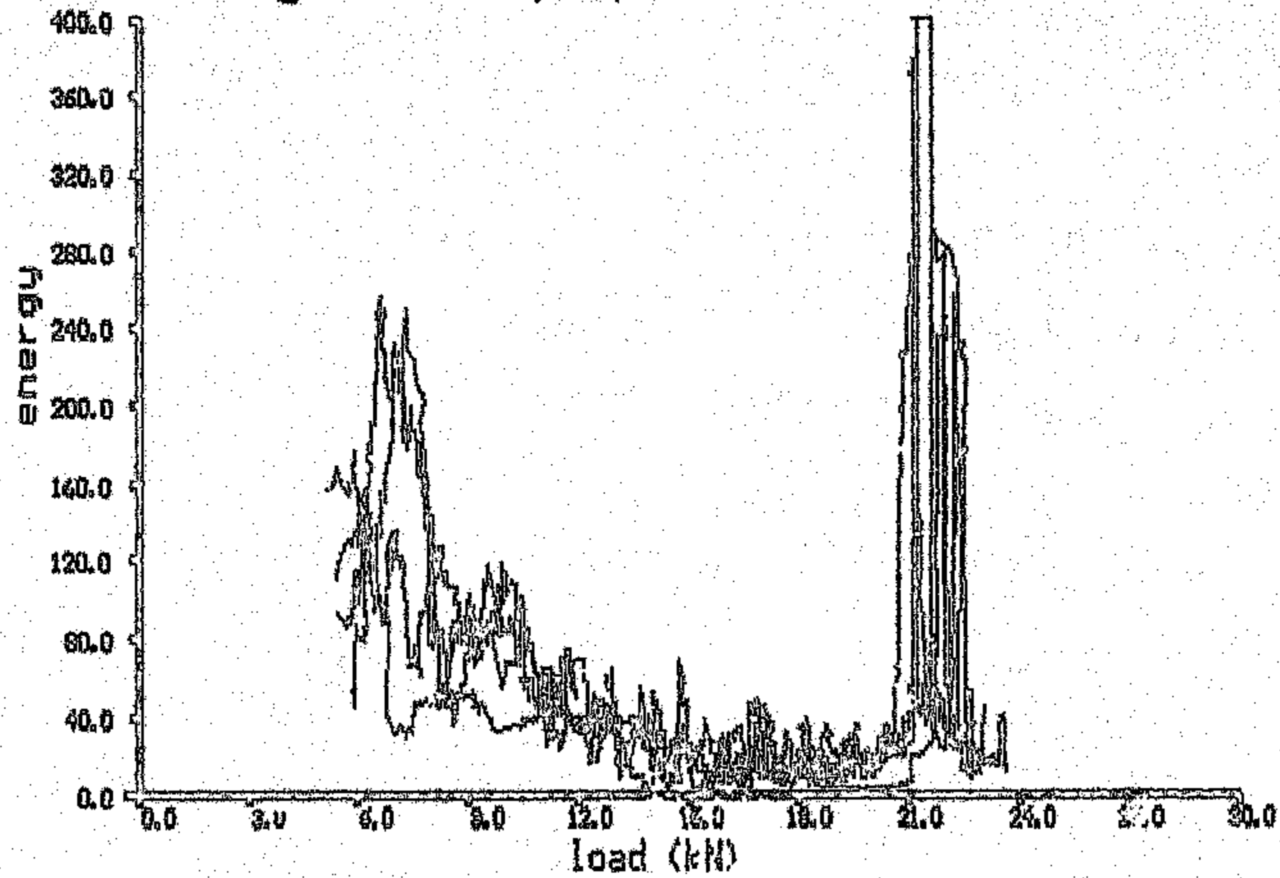


Figure C.8 0/90/+-45 Laminate

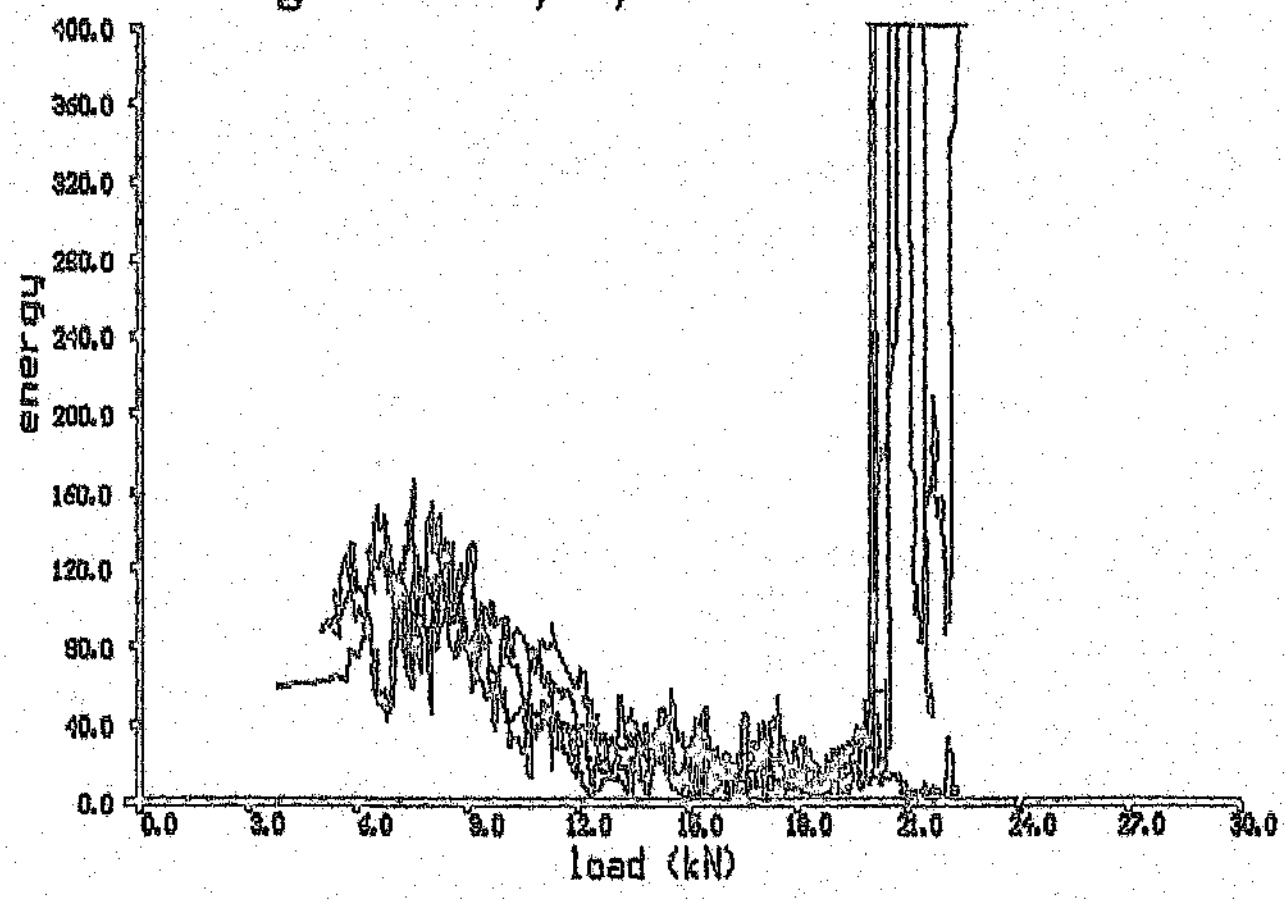
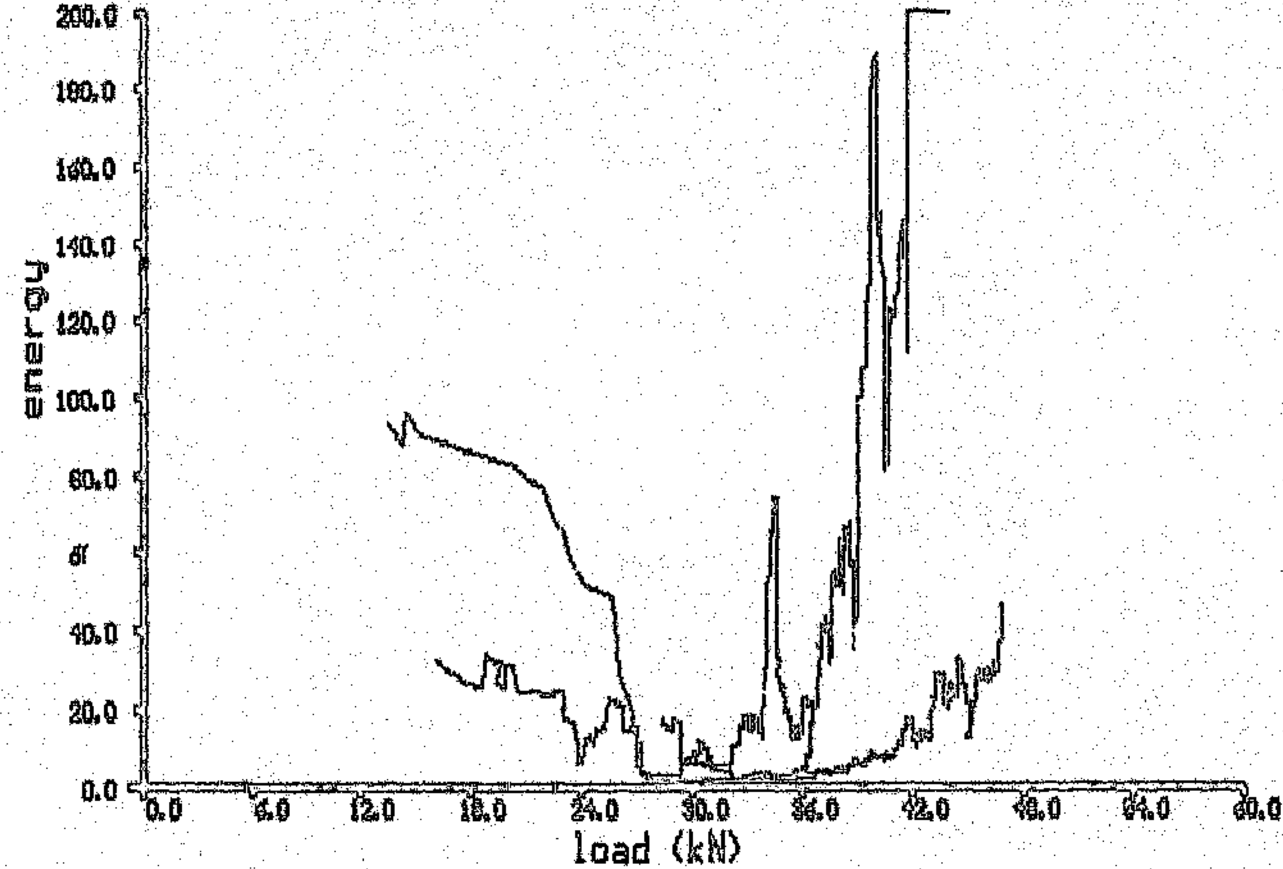


Figure C.10 0/+-45 Laminate



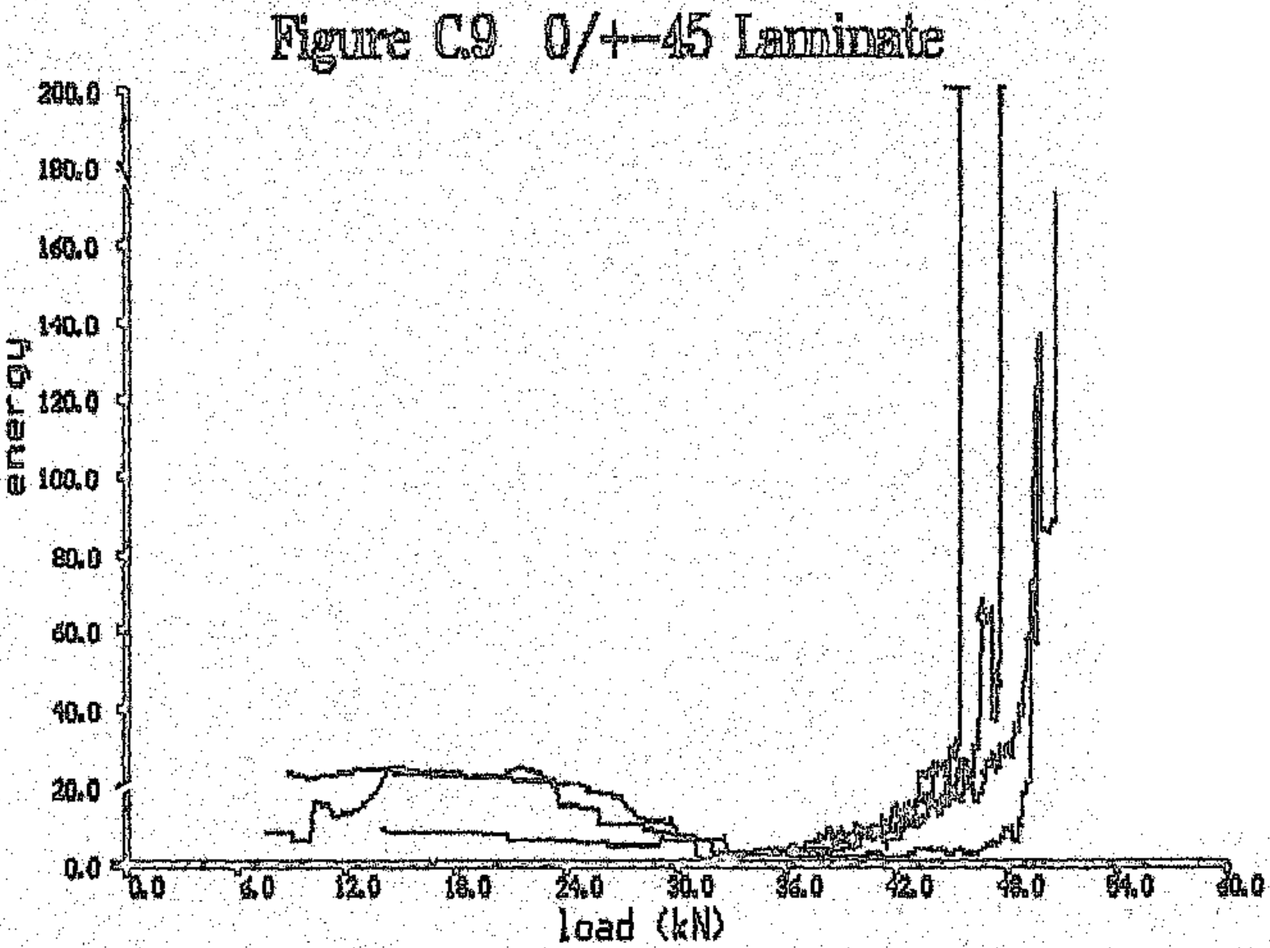


Figure C.9 0/+-45 Laminate
energy
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
6.0
12.0
18.0
24.0
30.0
36.0
42.0
48.0
54.0
60.0
load (kN)

Figure C.12 +-45 Laminate

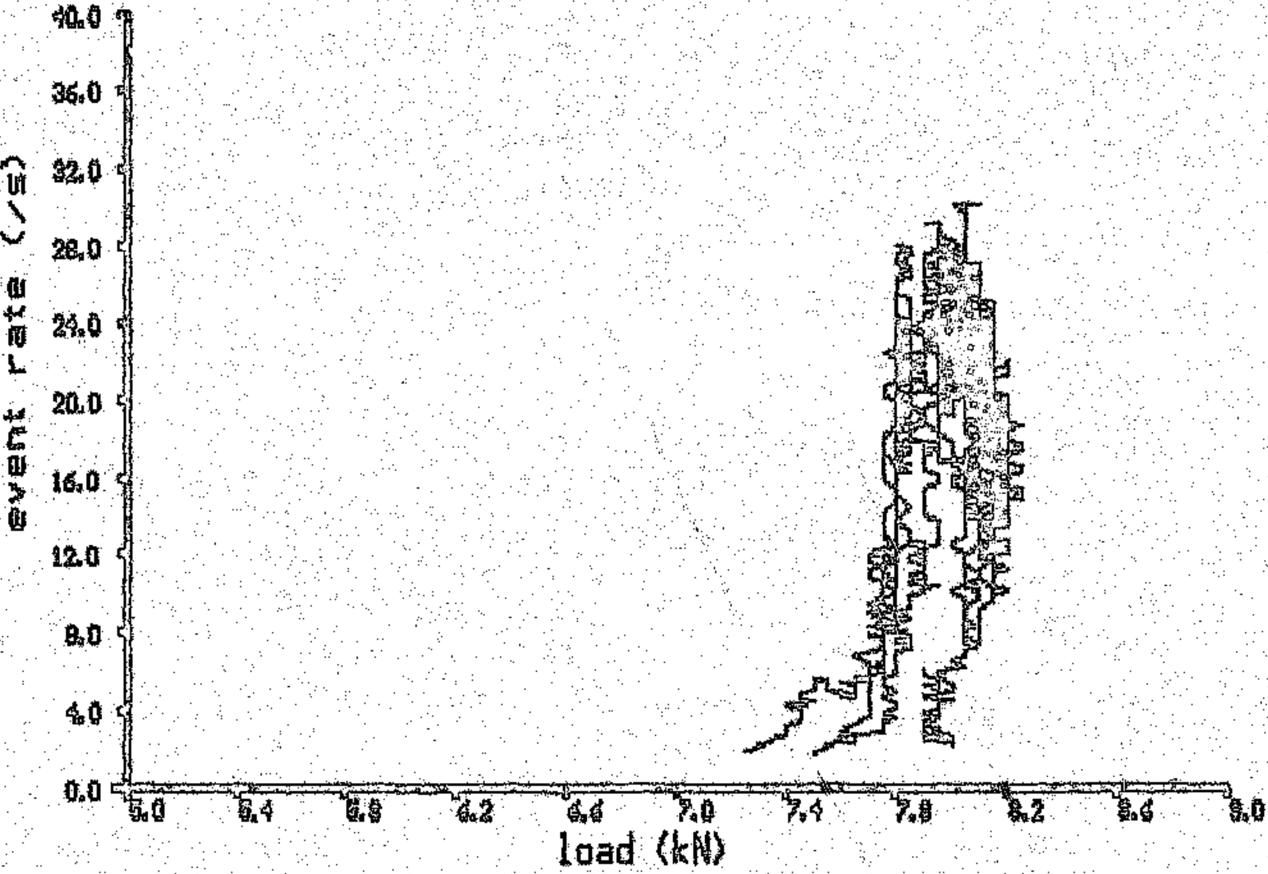


Figure C.11 +-45 Laminate

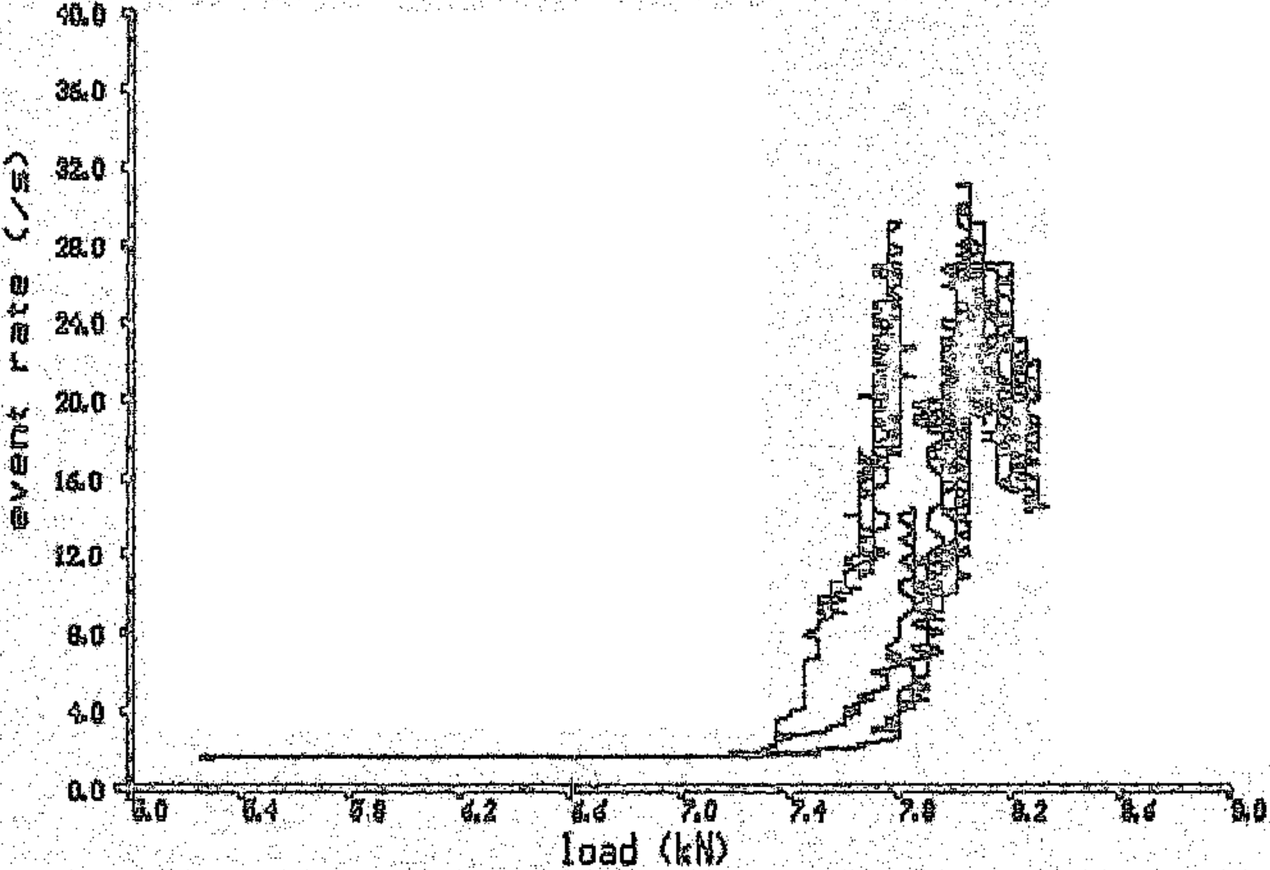


Figure C.14 0/90 Laminate

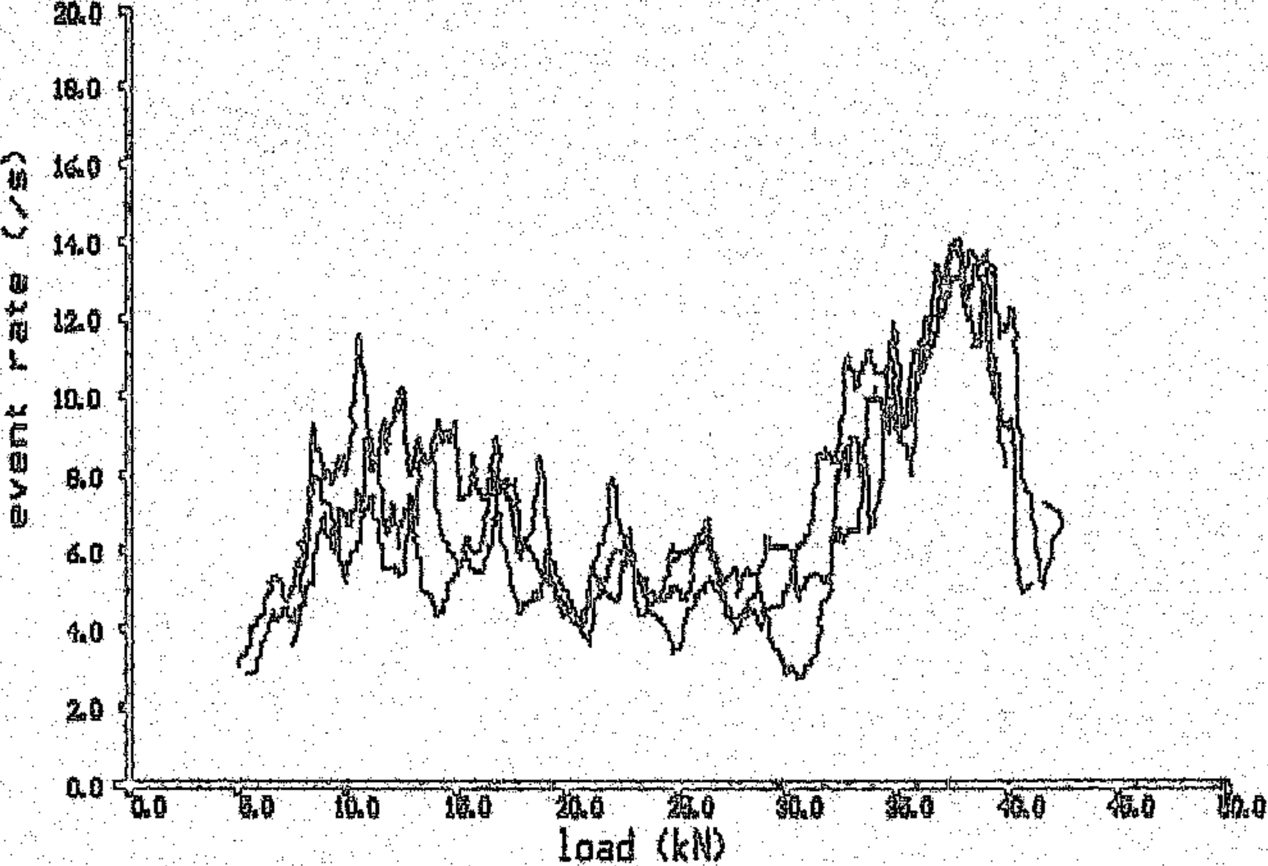


Figure C.13 0/90 Laminate

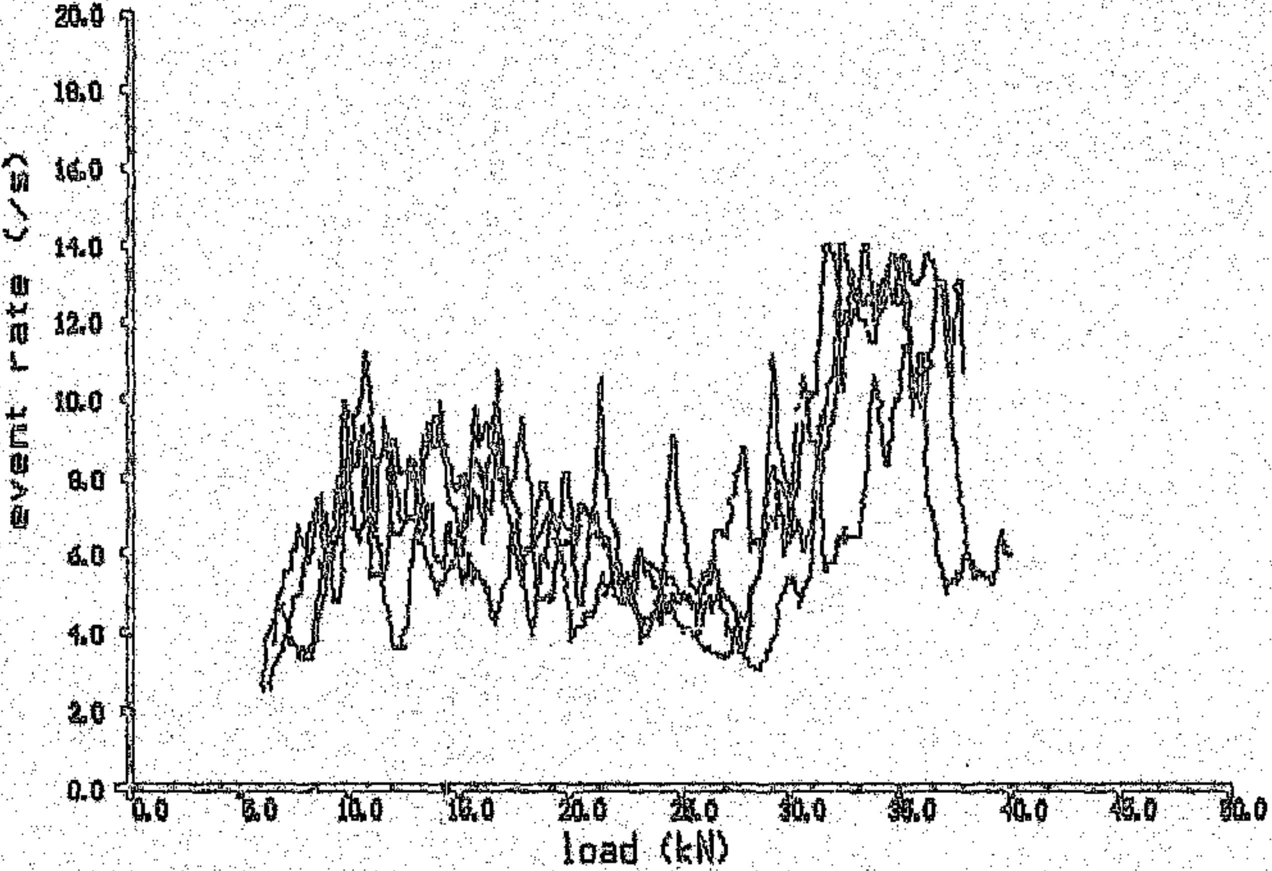


Figure C.15 90/+-45 Laminate

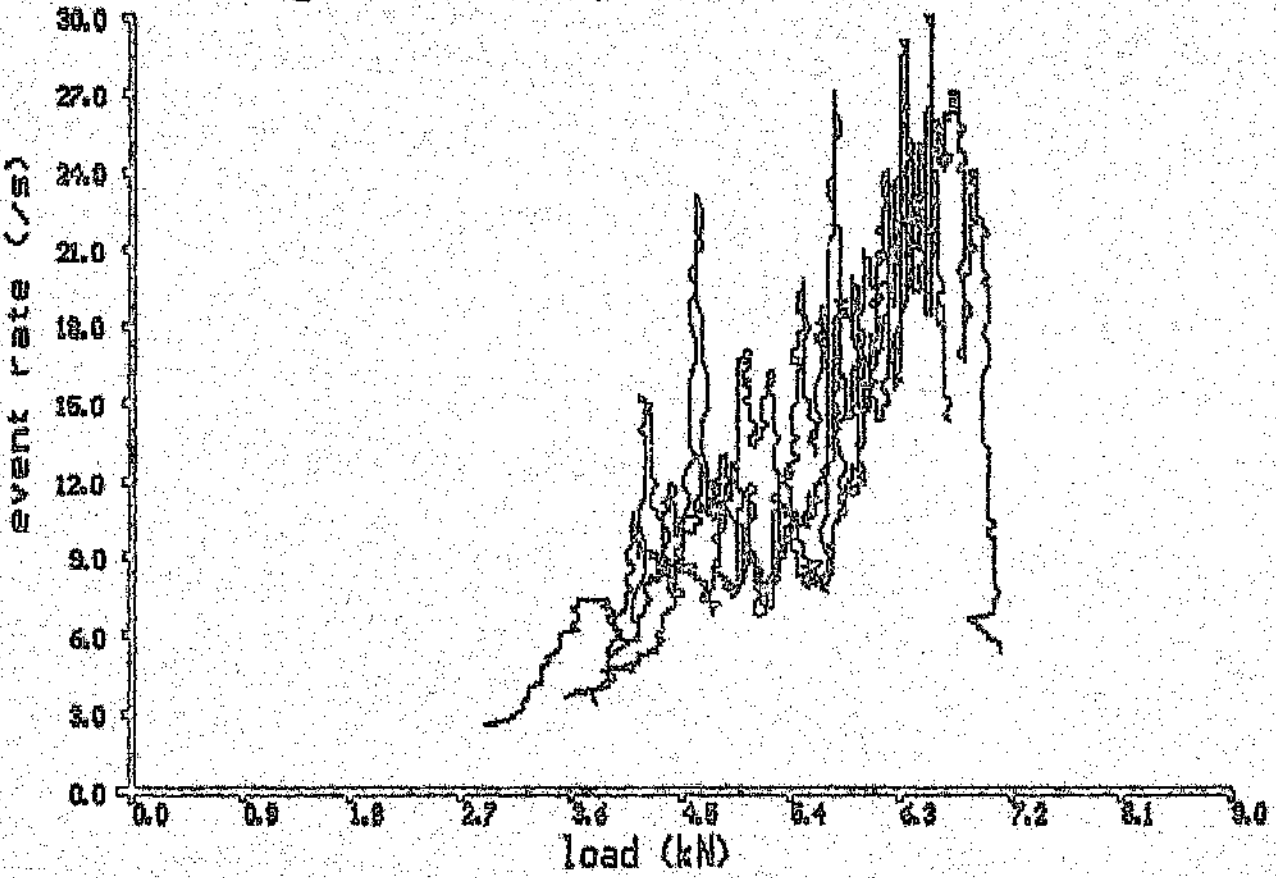


Figure C.16 90/+-45 Laminate

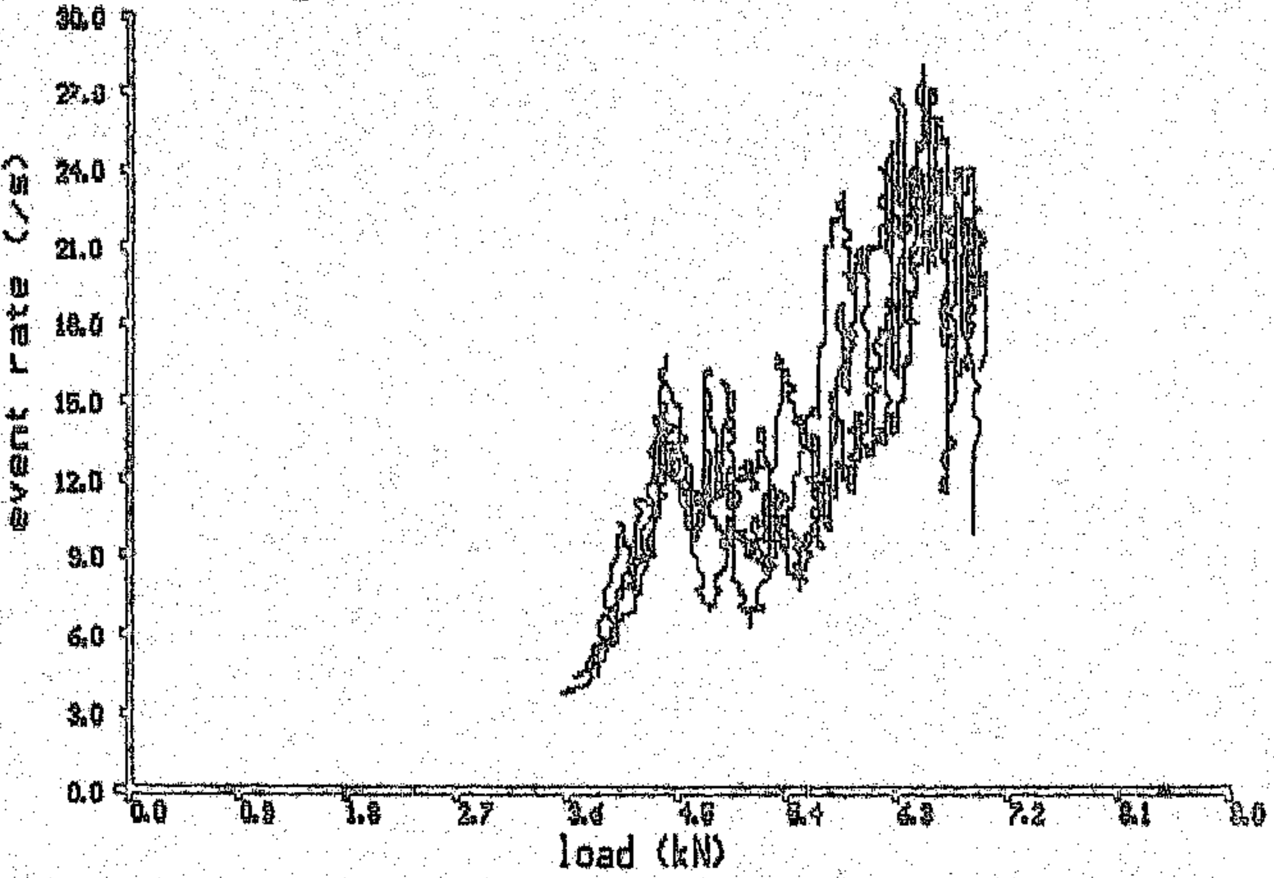


Figure C.18 0/90/+-45 Laminate

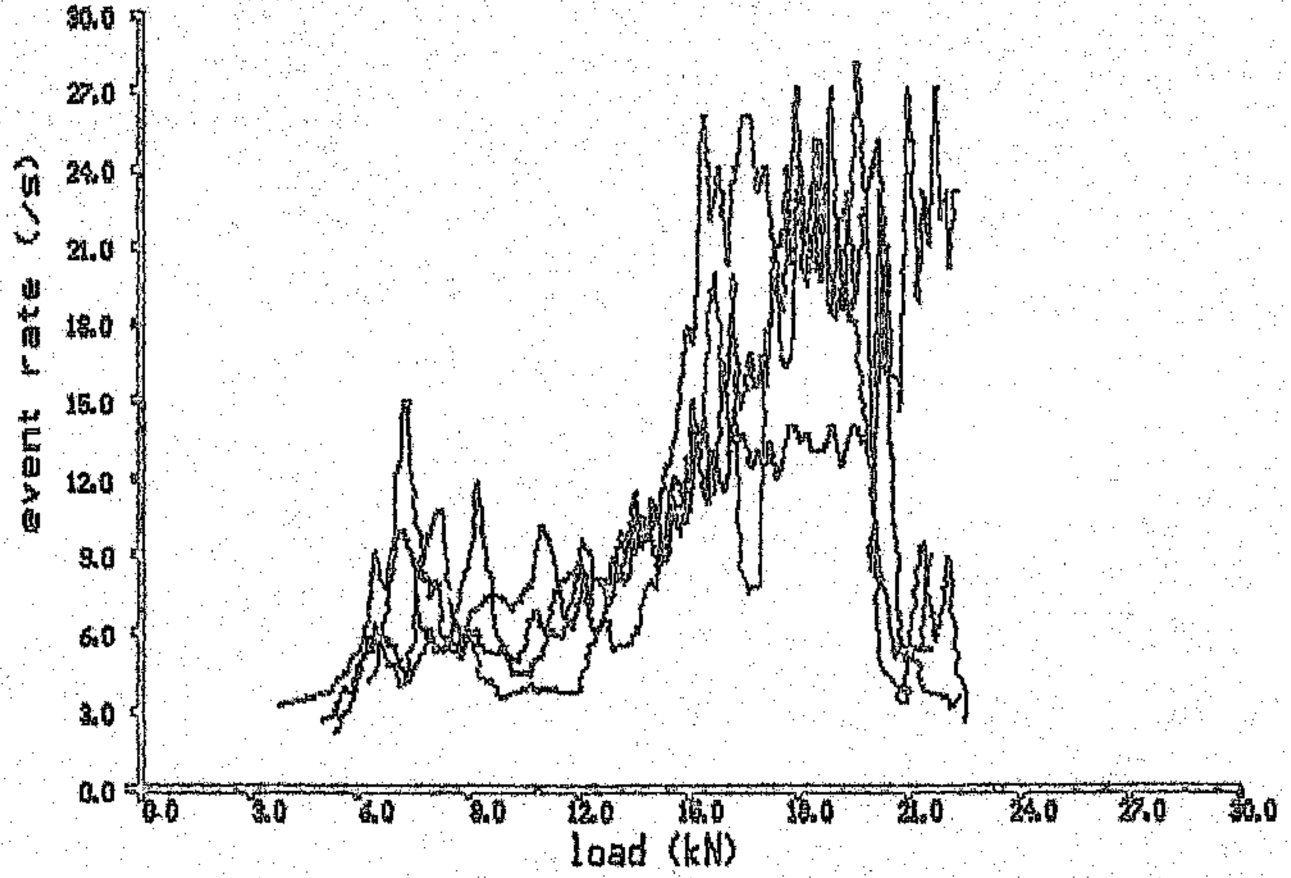


Figure C.17 0/90/+-45 Laminate

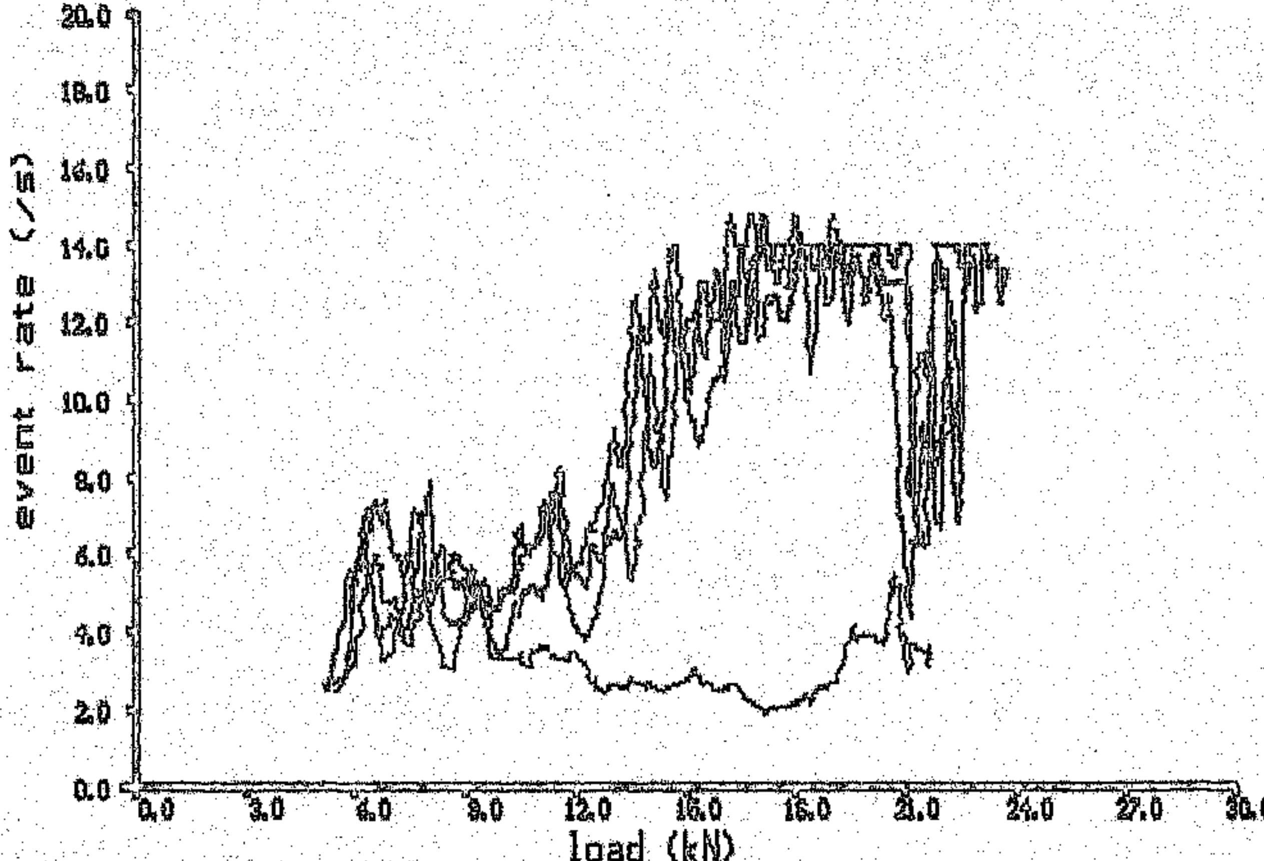


Figure C.19 0/+-45 Laminate

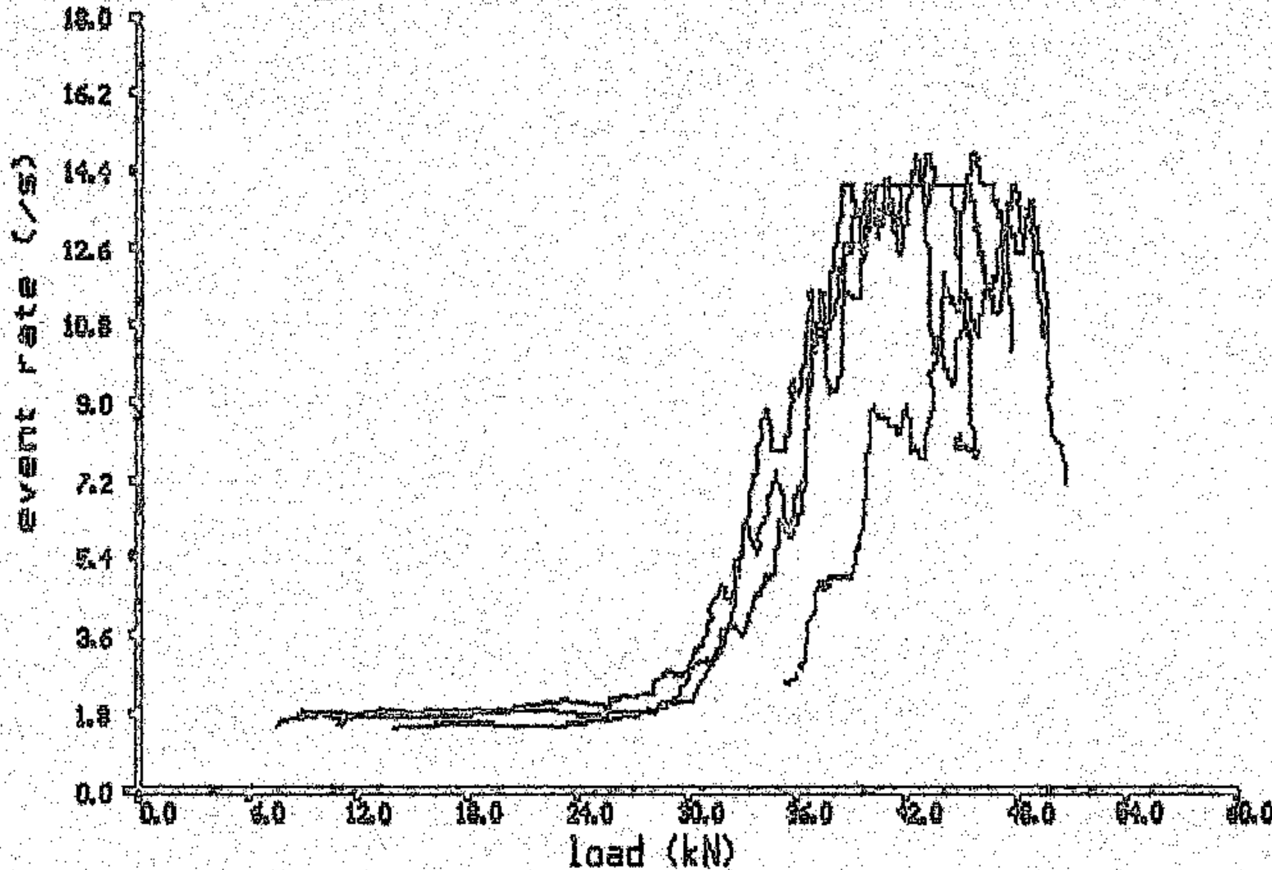


Figure C.20 0/+-45 Laminate

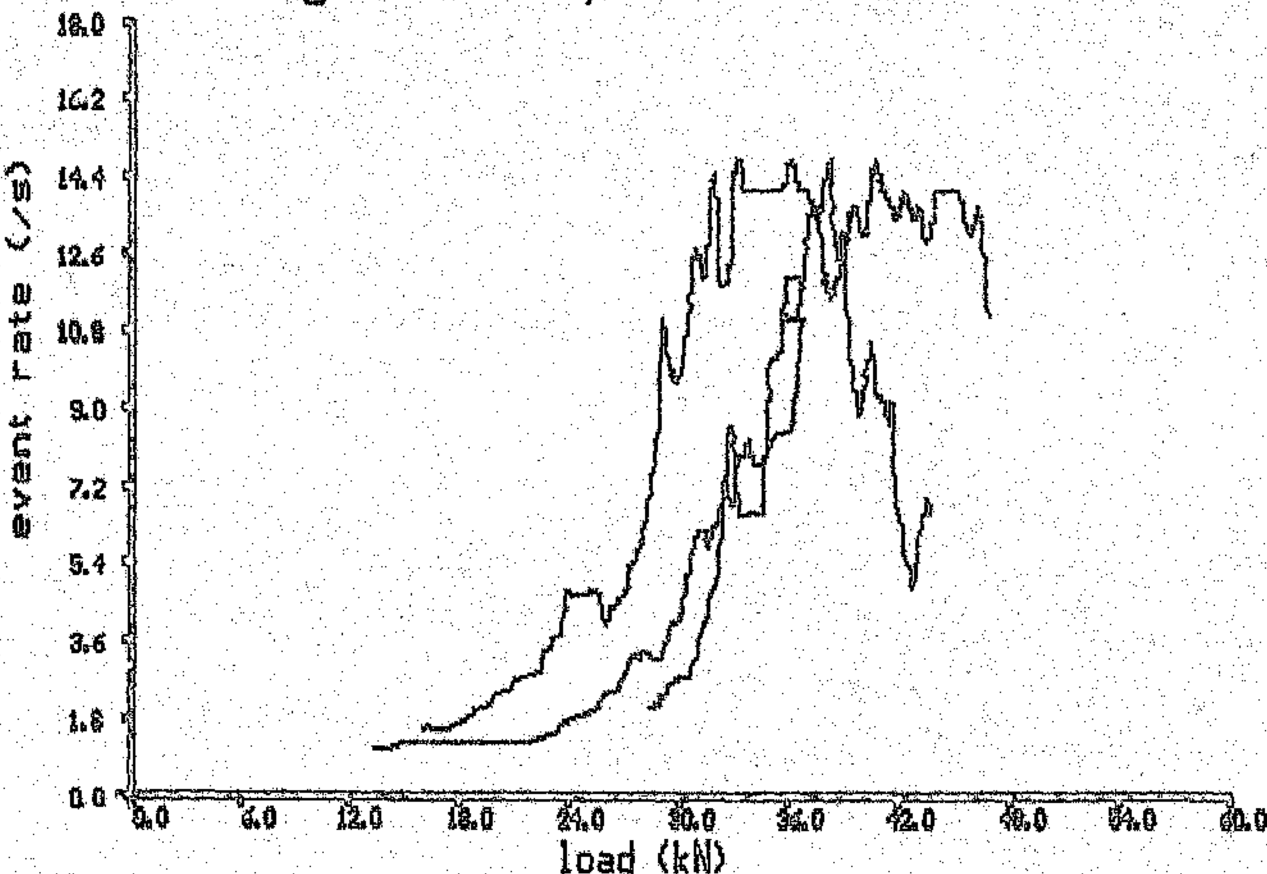


Figure C.22 +-45 Laminate

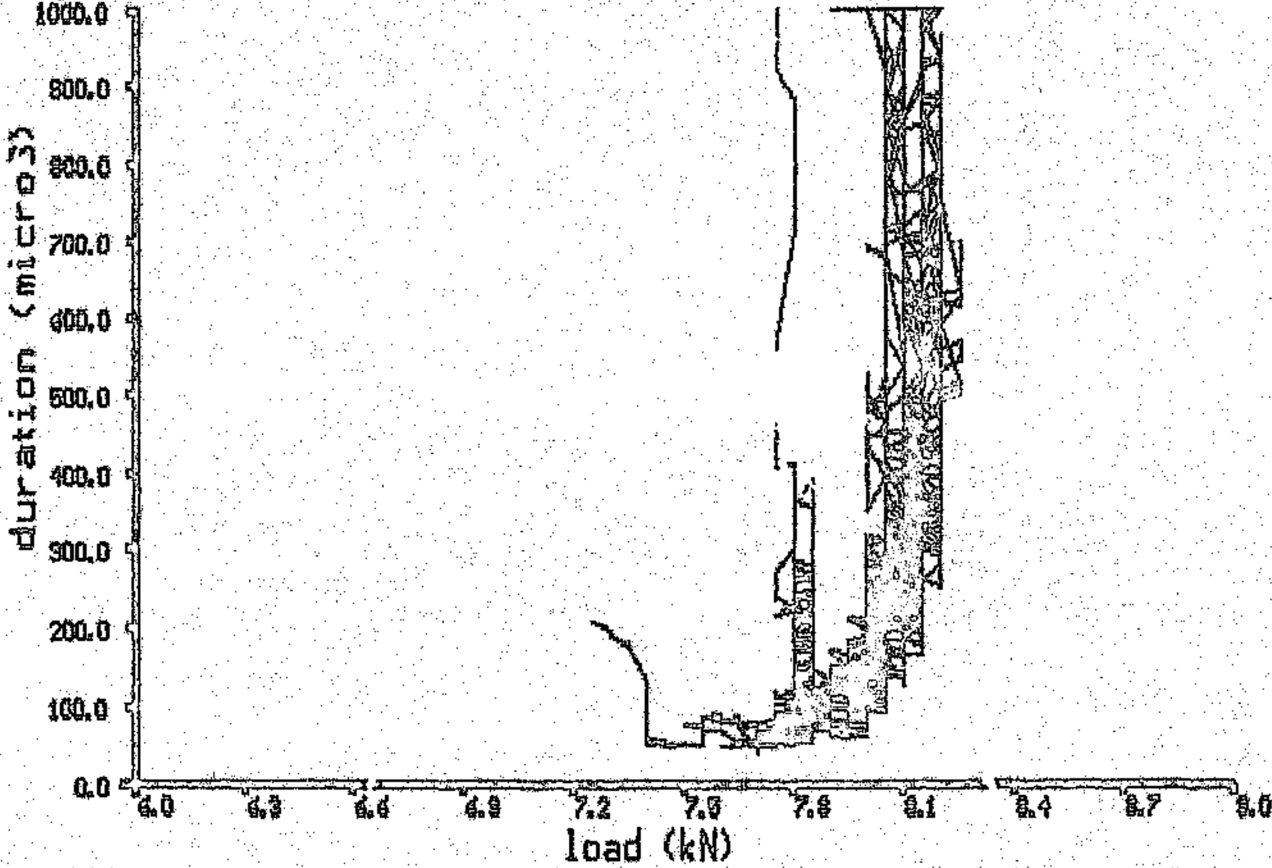


Figure C.21 +-45 Laminate

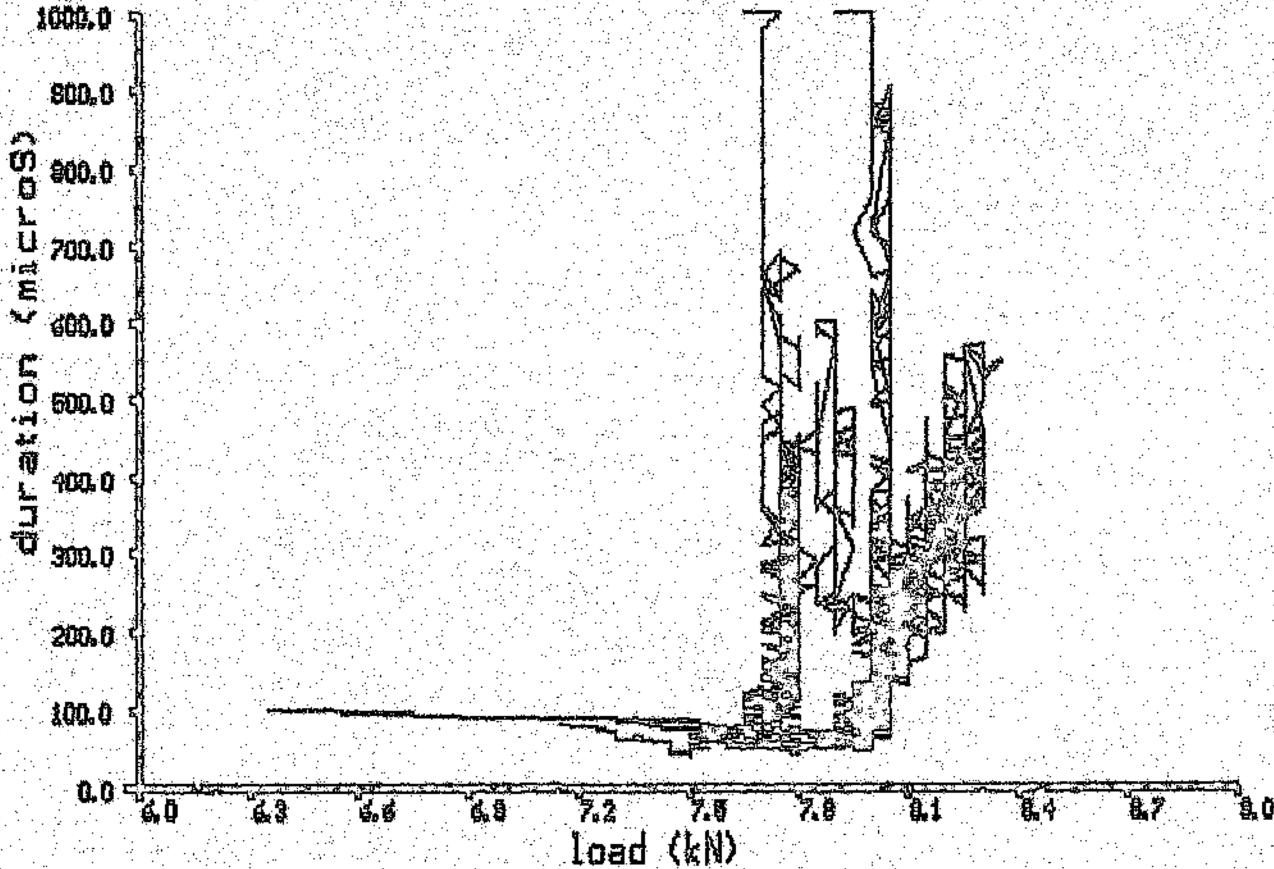


Figure C.24 0/90 Laminate

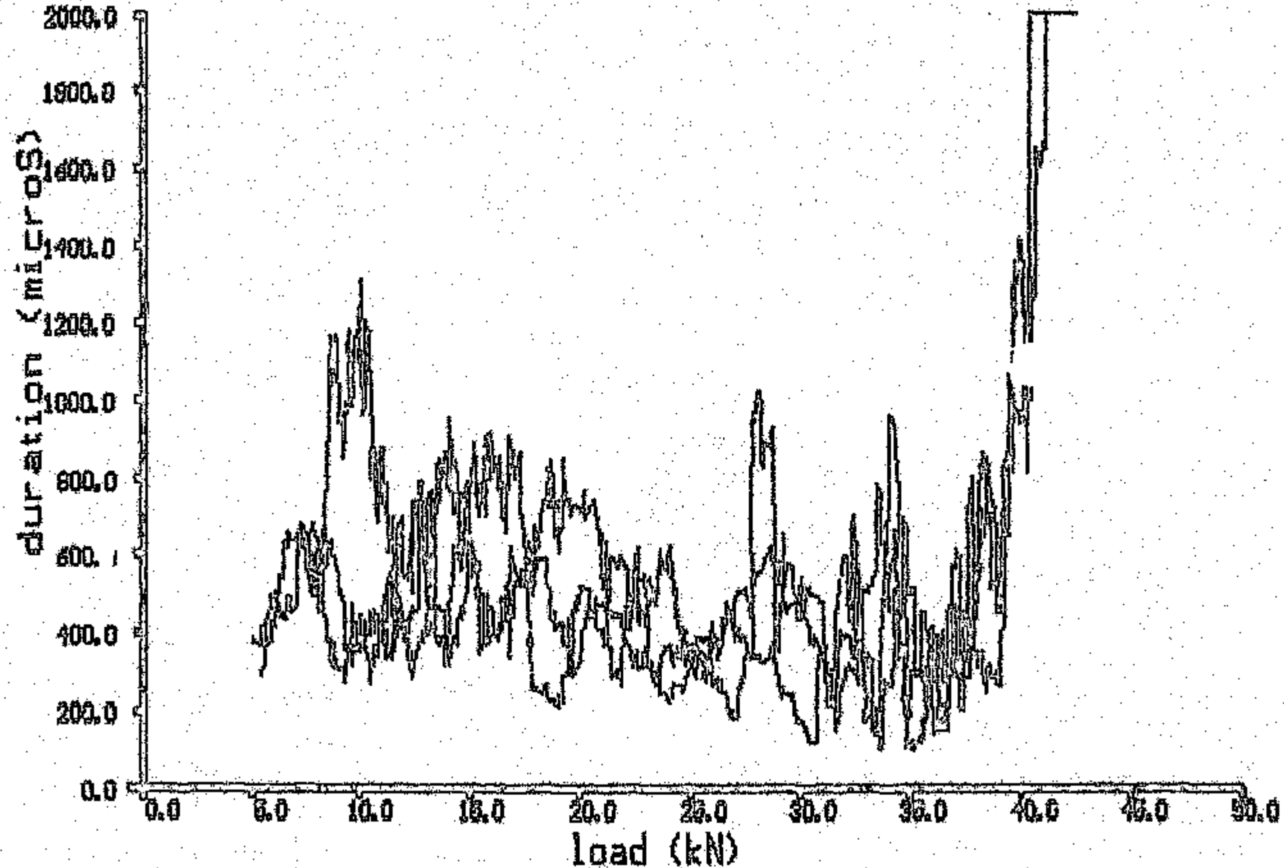


Figure C.23 0/90 Laminate

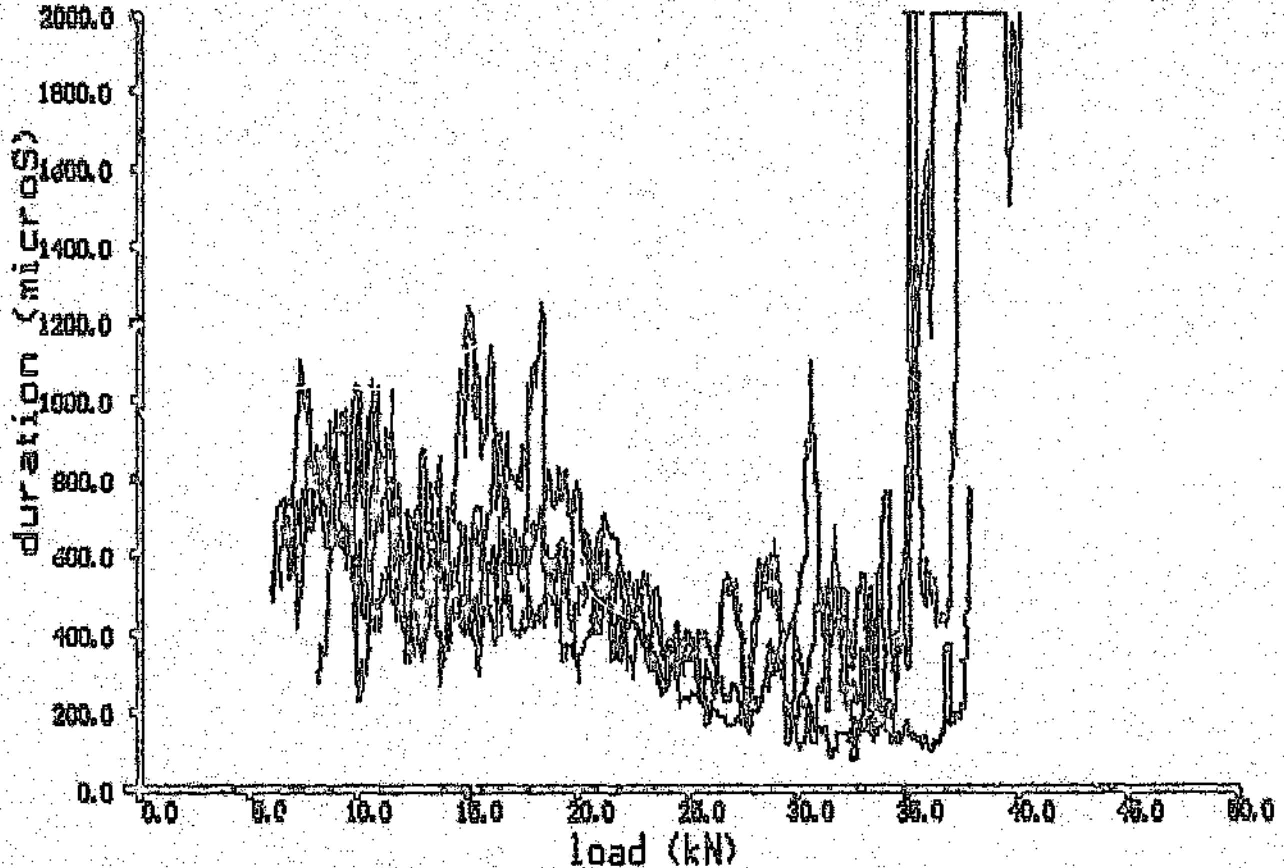


Figure C.25 90/+-45 Laminate

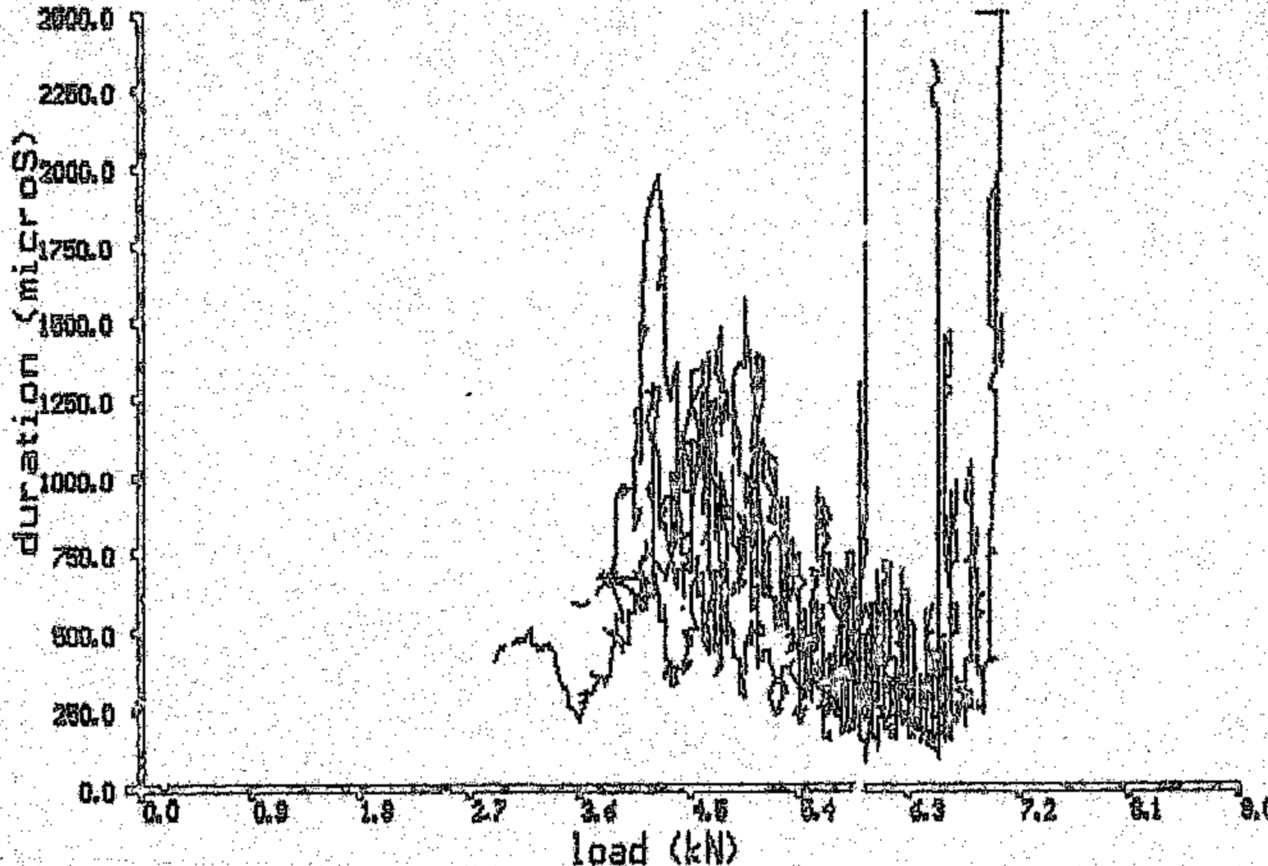


Figure C.26 90/+-45 Laminate

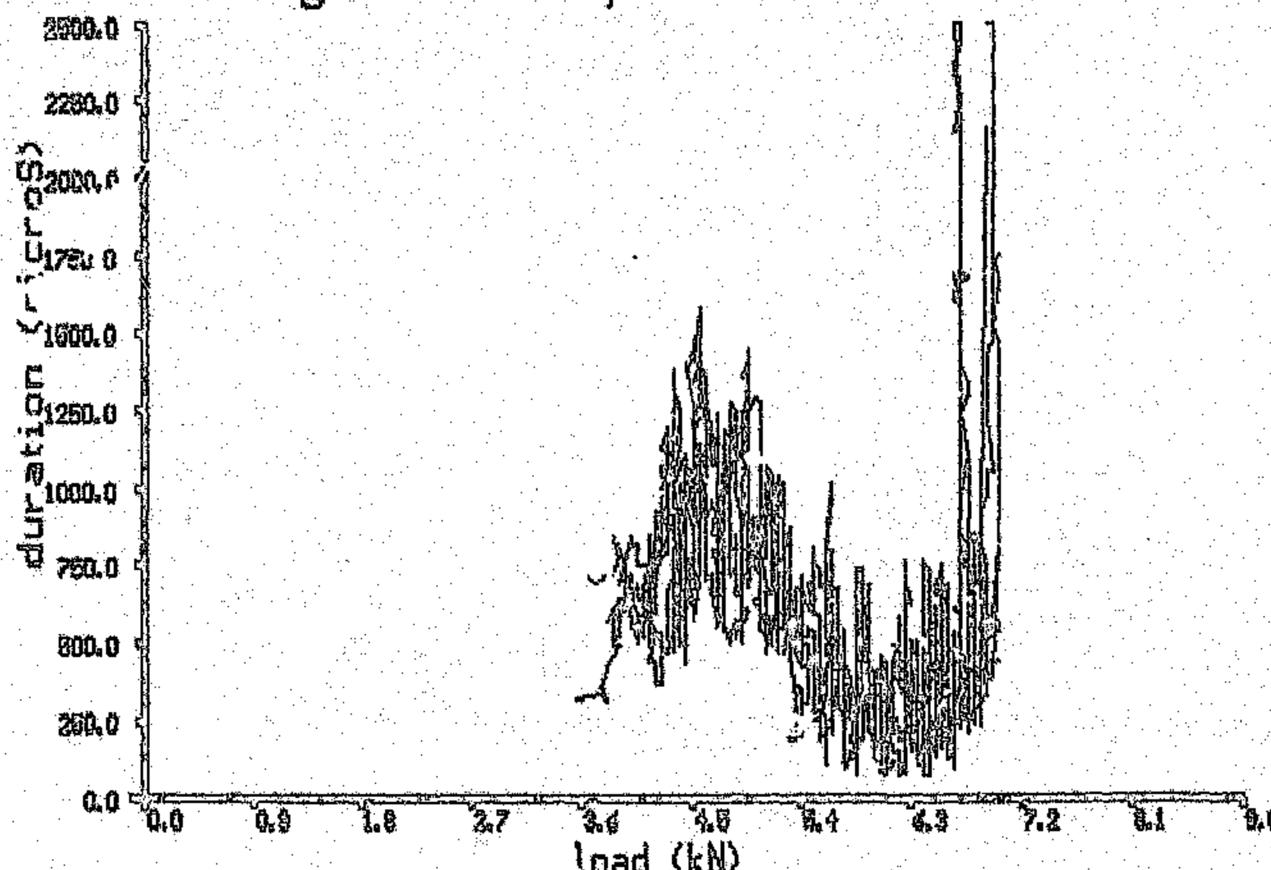
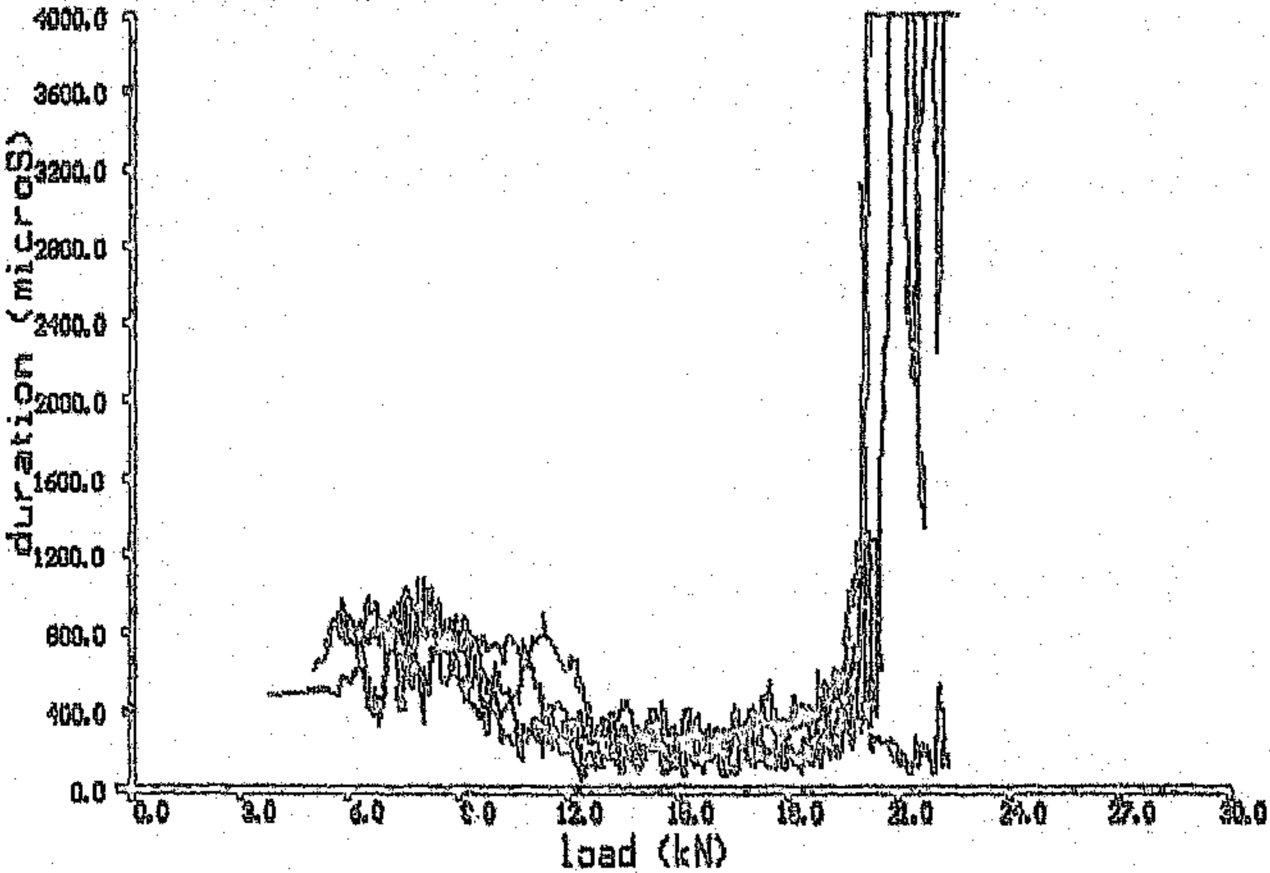


Figure C.28 0/90/+-45 Laminate



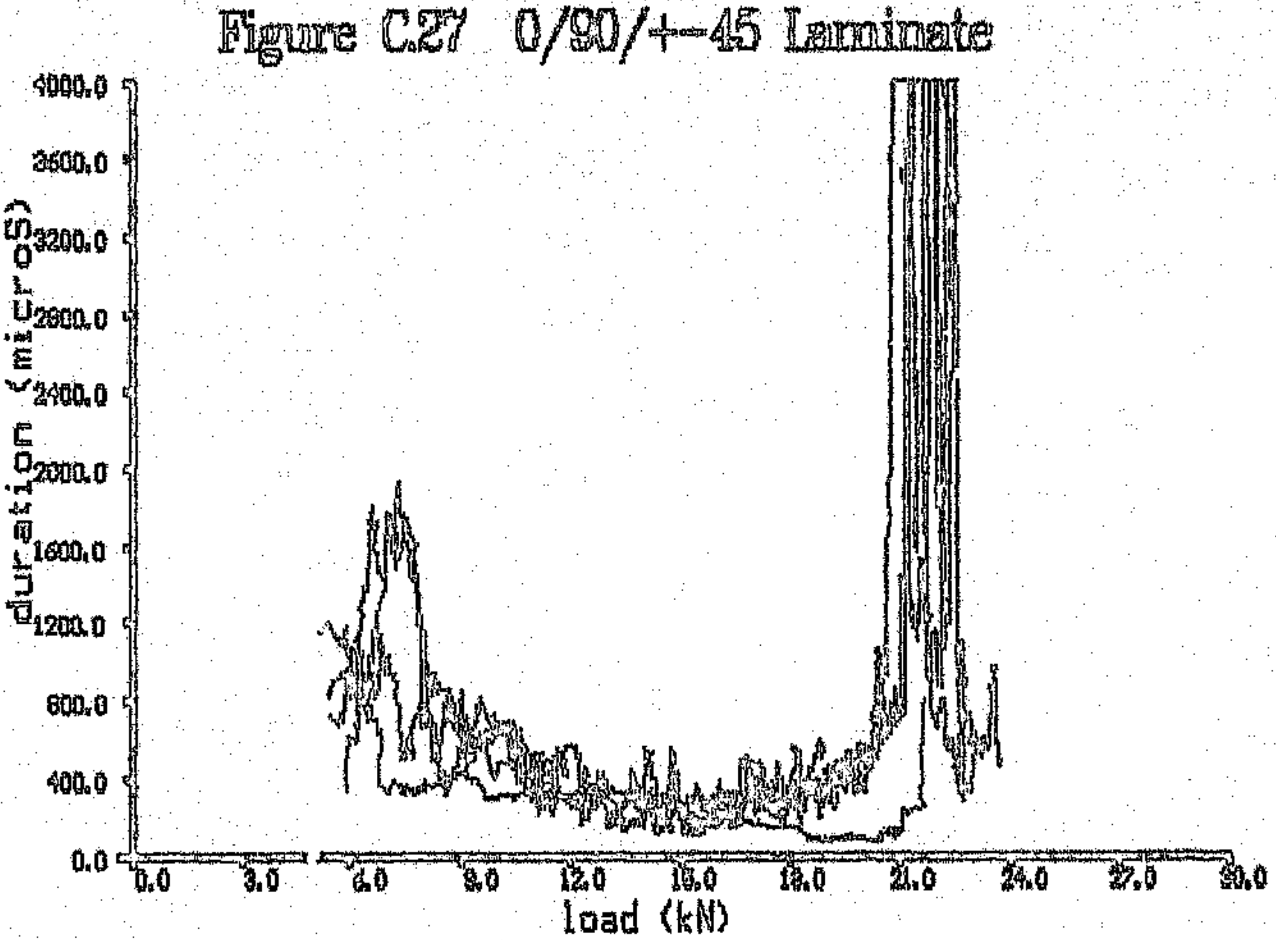


Figure C.27 0/90/+-45 Laminate
duration (micros)
4000.0
3600.0
3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
0.0
3.0
6.0
9.0
12.0
15.0
18.0
21.0
24.0
27.0
30.0
load (kN)

Figure C.29 0/+-45 Laminate

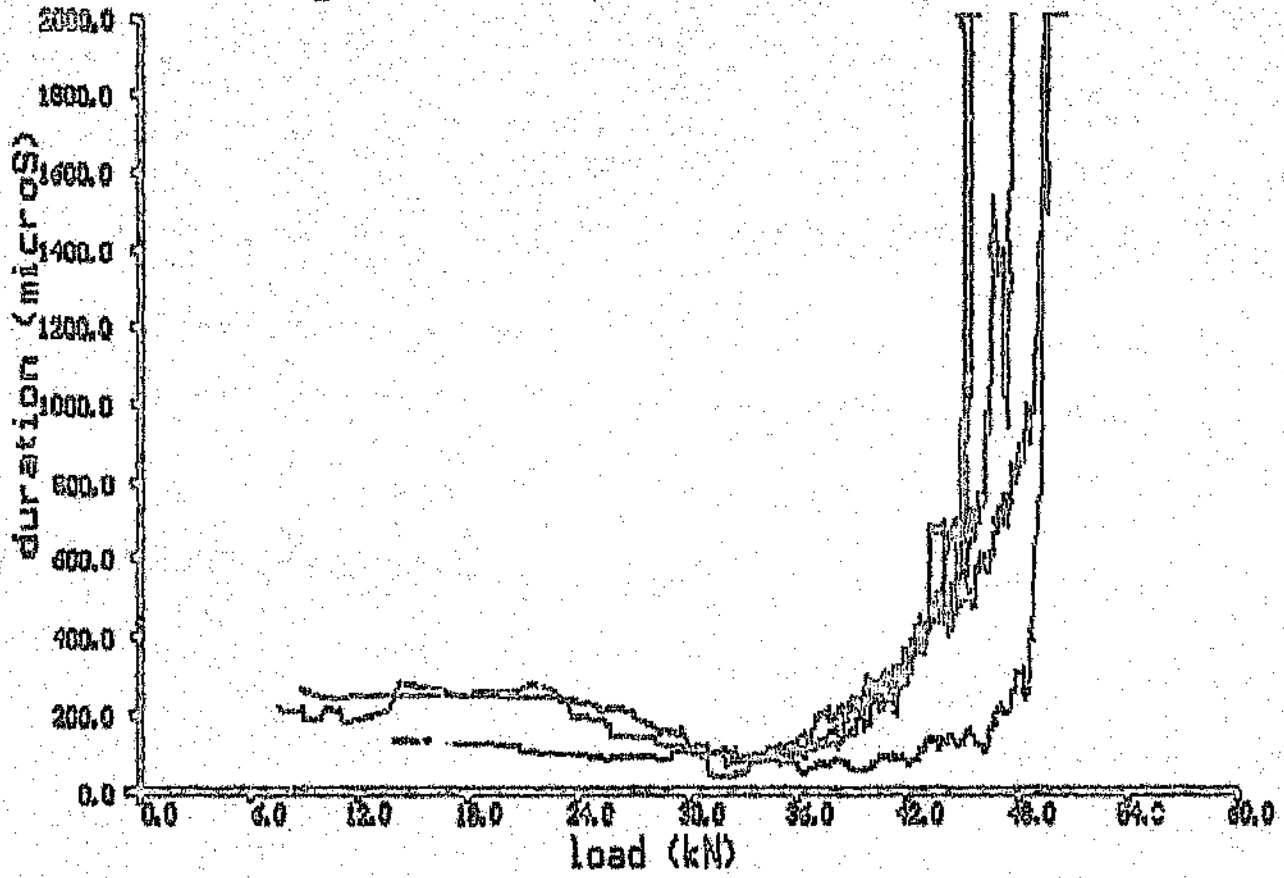
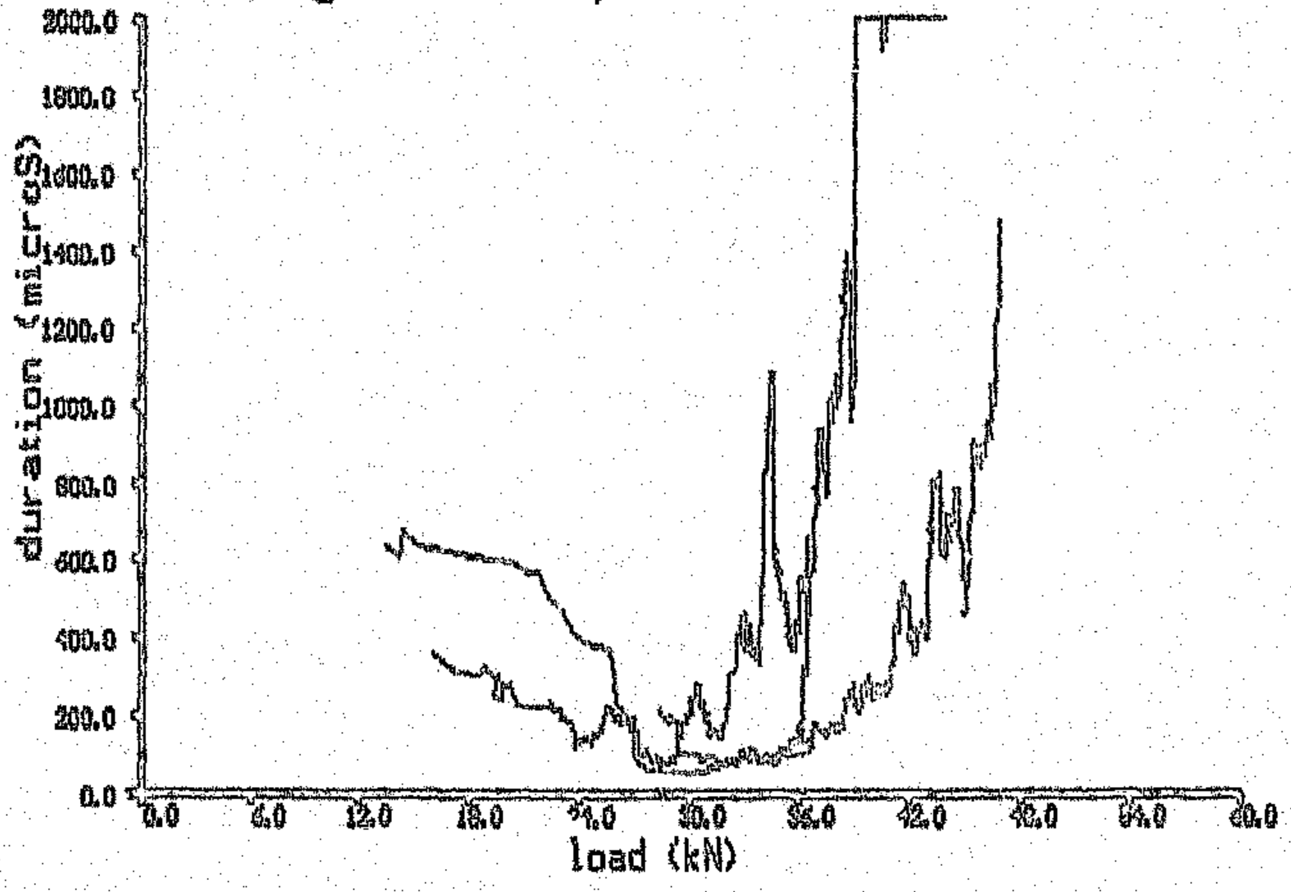


Figure C.30 0/+-45 Laminate



APPENDIX D - Computer Program

The computer program used to calculate the theoretical results is listed. An example of the output file obtained after each analysis is also included.

```
unit failures;

INTERFACE

USES
  globcrit,files,calculat,FailVer2,Crt,glob,menus,spreads,frames,strings;

VAR
  upto : integer;
  filesave,loadflag:boolean;
  filepath,directo,direct :string;
  tangle :array[1..25] of real;
  ExitSave : pointer;
  TWfact :real;

PROCEDURE FAILUR;

IMPLEMENTATION

PROCEDURE DEFN2;

Begin
word1[1]:='Number of layers';  {nlayers}
word1[2]:='No. of material types';      {types}
word1[3]:='No. of different angles';              {nangles}
value[1]:=nlayers;
value[2]:=types;
value[3]:=nangles;
End;


PROCEDURE DEFN2A;

Begin
nlayers:=trunc(value[1]);
types:=trunc(value[2]);
nangles:=trunc(value[3]);
End;

PROCEDURE DEFN3;

Begin
word1[1]:= 'E1';
word1[2]:= 'E2';
word1[3]:='G12';
word1[4]:='mew12';
word1[5]:= 'Xt';
word1[6]:= 'Xc';
word1[7]:= 'Yt';
word1[8]:= 'Yc';
word1[9]:= 'S';
word1[10]:= 'thickness';
value[1]:=ec1[i];
value[2]:=ec2[i];
value[3]:=gc12[i];
value[4]:=mewc12[i];
value[5]:=xtc[i];
value[6]:=xcc[i];
value[7]:=ytc[i];
value[8]:=ycc[i];
value[9]:=sc[i];
value[10]:=tc[i];
End;


PROCEDURE DEFN3A;
```

```
End;


PROCEDURE LAMINPUT1;  { to input laminate details from the keyboard }

{materials and their properties}

Begin
      assign(input,'');
      reset(input);
      clrscr;
      gotoxy(20,15);
      write('Enter material ',i,' name.....');
      read(materialname[i]);
      clrscr;
      position:=1;
      totx:=10;
      DEFN3;
      gotoxy(15,24);
      write('material: ',materialname[i]);
      spreadsheet(totx,position);
      DEFN3A;
End;


PROCEDURE LAMINPUT2; {material types for each layer}

Begin
  clrscr;
  upto :=trunc(types/3);
  if upto<(types/3) then upto:=upto+1;
  for i:=0 to upto-1 do
    begin
    gotoxy(i*20+1,i+2);
    write(i,' : ',materialname[i+1]);
    end;
  frame(1,1,80,upto+3);
  if types > 1 then
    begin
  gotoxy(3,upto+5);
  write('Enter material type for layer  ');
  for k:= 1 to nlayers div 2 do
    begin
      gotoxy(35,upto+5);
      write(k,'......');
      read(mattype[k]);
      mattype[nlayers-k+1]:=mattype[k];
    end;
    end
    else
      for k:= 1 to nlayers div 2 do
        begin
        mattype[k]:=1;
        mattype[nlayers-k+1]:=mattype[k];
        end;
End;


PROCEDURE LAMINPUT3; {angle sizes corresponding to types}


Begin
  clrscr;
  gotoxy(3,12);
  write('Enter size of angle number ');
  for i:= 1 to nangles do
```

```
Begin
  clrscr;
  upto :=trunc(types/3);
  if upto<(types/3) then upto:=upto+1;
  for i:=0 to upto-1 do
    begin
    gotoxy(i*20+1,i+2);
    write(i,' : ',angle[i]:3,' degrees');
    end;
  frame(1,1,80,upto+3);
  if nangles > 1 then
    begin
  gotoxy(3,upto+5);
  write('Enter angle type for layer  ');
  for k:= 1 to nlayers div 2 do
    begin
      gotoxy(35,upto+5);
      write(k,'.....');
      read(angletype[k]);
      angletype[nlayers-k+1]:=angletype[k];
    end;
    end
    else
      for k:= 1 to nlayers div 2 do
        begin
        angletype[k]:=1;
        mattype[nlayers-k+1]:=mattype[k];
        end;
End;




PROCEDURE LAMINATESAVE;

Begin
      FilInput(inpresp);
      Name(inpresp,directo,'lam');
      assign(inputf,inpresp);
      rewrite(inputf);
      writeln(inputf);
      writeln(inputf,nlayers);
      writeln(inputf,types);
      writeln(inputf,nangles);
      for i := 1 to types do
        begin
          writeln(inputf,materialname[i]);
          writeln(inputf,Ec1[i]);
          writeln(inputf,ec2[i]);
          writeln(inputf,gc12[i]);
          writeln(inputf,xtc[i]);
          writeln(inputf,xcc[i]);
          writeln(inputf,ytc[i]);
          writeln(inputf,ycc[i]);
          writeln(inputf,sc[i]);
          writeln(inputf,mewc12[i]);
          writeln(inputf,tc[i]);
        end;
      for i := 1 to nangles do
        writeln(inputf,angle[i]);
      for i := 1 to nlayers div 2 do
        begin
        writeln(inputf,mattype[i]);
        mattype[nlayers-i+1]:=mattype[i];
        end;
      for i := 1 to nlayers div 2 do
```

```
clrscr;
word1[1]:='Nx';
word1[2]:='Ny';
word1[3]:='Nxy';
word1[4]:='Mx';
word1[5]:='My';
word1[6]:='Mxy';
for i := 1 to 6 do
    value[i]:=loading[i];
totx:=6;
position:=1;
SpreadSheet(totx,position);
for i := 1 to 6 do
    loading[i]:=value[i];
End;

PROCEDURE INPUT2; { load input }


Begin
  writeln('input2 ');
  for k:= 1 to nlayers do
    begin
      for i:= 1 to types do
        if (mattype[k] = i) then
          begin

            e1[k] := ec1[i];
            e2[k] := ec2[i];
            g12[k] := gc12[i];
            xt[k] := xtc[i];
            xc[k] := xcc[i] ;
            yt[k] := ytc[i] ;
            yc[k] := ycc[i] ;
            s[k] := sc[i] ;
            mew12[k] := mewc12[i];

            t[k] := tc[i];
          end;
      for i:= 1 to nangles do
        begin
          if (angletype[k] = i) then theta[k] := angle[i];
        end;
    end;
  for k:= 1 to nlayers do
    mew21[k] := mew12[k] * e2[k] / e1[k] ;
  for i:=1 to nangles do
    tangle[i] := angle[i] / 3.14159 * 180 ;
  for k:= 1 to nlayers do
        writeln(' layer ',k,' at angle ',tangle[angletype[k]]:5:2);
  writeln;
end;



PROCEDURE INPUTFILE;    { input of data from file  }

Var
  inputf   :text;


Begin
 clrscr;
 filepath:=directo;
 insert('\*.lam',filepath,length(filepath)+1);
 filelist(filepath,'Available files...');
```

```
      readln(inputf,materialname[i]);
      readln(inputf,Ec1[i]);
      readln(inputf,ec2[i] );
      readln(inputf,gc12[i]  );
      readln(inputf,xtc[i]    );
      readln(inputf,xcc[i]      );
      readln(inputf,ytc[i]        );
      readln(inputf,ycc[i]          );
      readln(inputf, sc[i]);
      readln(inputf,mewc12[i]);
      readln(inputf,tc[i]);
    end;
    for i:= 1 to nangles do
      begin
      readln(inputf,angle[i]);
      writeln('angle[',i,']   ',angle[i]:8:2);
      end;
    for i:= 1 to nlayers div 2 do
      begin
      readln(inputf,mattype[i]);
      writeln('material type[',i,']     ',mattype[i]:8:2);
      mattype[nlayers-i+1]:=mattype[i];
      end;
    for i:= 1 to nlayers div 2 do
      begin
      readln(inputf,angletype[i]);
      writeln('angle type[',i,']    ',angletype[i]);
      angletype[nlayers-i+1]:=angletype[i];
      end;
    close(inputf);
   for i:= 1 to types do
    begin
     writeln(' E1[',i,'] = ',ec1[i]:8:2);
     writeln(' E2[',i,'] = ',ec2[i]:8:2);
     writeln(' G12[',i,'] = ',gc12[i]:8:2);
     writeln(' Xt[',i,'] = ',xtc[i]:8:2);
     writeln(' Xc[',i,'] = ',xcc[i]:8:2);
     writeln(' Yt[',i,'] = ',ytc[i]:8:2);
     writeln(' Yc[',i,'] = ',ycc[i]:8:2);
     writeln(' S[',i,'] = ',sc[i]:8:2);
     writeln(' mew12[',i,'] = ',mewc12[i]:8:2);
     writeln(' t[',i,'] = ',tc[i]:8:2);
    end;
   ch:=readkey;
 end;





PROCEDURE BOOST;  { to boost the loading }

Var
  R,R1max,R2max,R12max      :real;


Begin
  writeln('boost ');
  for k:= 1 to nlayers do
    begin
      R1[k] := abs(R1[k]);
      R2[k] := abs(R2[k]);
```

```
  R12max := R12[1];
  for k:= 2 to nlayers do
    begin
      if ( R1[k] > R1max )  then  R1max := R1[k] ;
      if ( R2[k] > R2max ) then R2max := R2[k] ;
      if ( R12[k] > R12max ) then R12max := R12[k] ;
    end;
   if filesave=true then
   begin
   writeln(outputf);
   writeln(outputf,'failure ratios...');
   for k:= 1 to nlayers do
    begin
      writeln(outputf,'r1=',r1[k]:6:5,'   r2=',r2[k]:6:5,'   r12=',r12[k]:6:5);
    end;
   writeln(outputf);
   end;
  R := R12max;
  if (R1max > R2max) and (R1max > R12max) then R := R1max ;
  if (R2max > R1max) and (R2max > R12max) then  R := R2max ;
  if filesave=true then
  begin
  writeln(outputf,' ratio used...',R:6:5);
  writeln(outputf);
  end;
  if (R <> 0  ) then
for k:= 1 to 6 do
 begin
  loading[k] := loading[k] / R ;
  writeln(' New loading    ....',k,'....',loading[k]);
 end;

End;


PROCEDURE OUTPUT1;  { data output procedure }

Var
  outresp   :char;

Begin

  writeln('output1 ');
  if (failure =  true) then
    begin
      for k := 1 to nlayers do
        begin
          if ( fail[k] = true ) then
            begin
              writeln(' The ',k,'  layer has failed.');
              writeln;
            end;
        end;
     end
  else writeln(' No ply failure ');
  if (failcount >= nlayers ) then writeln('complete failure');


      writeln(' Layer No      stress 1      stress 2     shear stress');
      for k := 1 to nlayers do
        writeln('   ',k,'            ',(stress1[k]):6:2,'          ',(stress2[k]):6:2

      if filesave=true then
       begin
      writeln(outputf);
```

```
         8  : write(outputf,'NORRIS DISTORTIONAL');
         9  : write(outputf,'FISCHER') ;
        10  : write(outputf,'GOLDENBLAT-KOPNOV');
        11  : write(outputf,'TSAI-WU') ;
        12  : write(outputf,'GERMAN STANDARD (HILL)');
        13  : write(outputf,'MARIN');
         end;
      writeln(outputf,' CRITERIA');
      writeln(outputf);
      if (criteria=10) or (criteria=11) then
        begin
        writeln(outputf,' A12 = ',A12);
        writeln(outputf);
        end;
      writeln(outputf,' Output number  ',count+1);
      writeln(outputf);
      Writeln(outputf,' Layer No      stress 1      stress 2       shear stress');
      for k := 1 to nlayers do
        writeln(outputf,'   ',k,'           ',stress1[k]:6:2,'           ',stress2[k]
      writeln(outputf);
      writeln(outputf,' Layer No         strain 1                    strain 2
      for k := 1 to nlayers do
        writeln(outputf,    ',k,'           ',strain1[k],'      ',strain2[k],'
      ' .iteln(outputf);
      writeln(outputf,' Layer No         strain x                   strain y
      for k := 1 to nlayers do
        writeln(outputf,'   ',k,'           ',strainx[k],'      ',strainy[k],'
      writeln(outputf);
      writeln(outputf,'Exx = ',ex:6:2,'   Eyy = ',ey:6:2,'   Gxy = ',gxy:6:2,'
      writeln(outputf);
      for k := 1 to nlayers do
        begin
        if (fail[k] = true) then
          begin
          write(outputf,'The ',k,' layer has failed  ');
          case failtype[k] of
            1 : writeln(outputf,'by principle stress X ');
            2 : writeln(outputf,'by principle stress Y');
            3 : writeln(outputf,'by interaction term');
          end;
          end;
        end;
      writeln(outputf);
      writeln(outputf);
      Writeln(outputf,'-------------------------------------------------------'
      writeln(outputf);
      writeln(outputf);
   end;
  count:= count + 1 ;
end;


PROCEDURE GRAPH;  { placing the load-strain points in a data file
                   for incorporating in a lotus worksheet }

Var
  dat      :string;
  data     :text;
  dataresp:char;

Begin

      clrscr;
      filinput(dat);
      Name(dat,directo,'.dat');
      assign(data,dat);
      rewrite(data);
```

```
Begin
    writeln('Coords  ....no. of points = ',nfails);
    ss := strainx[1] ;
    for k := 1 to nlayers do
        if (strainx[k] > ss)  then  ss := strainx[k] ;
    xcoord[nfails] := ss;
    ycoord[nfails] := loading[1];
End;


PROCEDURE FILEOUTPUT;

Begin
filesave:=true;
filinput(outputfilename);
assign(outputf,outputfilename);
rewrite(outputf);
gotoxy(5,24);
write('Label for output file?  ');
assign(input,'');
reset(input);
readln(labe);
writeln(outputf,labe);
writeln(outputf);
      writeln(outputf,'number of layers = ',nlayers);
      writeln(outputf,'number of material types = ',types);
      writeln(outputf,'number of lay-up angles = ',nangles);
      writeln(outputf);
      for i := 1 to types do
        begin
          writeln(outputf,materialname[i]);
          writeln(outputf,'E1 = ',Ec1[i]:8:2,'  E2 = ',ec2[i]:8:2,'  G12 = ',gc1
          writeln(outputf,'Xt = ',xtc[i]:8:2,'  Xc = ',xcc[i]:8:2);
          writeln(outputf,'Yt = ',ytc[i]:8:2,'  Yc = ',ycc[i]:8:2);
          writeln(outputf,'S = ',sc[i]:8:2,'  mew12 = ',mewc12[i]:8:2,'  thickne
        end;
      writeln(outputf);
      writeln(outputf,'Angles');
      for i := 1 to nangles do
        write(outputf,i,' = ',angle[i]:8:2,'  ');
      writeln(outputf);
      writeln(outputf,'layer material types');
      for i := 1 to nlayers do
        write(outputf,i,' = ',ma :type[i]:8:2,'  ');
      writeln(outputf);
      writeln(outputf,'layer angle types');
      for i := 1 to nlayers do
        write(outputf,i,' = ',angletype[i],'  ');
      writeln(outputf);
End;


PROCEDURE DEFN;

Begin
nheads:=4;
word[1]:='input';
word[2]:='calculate';
word[3]:='options';
word[4]:='quit';
pnheads[1]:=5;
  head[1,1]:='use file';
  head[1,2]:='use kbd';
  head[1,3]:='change laminate';
  head[1,4]:='loading';
  head[1,5]:='change directory';
```

```
  head[2,11]:='TSAIWU' ;
  head[2,12]:='GERMAN STD';
  HEAD[2,13]:='MARIN';
pnheads[3]:=5;
  head[3,1]:='screen';
  head[3,2]:='save laminate';
  head[3,3]:='open file for output';
  head[3,4]:='view laminate';
  head[3,5]:='save load-strain data';
pnheads[4]:=0;

End;


PROCEDURE CALC;

begin
   nfails := 0;
   count:=0;
   failcount := 0 ;
   counter :=0 ;
   for k := 1 to Nlayers do
   fail[k] := false ;
   thickness := 0;
   for k:= 1 to nlayers do
    thickness := thickness + t[k];
   writeln('thickness   = ',thickness:5:3);
   z[0] := -thickness/2;writeln('     z[0]    ',z[0]);
        for k := 1 to nlayers do
          begin
            z[k] := ( z[k-1] + t[k]) ;
            writeln('  z[',k,'] =  ',z[k]);
          end;
   repeat
    begin
      repeat
        begin
          MATRIXCALC;
          for i := 1 to 6 do
            begin
            if loading[i]<1e-10 then loading[i]:=1e-15;
            load[i] := loading[i];
            end;
          SOLVE;
          STRESS;
          failure:=false;
          case ( criteria ) of
          1  : MAXSTRESS;
          2  : MAXSTRAIN;
          3  : PUCKSIMPLE  ;
          4  : PUCKMODIFIED ;
          5  : TSAIHILL ;
          6  : PUPPOEVENSEN;
          7  : NORRISMcKINNON ;
          8  : NORRISDIST;
          9  * FISCHER ;
         10  : GOLDENBLAT;
         11  : TSAIWU;
         12  : GERMANSTD;
         13  : MARIN;
          end;
        OUTPUT1;
            nfails := nfails + 1.
            COORDS;
        end;
      until ( failure = false ) or ( failcount >= nlayers ) or (h='n');
      if (failcount < nlayers ) then
```

```
PROCEDURE PREDEFN;

Begin
 for i:=1 to 6 do
   begin
   loading[i]:=1e-15;
   load[i]:=1e-15;
   end;
 nlayers:=0;
 types:=0;
 nangles:=0;
 for i:= 1 to types do
   begin
     materialname[i]:='';
     Ec1[i]:=0;
     ec2[i]:=0;
     gc12[i]:=0;
     xtc[i]:=0;
     xcc[i]:=0;
     ytc[i]:=0;
     ycc[i]:=0;
     sc[i]:=0;
     mewc12[i]:=0;
     tc[i]:=0;
   end;
   for i:= 1 to 5 do
     angle[i]:=0;
   for i:= 1 to 16 do
     mattype[i]:=0;
   for i:= 1 to 16 do
     angletype[i]:=0;

End;

PROCEDURE MATRIXSAVE;

Begin
      writeln(outputf,'stiffness matrix for this laminate:');
      writeln(outputf);
      writeln(outputf);
      for i:= 1 to 6 do
        begin
          for j:= 1 to 6 do
           begin
            write(outputf,matrix[i,j],' ');
           end;
          writeln(outputf);
        end;
      close(outputf);
end;

PROCEDURE FAILUR;

BEGIN   { main program }
  {ExitSave:=ExitProc;
  ExitProc:=@MyExit;}
  clrscr;
  filepath:='c:\ian\pas\*.*';
  directo:='c:\ian\pas';
  filesave:=false;
  PREDEFN;
  DEFN;
  counterflag:=true;
  posj:=1;
  posn:=1;
  clrscr;
  repeat
```

```
          DEFN2A;
          clrscr;
          for i := 1 to types do
            begin
            LAMINPUT1;
            end;
          LAMINPUT2;
          LAMINPUT3;
          LAMINPUT4;
          End;
      3 : Begin
          clrscr;
          writeln('1  materials and their properties');
          writeln('2  material type sequence');
          writeln('3  angle sizes');
          writeln('4  angle type sequence');
          writeln('5  no. of angles');
          writeln('6  no. of material types');
          writeln('7  no of layers');
          writeln;
          write('What do you want to change? ');
          ch:=readkey;
          case ch of
            '1' : begin
                  write('Enter material type number.... ');
                  readln(i);
                  LAMINPUT1;
                  end;
            '2' : LAMINPUT2;
            '3' : LAMINPUT3;
            '4' : LAMINPUT4;
            '5' : begin
                  writeln;
                  write('Enter no. of ang.   ...');
                  readln(nangles);
                  end;
            '6' : begin
                  writeln;
                  write('Enter no. of material types...');
                  readln(types);
                  end;
            '7' : begin
                  writeln;
                  write('Enter no. of layers...');
                  readln(nlayers);
                  end;
          end;
          end;
      4 : DEFN4;
      5 : begin
          gotoxy(1,10);
          writeln(' Old directory...',directo);
          write(' Enter new directory...');
          READLN(direct);
          if direct='' then direct:=directo;
          directo:=direct;
          end;
    end;
 2 . begin
    loadflag:=false;
    for i:=1 to 6 do
      if loading[i]>0.00001 then loadflag:=true
    criteria:=posn;
    if loadflag=true then
      begin
    INPUT2;
    CALC;
```

```
            ch:=readkey;
            end;
        2 : LAMINATESAVE;
        3 : begin
            if filesave= false then FILEOUTPUT
            else
              begin
              clrscr;
              write('A f    is already open for output. Want to change it? '
              ch:=readkey;
              if ch in ['y','Y'] then
                begin
                MATRIXSAVE;
                FILEOUTPUT;
                end;
              end;
            end;
        4 : Begin
            for i:= 1 to types do
              begin
              writeln(' E1[',i,'] = ',ec1[i]:8:2);
              writeln(' E2[',i,'] = ',ec2[i]:8:2);
              writeln(' G12[',i,'] = ',gc12[i]:8:2);
              writeln(' Xt[',i,'] = ',xtc[i]:8:2);
              writeln(' Xc[',i,'] = ',xcc[i]:8:2);
              writeln(' Yt[',i,'] = ',ytc[i]:8:2);
              writeln(' Yc[',i,'] = ',ycc[i]:8:2);
              writeln(' S[',i,'] = ',sc[i]:8:2);
              writeln(' mew12[',i,'] = ',mewc12[i]:8:2);
              writeln(' t[',i,'] = ',tc[i]:8:2);
              ch:=readkey;
              end;
            clrscr;
            writeln('number of layers.. ',nlayers);
            writeln('number of material types...',types);
            writeln('number of angles...',nangles);
            ch:=readkey;
            End;
        5 : GRAPH;
      end;
  end;
  counterflag:=false;
  end;
until posj=4;
if filesave=true then  MATRIXSAVE;
clrscr;
END;
END .
```

```
unit Calculat;

interface

uses globcrit,crt;

PROCEDURE MATRIXCALC; { calculating the laminate matrix }
PROCEDURE STRESS;
PROCEDURE SOLVE;

IMPLEMENTATION

PROCEDURE SOLVE;  { solves the matrix }

BEGIN
  for k:= 1 to 5 do
           for i:= k + 1 to 6 do
             begin
                 mult[i]  := matrix[i,k]/matrix[k,k];
                 for j := k+1 to 6 do
                  begin
                   matrix[i,j]:= matrix[i,j] - mult[i]*matrix[k,j];
                  end;
                   load[i] := load[i] - mult[i] * load[k];
             end;
      straino[6] := load[6]/matrix[6,6];
      for i := 5 downto 1 do
        begin
           straino[i] := load[i];
           for j := i+1 TO 6 DO
             begin
               straino[i] := straino[i] - straino[j] * matrix[i,j];
             end;
           straino[i] := straino[i] / matrix[i,i] ;
         end;
      end;


PROCEDURE MATRIXCALC;

var

  x  :real;
h,  store :char; check :text;


Begin
  for k:= 1 to nlayers  do
    begin
      x := 1 - (mew12[k] * mew21[k]) ;
      Q11[k] := E1[k] / x ;
      Q12[k] := mew12[k]  * E2[k] / x ;
      Q22[k] := E2[k] / x ;
      Q66[k] := G12[k] ;
      s1 := sin(theta[k]);
      s2 := sqr(s1);
      s3 := s2 * s1 ;
      s4 := sqr(s2) ;
      c1:=cos(theta[k]) ;
      c2:= sqr(c1);
      c3 := c1 * c2 ;
      c4 := sqr(c2) ;
      QT[1,1,k]:=Q11[k]*c4+2*(Q12[k]+2*Q66[k])*s2 * c2 + Q22[k] * s4;
      QT[1,2,k] :=( Q11[k] + Q22[k] - 4 * Q66[k])*s2 * c2 + Q12[k] * (s4 + c4);
      QT[2,2,k] := Q11[k] *  s4 + 2*(Q12[k] + 2*Q66[k]) * s2 * c2 +  Q22[k] * c4
      QT[1,3,k] := (Q11[k] - Q12[k] - 2*Q66[k]) * s1 * c3  + (Q12[k] - Q22[k] +
```

```
unit Calculat;

interface

uses globorit,crt;

PROCEDURE MATRIXCALC; { calculating the laminate matrix }
PROCEDURE STRESS;
PROCEDURE SOLVE;

IMPLEMENTATION

PROCEDURE SOLVE;  { solves the matrix }

BEGIN
  for k:= 1 to 5 do
         for i:= k + 1 to 6 do
           begin
               mult[i]  := matrix[i,k]/matrix[k,k];
               for j := k+1 to 6 do
                begin
                 matrix[i,j]:= matrix[i,j] - mult[i]*matrix[k,j];
                end;
                 load[i] := load[i] - mult[i] * load[k];
           end;
     straino[6] := load[6]/matrix[6,6];
     for i := 5 downto 1 do
       begin
          straino[i] := load[i];
          for j := i+1 TO 6 DO
            begin
              straino[i] := straino[i] - straino[j] * matrix[i,j];
            end;
          straino[i] := straino[i] / matrix[i,i] ;
        end;
     end;


PROCEDURE MATRIXCALC;

var

  x  :real;
h,  store :char; check :text;


Begin
  for k:= 1 to nlayers  do
    begin
      x := 1 - (mew12[k] * mew21[k]) ;
      Q11[k] := E1[k] / x ;
      Q12[k] := mew12[k]  * E2[k] / x ;
      Q22[k] := E2[k] / x ;
      Q66[k] := G12[k] ;
      s1 := sin(theta[k]);
      s2 := sqr(s1);
      s3 := s2 * s1 ;
      s4 := sqr(s2) ;
      c1:=cos(theta[k]) ;
      c2:= sqr(c1);
      c3 := c1 * c2 ;
      c4 := sqr(c2) ;
      QT[1,1,k]:=Q11[k]*c4+2*(Q12[k]+2*Q66[k])*s2 * c2 + Q22[k] * s4;
      QT[1,2,k] :=( Q11[k] + Q22[k] - 4 * Q66[k])*s2 * c2 + Q12[k] * (s4 + c4);
      QT[2,2,k] := Q11[k] *  s4 + 2*(Q12[k] + 2*Q66[k]) * s2 * c2 +  Q22[k] * c
      QT[1,3,k] := (Q11[k] - Q12[k] - 
```

```
        B[i,j] := 0;
        D[i,j] := 0;
        for k:= 1 to nlayers  do
          begin
            s2 := sqr(Z[k]);
            s3 := Z[k] * s2 ;
            c2 := sqr(z[k-1]);
            c3 := z[k-1] * c2 ;
            A[i,j] := A[i,j] + ( QT[i,j,k] * (Z[k] - Z[k-1] ));
            B[i,j] := B[i,j] + ( QT[i,j,k] * (s2 - c2 ));
            D[i,j] := D[i,j] + ( QT[i,j,k] * (s3 - c3 ));
          end;
        B[i,j] := B[i,j] / 2 ;
        D[i,j] := D[i,j] / 3 ;
      end;
    Ex := ( A[1,1] - sqr(A[1,2]) / A[2,2] ) /thickness;
    Ey := ( A[2,2] - sqr(A[1,2]) / A[1,1] ) /thickness;
    Gxy := A[3,3] / thickness;
    mewxy := A [1,2] / A[2,2] ;
    for i:= 1 to 3 do
      for j:= 1 to 3 do
        begin
          matrix[i,j] := A[i,j];
          matrix[i+3,j] := B[i,j];
          matrix[i,j+3] := B[i,j];
          matrix[i+3,j+3] := D[i,j];
        end;
 counter := counter +1 ;
end;




PROCEDURE STRESS;    { stress calculation }


Begin
  for k := 1 to Nlayers do
   begin
    s1 := sin(theta[k]);
    s2 := sqr(s1);
    c1 := cos(theta[k]);
    c2:=  sqr(c1);
    strainx[k] := straino[1] + z[k] * straino[4] ;
    strainy[k] := straino[2] + z[k] * straino[5] ;
    strainxy[k] :=straino[3] + z[k] * straino[6] ;
    stressx[k] := QT[1,1,k] * strainx[k] + QT[1,2,k] * strainy[k] + QT[1,3,k] *
    stressy[k] := QT[2,1,k] * strainx[k] + QT[2,2,k] * strainy[k] + QT[2,3,k] *
    stressxy[k]:= QT[3,1,k] * strainx[k] + QT[3,2,k] * strainy[k] + QT[3,3,k] *
    stress1[k] := c2 * stressx[k] + s2 * stressy[k] + 2 * s1*c1 *  stressxy[k];
    stress2[k] := s2 * stressx[k] + c2 * stressy[k] - 2 * s1*c1 *  stressxy[k];
    stress12[k] :=-1 * s1 * c1 * stressx[k] +   s1 * c1 * stressy[k] + (c2 - s2)
    strain1[k] := c2 * strainx[k] + s2 * strainy[k] + 2 * s1 * c1 * strainxy[k];
    strain2[k] := s2 * strainx[k] + c2 * strainy[k] - 2 * s1 * c1 * strainxy[k];
    strain12[k] := -1 * s1 *c1 * strainx[k] + s1*c1 * strainy[k] + (c2-s2) * str
   end;
End;
END.
```

```
    unit FailVer2;

interface

uses crt,globcrit;


PP^CEDURE MAXSTRESS;   { specific criteria procedures }
PROCEDURE MAXSTRAIN;
PROCEDURE PUCKSIMPLE;
PROCEDURE PUCKMODIFIED;
PROCEDURE TSAIHILL;
PROCEDURE TSAIWU;
PROCEDURE PUPPOEVENSEN;
PROCEDURE NORRISMCKINNON;
PROCEDURE NORRISDIST;
PROCEDURE FISCHER;
PROCEDURE GOLDENBLAT;
PROCEDURE GERMANSTD;
PROCEDURE MARIN;

IMPLEMENTATION

VAR
  xx,yy,m,p,q,n,s1,s2,s3 :real;

PROCEDURE LAYERFAIL;
Begin
fail[k] := true   ;
failure := true ;
failcount := failcount +1 ;
E2[k]:=0;
G12[k]:=0;
if (stress1[k]/xx >= 0.999) then E1[k] := 0 ;
End;


PROCEDURE R1TEST;
Begin
if (R1[K] >= 0.999) then
        begin
        failtype[k]:=1;
        LayerFail;
        end;
End;

PROCEDURE R2TEST;
Begin
if (R2[k] >= 0.999) then
        begin
        failtype[k]:=2;
        LayerFail;
        end;
End;

PROCEDURE R12TEST;
Begin
if (R12[k] >= 0.999) then
        begin
        failtype[k]:=3;
        LayerFail;
        end;
End;

PROCEDURE XTEST;
Begin
```

```
Begin
R12[k] := stress12[k] /  S[k] ;
R12Test;
End;

PROCEDURE STRXTEST;
Begin
R1[k] := (STRESS1[K] - MEW12[K] * STRESS2[K])/ xx ;
R1Test;
End;

PROCEDURE STRYTEST;
Begin
R2[k] := (stress2[k] - mew21[k] * stress1[k])/ yy ;
R2Test;
End;

PROCEDURE STRXYTEST;
Begin
R12[k] := abs(stress12[k])/S[k];
R12Test;
End;

PROCEDURE PUCKSIMPLETEST;
Begin
R12[k]:= (sqr(stress2[k]/yy)) + sqr(stress12[k]/s[k]);
R12Test;
if fail[k]=false then
  begin
  m := sqrt(sqr(c1/yy) + sqr(c2/s[k]));
  R12[k] := (m * stress1[k]);
  end;
End;

PROCEDURE PUCKMODTEST;
Var
  Dummy : real;
Begin
R12[k]:= (sqr(stress2[k])/(yt[k]* yc[k])) + stress2[k] * (1/yt[k] - 1/yc[k]) + s
R12Test;
if fail[k]=false then
  begin
  m := sqr(c1)/(yt[k] * yc[k]) + sqr(c2/s[k]) ;
  n := c1*( 1/yt[k] - 1/yc[k] );
  dummy := ( 2* m * stress1[k] )/( -n + sqrt( sqr(n) + 4*m));
  R12[k] := ( 2 * m * stress1[k] )/( -n - sqrt( sqr(n) + 4*m));
  if dummy>R12[k] then R12[k]:=dummy;
  end;
End;

PROCEDURE TSAIHILLTEST;
Begin
s1 := sqr(stress12[k]/s[k]);
s2 :=  sqr(stress2[k]/yy );
R12[k]:= sqr(stress1[k]/xx ) - (stress2[k] * stress1[k])/sqr(xx) + s2 + s1;
R12Test;
if fail[k]=false then
  begin
  m := sqrt( 1/sqr(xx) - c1/sqr(xx) + sqr(c1/yy) + sqr(c2/s[k]) ) ;
  R12[k] := ( m * stress1[k] );
  end;
End;

PROCEDURE TSAIWUTEST;
Var
  Dummy : real;
Begin
```

```
  end;
End;

PROCEDURE PUPPOEVENSENTEST;
Var
  Dummy : real;

Begin
s1 := 3 * sqr(s[k])/ (xt[k] * yt[k]);
s2 := s1 * stress1[k] * stress2[k] / sqr(yy) ;
s3 := s1 * stress1[k] * stress2[k] / sqr(xx) ;
if ( s1 <= 1 ) then
        begin
        R12[k]:= sqr(stress1[k]/xx)-s2+s1*sqr(stress2[k]/yy)+sqr(stress12[k]/s[k
        R12Test;
        if fail[k]=false then
          begin
          dummy:=R12[k];
          R12[k]:= s1*sqr(stress1[k]/xx)-s3+sqr(stress2[k]/yy)+sqr(stress12[k]/s
          R12Test;
          if fail[k]=false then
            begin
            m := ( 1/sqr(xx) + s1*c1/sqr(yy)*(c1-1) + sqr( c2/s[k] ) ) ;
            if ( m > 0 ) then m:= sqrt(m) else m:= 0;
            R12[k] :=  m * stress1[k] ;
            n := ( s1/sqr(xx) - s1*c1/sqr(xx) + sqr(c1/yy) + sqr(c2/s[k]) ) ;
            if ( n > 0 ) then n:= sqrt(n) else n:= 0;
            dummy := n * stress1[k] ;
            if dummy>R12[k] then R12[k]:=dummy;
            end;
          end;
        end
else
        begin
        writeln(' FATAL ERROR....');
        writeln(' 3 * sqr(s[k])/ (xt[k] * yt[k]) is greater than 1 !!!');
        ch:=readkey;
        end;
End;

PROCEDURE NORRISMCKINNONTEST;
Begin
R12[k]:= sqr(stress1[k]/xx) + sqr(stress2[k]/yy) + sqr(stress12[k]/s[k]);
R12Test;
if fail[k]=false then
  begin
  m  := sqrt( 1/sqr(xx) + sqr(c1/yy) + sqr(c2/s[k]) ) ;
  R12[k] :=  m * stress1[k];
  end;
End;

PROCEDURE NORRISDISTTEST;
Begin
R12[k]:= sqr(stress1[k]/xx)-stress1[k]*stress2[k]/(xx*yy)+sqr(stress2[k]/yy)+sqr
R12Test;
if fail[k]=false then
  begin
  m  := sqrt( 1/sqr(xx) - c1/(xx*yy) + sqr(c1/yy) + sqr(c2/s[k]) ) ;
  R12[k] := m * stress1[k];
  end;
End;

PROCEDURE FISCHERTEST;
Begin
if ( 0 <> 2*sqrt(e1[k]*e2[k]*(1+mew12[k])*(1+mew21[k])) ) then
          begin
          m:=(e1[k]*(1+mew21[k])+e2[k]*(1+mew12[k]))/(2*sqrt(e1[k]*e2[k]*(1+mew]
```

```
PROCEDURE GOLDENBLATTEST;
Begin
p := 1/xt[k] - 1/xc[k];
q := 1/yt[k] - 1/yc[k];
n := sqr(stress1[k])/4*sqr(p)+sqr(stress2[k])/4*sqr(q)+A12*stress1[k]*stress2[k]
n := abs(n);
s1:=sqrt(n);
R12[k]:= stress1[k]/2*p+stress2[k]/2*q+s1;
R12Test;
if fail[k]=false then
  begin
  s2 := abs(sqr(p/2) + sqr(c1*q/2) + A12*c1 + sqr(c2/s[k]));
  m  := p/2 + q*c1/2 + sqrt( s2 );
  R12[k] :=  m * stress1[k] ;
  end;
End;

PROCEDURE GERMANSTDTEST;
Begin
R12[k]:=sqr(stress2[k])/(yt[k]*yc[k])+stress2[k]*(1/yt[k]-1/yc[k])+sqr(stress12[
R12Test;
if fail[k]=false then
  begin
  m:=c1*stress2[k]/(yt[k]*yc[k])+c1*(1/yt[k]-1/yc[k])+c2*stress12[k]/sqr(s[k]);
  R12[k]:=m*stress1[k];
  end;
End;

PROCEDURE MARINTEST;
Begin
p:=(xt[k]-xc[k])/(xt[k]*xc[k]);
q:=(1/yt[k]-yt[k]/(xt[k]*xc[k]));
m:=(2/(xt[k]*xc[k])-(xc[k]*xt[k]-s[k]*(     ]-xt[k]-xc(k]*(xt[k]/yt[k])+yt[k]))/(
n:=1/(xt[k]*xc(k]);
R12[k]:=p*stress1[k]+q*stress..[k]+m*stress1[k]*stress2[k]+sqr(stress1[k])*n+sqr(
R12Test;
if fail[k]=false then
  begin
  R12[k]:=p+q*c1+m*stress2[k]+stress1[k]*n+c1*stress2[k]*n;
  end;
End;

PROCEDURE PRECALC;
Begin
R1[k]:=0;
R2[k]:=0;
R12[k]:=0;
if stress1[k]<0 then xx:=xc[k] else xx:=xt[k];
if stress2[k]<0 then yy:=yc[k] else yy:=yt[k];
c1 := stress2[k] / stress1[k] ;
c2 := stress12[k] / stress1[k] ;
End;


PROCEDURE MAXSTRESS;    { specific criteria procedures }
Begin
for k:= 1 to Nlayers do
  begin
  PRECALC;
  XTEST;
  YTEST;
  STEST;
  end;
End;

PROCEDURE MAXSTRAIN;
```

```
Begin
for k:= 1 to Nlayers do
  begin
  PRECALC;
  XTest;
  PuckSimpleTest;
  end;
End;

PROCEDURE PUCKMODIFIED;
Begin
for k:= 1 to Nlayers do
  begin
  PRECALC;
  PuckModTest;
  XTest;
  end;
End;

PROCEDURE TSAIHILL;

Begin
for k:= 1 to Nlayers do
  begin
  PRECALC;
  TsaiHillTest;
  end;
End;

PROCEDURE FACTORCALC;
Begin
     A11 := 1/ (xt[k] * xc[k]);
     A22 := 1/ (yt[k] * yc[k] );
     if (A12 = -0.5 ) then A66 := 0
        else A66 := 1/sqr(s[k]) ;
     B1 := 1/xt[k] - 1/xc[k] ;
     B2 := 1/yt[k] - 1/yc[k] ;
End;

PROCEDURE TSAIWU;
Begin
  if (count = 0) then
  begin
    clrscr;
    writeln('Tsai-Wu ');
    writeln;
    writeln(' For this criterion you will need the material constant A12. ');
    writeln(' An estimate can be made for zero shear stress. Enter a 'y' if');
    writeln(' you require this estimate, otherwise enter 'n'.');
    ch:=readkey;
    factorflag:=true;
    if (ch='n') or (ch='N') then
      begin
      factorflag:=false;
      write(' Enter your value of A12. ');
      readln(A12);
      end;
  end;
  if factorFlag=false then
               begin
               for k:=1 to nlayers do
                 begin
                 PRECALC;
                 FactorCalc;
                 TsaiWuTest;
                 end;
```

```
                end;
End;

PROCEDURE PUPPOEVENSEN;
Begin
for k:=1 to nlayers do
  begin
  PRECALC;
  PuppoEvensenTest;
  end;
End;

PROCEDURE NORRISMCKINNON;
Begin
for k:=1 to nlayers do
  begin
  PRECALC;
  NorrisMcKinnonTest;
  end;
End;

PROCEDURE NORRISDIST;
Begin
for k:=1 to nlayers do
  begin
  PRECALC;
  NorrisDistTest;
  XTest;
  Ytest;
  end;
End;

PROCEDURE FISCHER;
Begin
for k:=1 to nlayers do
  begin
  PRECALC;
  FischerTest;
  end;
End;

PROCEDURE GOLDENBLAT;
Begin
writeln(' Goldenblat-Kopnov');
writeln;
if (count = 0 ) then
    begin
    writeln(' For this criterion you will need the material constant A12. ');
    write(' Enter your value. ');
    readln(A12);
    end;
for k:=1 to nlayers do
  begin
  PRECALC;
  GoldenblatTest;
  end;
End;

PROCEDURE GERMANSTD;
Begin
for k:=1 to nlayers do
  begin
  PRECALC;
  GermanStdTest;
  XTest;
  end;
End;
```

Maximum Stress Criterion

number of layers = 8
number of material types = 1
number of lay-up angles = 2

glass
E1 = 12.00 E2 = 7.00 G12 = 4.00
Xt = 1200.00 Xc = 120.00
Yt = 90.00 Yc = 80.00
S = 50.00 mew12 = 0.40 thickness = 0.15

Angles
1 = 1.57 2 = 0.00
layer material types
1 = 1.00 2 = 1.00 3 = 1.00 4 = 1.00 5 = 1.00 6 = 1.
layer angle types
1 = 1 2 = 2 3 = 1 4 = 2 5 = 2 6 = 1 7 = 2 8 = 1

Loading 1 1.00
Loading 2 0.00
Loading 3 0.00
Loading 4 0.00
Loading 5 0.00
Loading 6 0.00

MAXIMUM STRESS CRITERIA

Output number 1

Layer No	stress 1	stress 2	shear stress
1	-0.07	0.59	-0.00
2	1.07	0.07	-0.00
3	-0.07	0.59	-0.00
4	1.07	0.07	-0.00
5	1.07	0.07	-0.00
6	-0.07	0.59	-0.00
7	1.07	0.07	-0.00
8	-0.07	0.59	-0.00

Layer No	strain 1	strain 2	shear strain
1	-2.5671102482E-02	8.7098383422E-02	-1.1011675311E-07
2	8.7098383422E-02	-2.5671102482E-02	-3.9505182306E-08
3	-2.5671102482E-02	8.7098383422E-02	-1.1011675363E-07
4	8.7098383422E-02	-2.5671102482E-02	-3.9505181785E-08
5	8.7098383422E-02	-2.5671102482E-02	-3.9505181525E-08
6	-2.5671102482E-02	8.7098383422E-02	-1.1011675441E-07
7	8.7098383422E-02	-2.5671102482E-02	-3.9505181004E-08
8	-2.5671102482E-02	8.7098383422E-02	-1.1011675493E-07

Layer No	strain x	strain y	shear strain xy
1	8.7098383423E-02	-2.5671102483E-02	-3.9505182567E-08
2	8.7098383423E-02	-2.5671102483E-02	-3.9505182307E-08
3	8.7098383423E-02	-2.5671102483E-02	-3.9505182046E-08
4	8.7098383423E-02	-2.5671102483E-02	-3.9505181786E-08
5	8.7098383423E-02	-2.5671102483E-02	-3.9505181525E-08
6	8.7098383423E-02	-2.5671102483E-02	-3.9505181265E-08
7	8.7098383423E-02	-2.5671102483E-02	-3.9505181005E-08
8	8.7098383423E-02	-2.5671102483E-02	-3.9505180744E-08

Exx = 9.57 Eyy = 9.57 Gxy = 4.00 Mewxy = 0.29

---

ratio used...0.00659

Loading 1   151.73
Loading 2   0.00
Loading 3   0.00
Loading 4   0.00
Loading 5   0.00
Loading 6   0.00

MAXIMUM STRESS CRITERIA

Output number 2

Layer No	stress 1	stress 2	shear stress
1	-10.74	90.00	-0.00
2	162.88	10.74	-0.00
3	-10.74	90.00	-0.00
4	162.88	10.74	-0.00
5	162.88	10.74	-0.00
6	-10.74	90.00	-0.00
7	162.88	10.74	-0.00
8	-10.74	90.00	-0.00

Layer No	strain 1	strain 2	shear strain
1	-3.8949880669E+00	1.3215138084E+01	-1.6707636216E-05
2	1.3215138084E+01	-3.8949880669E+00	-5.9939853600E-06
3	-3.8949880669E+00	1.3215138084E+01	-1.6707636217E-05
4	1.3215138084E+01	-3.8949880669E+00	-5.9939853595E-06
5	1.3215138084E+01	-3.8949880669E+00	-5.9939853592E-06
6	-3.8949880669E+00	1.3215138084E+01	-1.6707636217E-05
7	1.3215138084E+01	-3.8949880669E+00	-5.9939853587E-06
8	-3.8949880669E+00	1.3215138084E+01	-1.6707636218E-05

Layer No	strain x	strain y	shear strain xy
1	1.3215138084E+01	-3.8949880669E+00	-5.9939853603E-06
2	1.3215138084E+01	-3.8949880669E+00	-5.9939853601E-06
3	1.3215138084E+01	-3.8949880669E+00	-5.9939853598E-06
4	1.3215138084E+01	-3.8949880669E+00	-5.9939853595E-06
5	1.3215138084E+01	-3.8949880669E+00	-5.9939853593E-06
6	1.3215138084E+01	-3.8949880669E+00	-5.9939853590E-06
7	1.3215138084E+01	-3.8949880669E+00	-5.9939853588E-06
8	1.3215138084E+01	-3.8949880669E+00	-5.9939853585E-06

Exx =   9.57   Eyy =   9.57   Gxy =   4.00 Mewxy =   0.29

The 1 layer has failed by principle stress Y
The 3 layer has failed by principle stress Y
The 6 layer has failed by principle stress Y
The 8 layer has failed by principle stress Y

Loading 1   151.73
Loading 2   0.00
Loading 3   0.00
Loading 4   0.00
Loading 5   0.00
Loading 6   0.00

MAXIMUM STRESS CRITERIA

Output number 3

1	-2.9159335628E+00	1.9786692033E+01	-4.2923043440E-05
2	1.9786692033E+01	-2.9159335628E+00	1.2801324259E-05
3	-2.9159335628E+00	1.9786692033E+01	-4.2923043441E-05
4	1.9786692033E+01	-2.9159335628E+00	1.2801324261E-05
5	1.9786692033E+01	-2.9159335628E+00	1.2801324262E-05
6	-2.9159335628E+00	1.9786692033E+01	-4.2923043444E-05
7	1.9786692033E+01	-2.9159335628E+00	1.2801324264E-05
8	-2.9159335628E+00	1.9786692033E+01	-4.2923043445E-05

Layer No	strain x	strain y	shear strain xy
1	1.9786692034E+01	-2.9159335629E+00	1.2801324259E-05
2	1.9786692034E+01	-2.9159335629E+00	1.2801324260E-05
3	1.9786692034E+01	-2.9159335629E+00	1.2801324260E-05
4	1.9786692034E+01	-2.9159335629E+00	1.2801324261E-05
5	1.9786692034E+01	-2.9159335629E+00	1.2801324262E-05
6	1.9786692034E+01	-2.9159335629E+00	1.2801324263E-05
7	1.9786692034E+01	-2.9159335629E+00	1.2801324264E-05
8	1.9786692034E+01	-2.9159335629E+00	1.2801324265E-05

Exx = 6.39 Eyy = 10.1? Gxy = 2.00 Mewxy = 0.15

The 1 layer has failed by principle stress Y
The 3 layer has failed by principle stress Y
The 6 layer has failed by principle stress Y
The 8 layer has failed by principle stress Y

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failure ratios...
r1=0.32161 r2=0.00000 r12=0.00000
r1=0.21073 r2=0.42881 r12=0.00000
r1=0.32161 r2=0.00000 r12=0.00000
r1=0.21073 r2=0.42881 r12=0.00000
r1=0.21073 r2=0.42881 r12=0.00000
r1=0.32161 r2=0.00000 r12=0.00000
r1=0.21073 r2=0.42881 r12=0.00000
r1=0.32161 r2=0.00000 r12=0.00000

ratio used...0.42881

Loading 1 353.83
Loading 2 0.00
Loading 3 0.00
Loading 4 0.00
Loading 5 0.00
Loading 6 0.00

MAXIMUM STRESS CRITERIA

Output number 4

Layer No	stress 1	stress 2	shear stress
1	-90.00	0.00	0.00
2	589.71	90.00	0.00
3	-90.00	0.00	0.00
4	589.71	90.00	0.00
5	589.71	90.00	0.00
6	-90.00	0.00	0.00
7	589.71	90.00	0.00
8	-90.00	0.00	0.00

Layer No	strain 1	strain 2	shear strain
1	-5.8000000001E+00	4.6142857144E+01	-1.0009716927E-04

3	4.6142857145E+01	-6.8000000003E+00	2.9852876652E-05
4	4.6142857145E+01	-6.8000000003E+00	2.9852876652E-05
5	4.6142857145E+01	-6.8000000003E+00	2.9852876653E-05
6	4.6142857145E+01	-6.8000000003E+00	2.9852876654E-05
7	4.6142857145E+01	-6.8000000003E+00	2.9852876655E-05
8	4.6142857145E+01	-6.8000000003E+00	2.9852876656E-05

Exx = 6.39 Eyy = 10.12 Gxy = 2.00 Mewxy = 0.15

The 1 layer has failed by principle stress Y
The 2 layer has failed by principle stress Y
The 3 layer has failed by principle stress Y
The 4 layer has failed by principle stress Y
The 5 layer has failed by principle stress Y
The 6 layer has failed by principle stress Y
The 7 layer has failed by principle stress Y
The 8 layer has failed by principle stress Y

Loading 1 353.83
Loading 2 0.00
Loading 3 0.00
Loading 4 0.00
Loading 5 0.00
Loading 6 0.00

MAXIMUM STRESS CRITERIA

Output number 5

Layer No	stress 1	stress 2	shear stress
1	-90.00	0.00	0.00
2	589.71	90.00	0.00
3	-90.00	0.00	0.00
4	589.71	90.00	0.00
5	589.71	90.00	0.00
6	-90.00	0.00	0.00
7	589.71	90.00	0.00
8	-90.00	0.00	0.00

Layer No	strain 1	strain 2	shear strain
1	-6.8000000001E+00	4.6142857144E+01	-1.0009716927E-04
2	4.6142857144E+01	-6.8000000003E+00	2.9852876650E-05
3	-6.8000000001E+00	4.6142857144E+01	-1.0009716927E-04
4	4.6142857144E+01	-6.8000000003E+00	2.9852876652E-05
5	4.6142857144E+01	-6.8000000003E+00	2.9852876653E-05
6	-6.8000000001E+00	4.6142857144E+01	-1.0009716927E-04
7	4.6142857144E+01	-6.8000000003E+00	2.9852876655E-05
8	-6.8000000001E+00	4.6142857144E+01	-1.0009716927E-04

Layer No	strain x	strain y	shear strain xy
1	4.6142857145E+01	-6.8000000003E+00	2.9852876650E-05
2	4.6142857145E+01	-6.8000000003E+00	2.9852876651E-05
3	4.6142857145E+01	-6.8000000003E+00	2.9852876652E-05
4	4.6142857145E+01	-6.8000000003E+00	2.9852876652E-05
5	4.6142857145E+01	-6.8000000003E+00	2.9852876653E-05
6	4.6142857145E+01	-6.8000000003E+00	2.9852876654E-05
7	4.6142857145E+01	-6.8000000003E+00	2.9852876655E-05
8	4.6142857145E+01	-6.8000000003E+00	2.9852876656E-05

Exx = 6.39 Eyy = 10.12 Gxy = 2.00 Mewxy 0.15

The 1 layer has failed by principle stress Y stiffness matrix for this laminate:

7.9411764704E+00	1.8529411764E+00	1.8547947257E-17	3.2299725594E-24	1.58222
1.8529411764E+00	1.2141176470E+01	1.0536309406E-05	1.5822275922E-14	-1.82268
1.8547947257E-17	1.0536309406E-05	2.4000000000E+00	-1.3730827080E-20	-1.52971
3.2299725594E-24	1.5822275922E-14	-1.3730827080E-20	5.9558823528E-01	1.38970
1.5822275923E-14	-1.8226812679E-12	-1.5297117756E-19	1.3897058823E-01	1.62529
-3.1554436209E-30	-1.7347234760E-18	2.4319595137E-13	3.0604112975E-18	1.73849