MICROMECHANICS, DAMAGE AND LIFE PREDICTION OF CARBON FIBRE COMPOSITE PRESSURE VESSELS

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ABSTRACT

A study by 3D finite element analysis has revealed the changes in the stress field around broken fibres in cfrp by considering the evolution of representative elementary volumes of the composite for both elastic and viscoelastic matrices and the effects of debonding. The viscoelastic behaviour of the matrix does not change the mechanism of load transfer but introduces time as a parameter. At a constant load, the relaxation of the matrix increases the coefficients of load transfer around broken fibres and causes new failures of fibres. This analysis relates the acoustic emission detected during steady loading to fibre failures. In this way a model to predict the lifetime of pressure vessels has been developed.

1. INTRODUCTION

The use of filament wound pressure vessels is hindered by the lack of effective means of determining the continuing reliability of the structure whilst in service. All pressure vessels require periodic testing and proof testing and, in service, techniques have been developed for metal structures. Some of these techniques require the vessel to be pressurised to above (usually 1.5 times) the maximum pressure in service. These techniques are not however applicable to fibre reinforced composite pressure vessels, as the nature of damage accumulation is different. Composite pressure vessels do not fail by simple crack propagation but, in the absence of stress raisers or localised damage, by the accumulation of a more diffuse and global type of damage, of which the most important is the failure of fibres. The overload test is therefore discredited as it leads to an increase in overall damage. There is no technique available which allows an evaluation of minimum residual lifetimes of composite pressure vessels to be made. Nevertheless the use of natural gas as a fuel for buses and trucks is increasing rapidly as it is environmentally friendly and of low cost. Such a pressure vessel, made of high strength carbon fibres in an epoxy matrix (cfrp), is shown in Figure 1. This study has used the acoustic emission technique in order to monitor the accumulation of damage.

Acoustic Emission (A.E.) has previously been shown to be a useful technique for monitoring damage in composites and, by localization, for identifying concentrated areas of damage. From earlier studies of cfrp, in the form of both plates and pressure vessels, and taking into account the shape of the stress fields within the filament wound pressure vessel, it has been possible to make an analogy between the accumulation of damage in these structures and in unidirectional cfrp, as, for both, the fibres are subjected to uniaxial loading. The present study has confirmed the observation that the number of emissions monitored versus time, under a constant load, obeys an empirical law which allows the calculation of damage accumulation as a function of time. An analysis of the fibre arrangement in composite pressure vessels shows that the damage monitored is due to fibre failure. In the absence of stress concentrations the fibre failures are distributed randomly in the composite structure.

The continuing accumulation of fibre failures under constant load is due to the effects of the viscoelastic properties of the matrix coupled to carbon fibres, which show a wide scatter in their strengths. The elastic nature of carbon fibres suggests that, after an initial strain, no further evolution of the composite, loaded parallel to the fibres, should be observed. As a consequence no emissions should be detected. However the experimental results show that damage continues to accumulate. This is interpreted as being due to local relaxation of the matrix around fibres breaks producing a local overload of the neighbouring intact fibres. This local increase in load, combined with the scatter in fibre strengths, leads to an increased probability of additional fibre failures. This process has been investigated in the present study.

A local finite element analysis, of the region around a fibre break, of the mechanisms governing composite damage, has shown that even a simple viscoelastic law describing the behaviour of the bulk epoxy resin leads to an increasing effective extra load on the neighbouring intact fibres, as a function of time. The calculations were carried out on different representative 3D unit cells (cf. Figure 2), corresponding to different states of composite damage. The results of the calculations agree well with the results found by different analytical methods of the shear-lag type. This agreement supports the conclusions arrived at in this study which could not be obtained by other methods, in particular because they result from a better definition of the local state of the stress fields in the vicinity of the broken fibres. The effects of the interfacial decohesion along part of the broken fibre near the break have been shown and the overload coefficients obtained without decohesion agree with those determined analytically by Hedgepeth and Von Dyke[1] and more recently by Landis[2]. Moreover, we can compare the effect of the fibre volume fraction on the ineffective length of the broken fibre. With this numerical approach, we can establish an accurate definition of the local load sharing versus time and along the fibre. In addition, this method can take into account all possible behaviour laws for the resin. In this way it is possible to determine the accumulation curve of fibre failures as a function of time induced by matrix relaxation around fibre breaks from results obtained using the statistics of carbon fibre failure and knowing the approximate number of fibre failures distributed randomly in the composite on initial loading at t=0 for a period of steady loading. The forms of the experimental curves obtained by acoustic emission on unidirectional composites and filament wound vessels and the theoretical curve obtained from the finite element calculation are identical.

The study has shown that the experimental A.E. curve representing the evolution of composite damage under a steady given load, can allow a minimal lifetime of the pressure vessel to be determined. In this way a limiting damage curve can be defined over the envisaged lifetime of the pressure vessel, which determines a master curve. A comparison between this master curve and the rate of damage accumulation of any other pressure vessel of the same type reveals if it will become unstable before or after the desired lifetime. It is proposed that the in service control of carbon fibre composite pressure vessels of the type used on many buses and other vehicles should be based on this approach.

2. MATERIALS

Plate and filament wound carbon fibre reinforced epoxy specimens have been tested. The plates were unnotched, rectangular, 270 x 15 x 0.9 mm unidirectional cfrp specimens with a fibre volume fraction of 60 %. The fibres in these specimens were aligned parallel to the long axis and had to be broken for the composite to fail. These specimens were subjected to tensile loading. Pressure vessels made of carbon fibres, filament wound onto an aluminium liner, which served both as a mandrel and provided a gas proof seal, have also been tested and comparisons made between the behaviours of the two. A typical pressure vessel as shown in Figure 1.

Figure 1: A typical carbon fibre pressure vessel

After manufacture, the pressure vessels had been subjected to hydraulic pressure tests of 300 atmospheres (~30 MPa), which corresponded to 1.5 times the operating pressure.

In this study, damage occurring in the two types of specimens was monitored with a MISTRAS 2001 acoustic emission system which comprised two R15 piezoelectric transducer with a resonant frequency of 30KHz, and two preamplifiers with fixed gains of 40 dB. The use of two detection channels permitted the location of the events.

The pressurization of the vessels was carried out with the assistance of a hydraulic pump operating up to a maximum pressure of 1000 bars (~100 MPa). The vessels were pressurised with water.

3. THEORY

The development of damage, in and ultimate failure of, a carbon fibre unidirectional or filament wound composite structure, in which the fibres are arranged so as to transfer maximum strength and rigidity to the structure, depends on the failure of the fibres. The failure probability as a function of applied stress on the fibres can be determined experimentally and is described by Weibull statistics, which gives the probability of fibre failure as :

$$P = 1 - \exp \{- \int [(\sigma - \sigma_u)/\sigma_o]^m V \qquad (1)$$

Where P is the failure probability of a fibre of volume V, σ is the applied stress, σ_u the stress failure threshold and σ_o and m material constants. The factor m is known as the Weibull modulus and describes the dispersion of fibre strength.

Loading the composite in the direction of the fibres produces fibre breaks which are randomly distributed in the volume of the composite, in the absence of any stress concentration, as there is a wide dispersion of fibres strengths
Each fibre break is isolated from other breaks by the shear of the matrix which produces a load transfer along the fibre so that at a critical distance from the break the fibre is able to continue to support the load [3].

This means that each fibre break creates a damage zone around the break, the limit of which is determined by the shear properties of the matrix and the Young's modulus of the fibre. In addition and importantly, there is a debonded length between the fibre and the matrix around the break which increases the load transfer length. The intact fibres neighbouring a broken fibre experience an increase in stress over a short length of each fibre as the total load supported by the plane passing through the fibre break has to remain unchanged. Shear stress relaxation of the matrix means that, with time, the lengths of the damage zones and the lengths of neighbouring intact fibres which experience increased stresses, become longer.

As the probability of failure increases with fibre length, for a given stress, additional fibres fail which can be detected by acoustic emission and the damage zone increases in area. When the damage zones begin to interact damage accumulation accelerates and this represents the onset of instability which is taken as the definition of the end of useful life of the pressure vessel.

Relaxation of the shear stress leads to an evolution of the size of the damage sites and an accumulation of fibre failures, detected as acoustic emission events, which has been shown to obey a law of the following form :

$$\frac{dN}{dt} = \frac{A}{(t+\tau)^n} \qquad (3)$$

where N is the number of acoustic emission events,

- t is the time
- A is a factor which depends only on the applied stress
- τ is a time constant
- and n is a factor less than unity.

By defining an upper damage threshold in terms of a maximum number of acoustic emission events which is acceptable it now becomes possible to use equation (3) to create master curves for structures which have exactly the lifetimes required, as shown in the curve of acoustic emission as a function of time, in Figure 2.

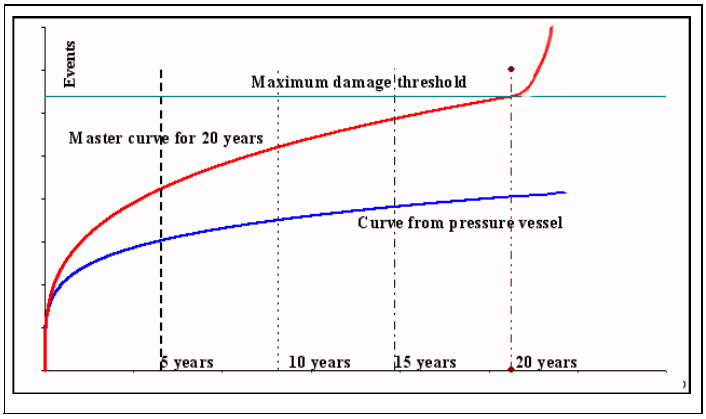


Figure 2 : The accumulated AE events curve is compared to a master curve calculated for a life of 20 years. If the composite structure is acceptable for further use its curve should be lower.

If a unidirectional specimen or a pressure vessel is expected to survive for more than the twenty years considered with the master curve the acoustic activity detected from the structure under predetermined steady loading conditions must lie on a curve under the appropriate master curve. It is not feasible to obtain all the curve of a pressure vessel however at any given time its rate of acoustic activity must be lower than that of the master curve. In this way a comparison of the activity during a short period with the activity predicted by the master curve allows an evaluation of the residual lifetime of the pressure vessel to be made. If the number of emissions during the test is less than that given by the master curve the vessel is acceptable. If not it should either be changed or subjected to further examination.

4. EXPERIMENTAL RESULTS

Unidirectional and pressure vessels have been taken to failure in order to obtain the value of the maximum threshold damage level. The numbers of events for each type of specimen differed, as would be expected due to their differing sizes and shapes, however for each type of specimen the total number of events to failure showed a dispersion of less than 10%. In order to verify the assumptions of the model, unidirectional specimens were subjected to steady loads of 70 to 95% of failure load for periods of twelve hours. Figure 3 shows that, in all cases, the numbers of events varied as the logarithm of time and that the higher the applied load the greater the number of events which were recorded. The curve shown for the highest applied stress shows a jump in numbers of events which occurred when a packet of fibres was observed to fail at the edge of the specimen. This event induced a redistribution of the load in the specimen and an increase in acoustic activity. This observation reveals how the evolution of a failure zone can lead to the increased rate of damage accumulation of the remaining intact material.

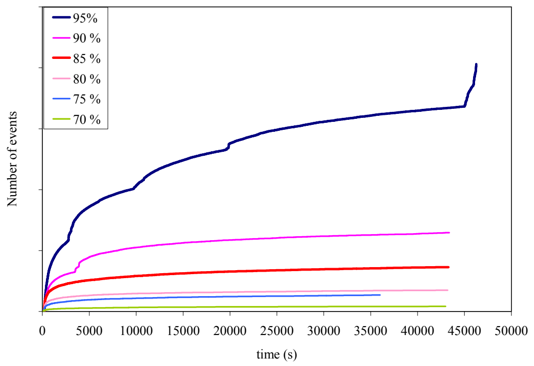


Figure 3 :

Acoustic events recorded at different steady stress levels on unidirectional specimens.

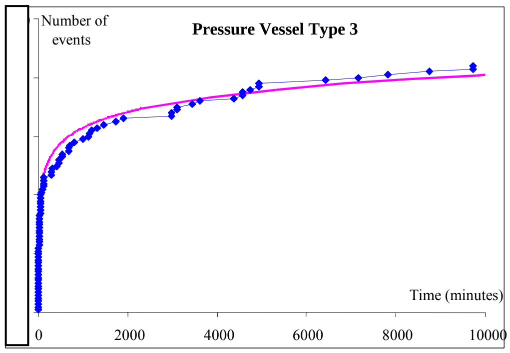


Figure 4:

Comparison between the experimental and theoretical curve of acoustic emission for different types of pressure vessel.

Tests were carried out on pressure vessels at different pressures but as the maximum service pressure was 200 atmospheres (20 Mpa) particular attention was paid to vessels pressurised to this level. Figure 4 shows a typical curve obtained with a pressure vessel.

It can be seen that the results obtained from both types of specimen are very similar.

5. THEORETICAL MODELLING

Since the aim is to explain the damage mechanics of unidirectional composites, the scale of the study that will reveal the beginning and the coalescence of these mechanisms must distinguish between the fibres and the matrix at the mesoscopic scale. At this scale, observations (by optical microscopic) of sections of the composite part of the pressure vessels show that the fibre distribution in the matrix is relatively regular. Consequently, the description of the R.E.V. (Representative Elementary Volume) which is the elementary periodic cell (or, more simply, the elementary cell) can be defined. Figure 5 shows a section of the composite and the distribution of the fibres and matrix. In places the fibres can be seen to be arranged in an hexagonal pattern whereas elsewhere there are resin rich areas. The relationship between the complexity of the cell geometry and the need to represent accurately the real material led to a square distribution of the fibres being adopted for the model.

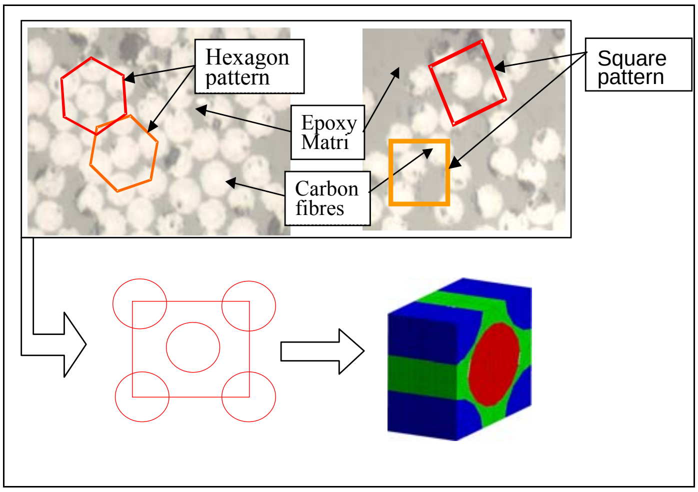


Figure 5 : The fibres can be seen to be organised in a square or hexagonal pattern in parts of the composite but there are also resin rich areas. An average square pattern has been modelled using finite element analysis.

The geometrical definition of the R.E.V. is important. Actually, studies [1,4,5,6] on the influence of one broken fibre on its surroundings have shown that the perturbation caused to the stress field is limited to the nearest neighbouring intact fibres: the intact fibres surrounding the broken fibre play a shielding role where other fibres further away from the break are concerned. Beyond the nearest third intact fibre the failure has almost no effect on the stress field. For this reason several R.E.V.s have been chosen to represent the different composite damage. Figure 6 shows an example of a typical R.E.V. used to represent the composite damage (the precision on these R.E.V. will be discussed in a subsequent article)

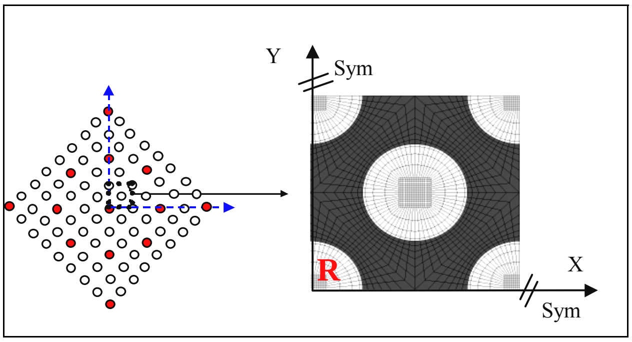


Figure 6: Example of a Representative Elementary Volume of a damage state and geometry of the Periodic Elementary Cell (the red circles and R represent the broken fibres)

For these calculations, the viscous nature of the matrix is represented by a linear viscoelastic model. The chosen model corresponds, in the one-dimensional case, to the model known as a Zener solid, in which the stress field is described as $\dot{\sigma}+\gamma\sigma=C_0\dot{\varepsilon}+\gamma C_\infty\varepsilon$ where γ is the relaxation tensor. C0 is the initial rigidity tensor and c the infinite rigidity tensor. In order to have a basis of comparison, a linear elastic analysis has been carried out followed by a viscoelastic analysis.

For the analysis of results, two coefficients K_r and L_c are used to evaluate the evolution of the stress in the fibres neighbouring the broken fibre and in the broken fibre as a function of time and debonded length.

Kr is equal to the average of the axial stress in the fibre between two sections of the fibre defined by the finite element mesh with respect to the value at that point before fibre failure.

L_c defines the inefficient length. The value of L_c is determined when the load transfer coefficient in the broken fibre is equal to 0.9.

6. MODELLING RESULTS AND DISCUSSION

a. Failure without debonded length

Figure 9 represents the evolution of the load transfer coefficient in the intact fibre nearest to the broken fibre for both an elastic and viscoelastic matrix. This Figure, in spite of the differences of behaviour, shows that the mechanisms of load transfer are identical.

At first, the coefficients determined for the elastic case with this cell, give a good estimation of the value of the overloading in the nearest fibres. The coefficients evaluated by this finite element method give coherent values (Figure 8) which are more reliable than those obtained by analytical methods. The evaluated coefficients K_r are much lower than those obtained by the Shear Lag method. With the variation of fibre volume fraction (Figure 8), the coefficient of load transfer is changed and as Van den Heuvel [5] noticed, the inefficient length decreases proportionally with an increase in fibre volume fraction. The length Lc is respectively 92µm, 68µm and 34µm for a volume fraction of 40%, 60% and 77%. It should be noted that the value of K_r in the plane of failure is independent of fibre volume fraction since Kr is constant. It is only along the length of the fibre that the influence of the fibre volume fraction changes the coefficient.

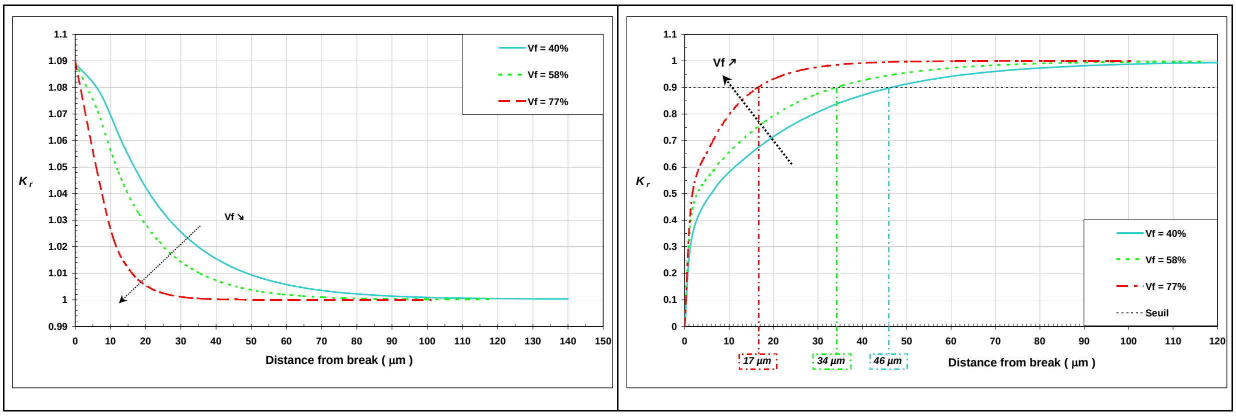
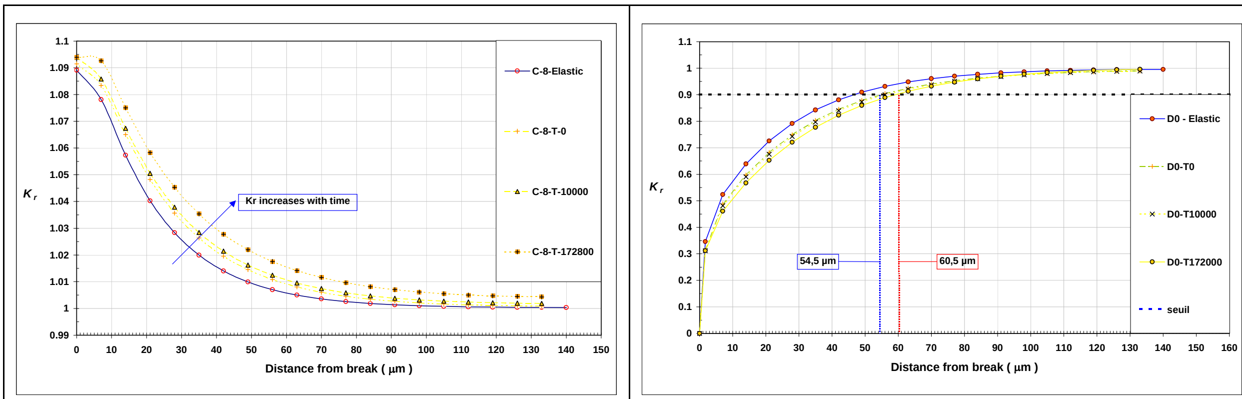


Figure 8: Evolution of load transfer coefficients as a function of fibre volume fraction

The viscoelastic matrix introduces time as a supplementary dimension. The introduction of time in the model enables the change from the static state to the fluid state to be described. At the beginning of the creep, the Kr coefficients agree with the coefficients obtained in the elastic model. The only distinction is the slope of the K_r curve that is more gradual for the viscoelastic matrix. For long term creep, compared to the elastic case, a notable modification of Kr and load transfer can be noticed. For the nearest fibre to the failure, independently of all damage phenomena, an increase of load transfer can be observed. So, in the broken fibre, the inefficient length grows between 0 and 172000s from 108 to 120µm. This observation justifies the requirements of our damage model based on the work of Lipschitz and Rotem [6] which explains the possibility of differed failure of unidirectional composites.

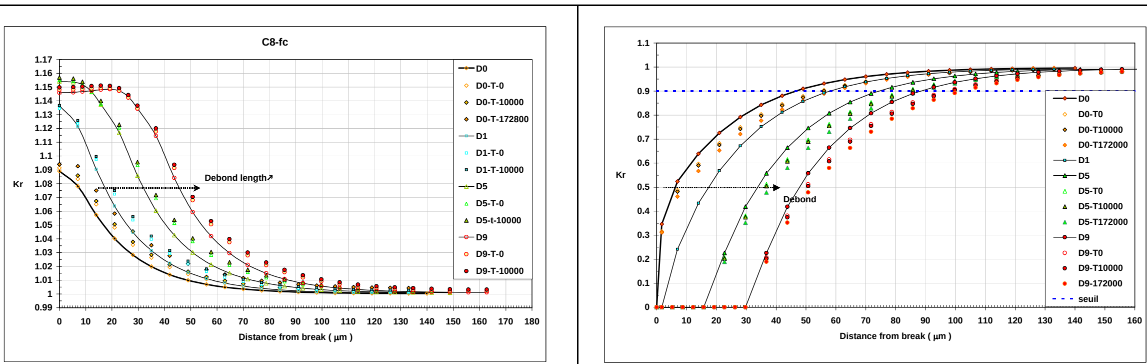


For all graphics the legend T- corresponds to creep time given in second

Figure 9: Comparison of the evolution of load transfer coefficient in the adjacent fibre and in the broken fibre for elastic and viscoelastic matrices

b. Failure with debonded length

The introduction of a debonded length (Figure 10) does not change the mechanics of load transfer but entails a important modification of load transfer coefficients from the broken fibre to the nearest intact fibres. A phenomenon, cited recently by Van den Heuvel [5], of growth and decrease of Kr with the rise of debonded length is observed with this model. A peak in the load transfer is located at the beginning of the zone of perfect adhesion. The debonded length increases proportionally with the inefficient length.



For all graphics the legend T- corresponds to creep time given in second

Figure 10: Evolution of load transfer coefficients for three debonded lengths

Nevertheless, this possibility of an evolution of the load transfer associated with the stochastic data of the carbon fibre failure can explain the possibility of differed failure of composite structures loaded in creep under the theoretical tensile failure load.

The solution is to make a multi scale process that could predict the structure lifetime from the data on the load transfer and on the probability of carbon fibre failure at the mesoscopic scale. The calculation made on the different cells gives, for macroscopic stresses, microscopic responses that can link the two scales.

The multi scale process coupled with a finite element calculation can simulate a tensile test of a unidirectional composite and predict the tensile failure and follow the fibre failures. The curve obtained is similar to the acoustic emission curve when a tensile test is being monitored by acoustic emission.

Most importantly the model allows the behaviour and failure of the composite to be predicted under steady loads, since, for every cell at the mesoscopic scale, the stress field changes with time and causes the degradation of the rigidity of the element, at the macroscopic scale, which in turn can cause the failure of the structure.

7. APPLICATION TO PRESSURE VESSELS

Using equation 3 this curve can be extrapolated over a period of twenty years and compared to a master curve giving an exact lifetime of twenty years, as shown in Figure 2. It is assumed that control tests have to be carried out after manufacture and then every three or five years. It can be seen that at each control the gradient of the experimental curve is less than that of the master curve for the case of a pressure vessel which is acceptable for further service. The values of A and τ in equation 3 for pressure vessels subjected to 200 atmospheres (~20 MPa) (were obtained from the experimental curve and this allowed the master curve to be calculated.

It now becomes possible to draw curves which can be used in a practical tests. The numbers of emissions expected from the master curve depend on the length of time the control test is conducted and this can be chosen so as to accommodate the needs of the bus operator. Figure 2 shows curves for a control period of 24 hours corresponding to pressure vessels which have been in service for different periods of time.

Figure 10 shows the numbers of events recorded for one such test over a period of 24 months. The master curve used presents a coefficient of security superior to 10 and predicts the acoustic behaviour of the vessels for 20 years in service. For the different control of 24 hours, the experimental points are under the master curve and shows perfect mechanical stability.

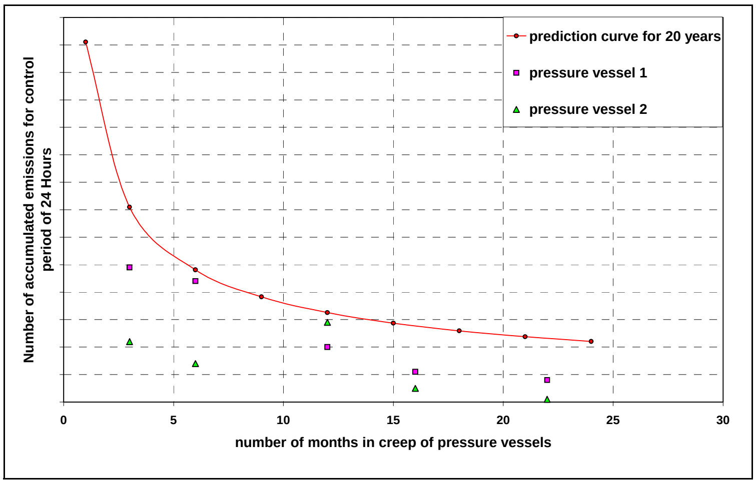


Figure 10: Comparison of the master curve and experimental results showing the stability of pressure vessels.

8. DISCUSSION

The monitoring of acoustic emission has shown that carbon fibre reinforced composites continue to accumulate failure events even when they are subjected to a constant load, or pressure in the case of a pressure vessel. The numerical investigations have justified the influence of the matrix relaxation and the effect of debonded length on the coefficients of load transfer. The relaxation mechanism control the delayed failure of neighbouring intact fibres around the broken fibres. This leads to an increasing influence of the break and an overload effect on the intact fibres. A local increase in stress on intact fibres inevitably causes further breaks, as the strength of fibres shows a wide scatter. Acoustic emission is a technique which allows this damage to be followed.

The regular rate of emission which is detected reflects the effects of shear stress relaxation around fibre breaks which leads to further failures. The accumulation of damage can therefore be modelled to give the accumulation of damage as a function of time. For a given series, of supposedly identical pressure vessels, initial tests can identify the maximum acoustic emission which is acceptable and so master curves can be drawn for pressure vessels with just the lifetimes required. Pressure vessels at manufacture or in service can be controlled periodically by a comparison between their actual acoustic emission count in a given period and the count predicted by the master curve for the same period. If the actual count is less than the limit given by the master curve the pressure vessel is deemed acceptable for further service. If not it should be withdrawn from service.

The technique which is proposed allows the natural overall ageing of carbon fibre pressure vessels to be determined and minimum residual lifetimes calculated. The acoustic emission technique can also be used to locate localised damage which may occur for example due to an impact.

9. CONCLUSION

The numerical studies on the influence of broken fibres on the neighbouring intact fibres in a viscoelastic matrix justifies the monitoring of pressure vessels under constant pressure by A.E. so as to determine their level of accumulated damage due to in-service use. By a Multi-scale process, a tensile test of a mesh, representing a unidirectional cfrp specimen, can be simulated, showing the accumulation of breaks similar to experimental results obtained by monitoring acoustic emissions from real specimens.

Thanks to this study, a non destructive evaluation technique has been developed for carbon fibre composite pressure vessels. The technique uses the acoustic emission technique to monitor damage accumulation during periods of fixed pressurisation. A model based on the relaxation of the resin around fibre breaks has been described which accounts for the delayed failure of fibres which can eventually lead to failure of the pressure vessel. The number of counts recorded in a given period is compared to those predicted by master curves and, depending on whether the counts are below or above the master curve for the pressure applied, the vessel is deemed acceptable for further service or not.

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11. ACKNOWLEDGEMENTS

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