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A METHODOLOGY FOR THE CONTROL OF THE RESIDUAL LIFETIMES OF CARBON FIBRE REINFORCED COMPOSITE PRESSURE VESSELS

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SUMMARY: Pressure vessels must be periodically proof tested. Traditional techniques for metal vessels are inapplicable for composite vessels as the latter do not break by crack propagation so that the reasoning behind the traditional testing procedures is not appropriate. Damage accumulation leading to the degradation of a composite vessel is by fibre failure. Fibres show a wide distribution in strengths and loading a composite inevitably breaks some. The method which has been developed is supported by an analysis of delayed fibre failure due to the relaxation of the resin around fibre breaks. This provokes overloading of intact fibres neighbouring breaks. The time until a critical density of breaks is reached can be calculated at which point the pressure vessel is deemed unstable. The test can be applied to pressure vessels which have been used in service and it is not necessary to know the details of their loading history with precision.

KEYWORDS: pressure vessels, carbon fibre composites, life time prediction, proof testing, acoustic emission, delayed fibre failure, resin relaxation.

INTRODUCTION

Filament wound fibre reinforced composite pressure vessels are replacing much heavier metal pressure vessels and are finding increasing numbers of applications. An expanding market is foreseen for these structures which are used as natural gas containers on buses, utility vehicles and even private vehicles. These applications can be seen to foreshadow the future use of composite pressure vessels in a hydrogen based economy. The attraction is, of course, weight saving and resistance to corrosion. A major difficulty is, however, that the legislation controlling the use of pressure vessels has been built on experience with steel pressure vessels and the nature of the material used is often not even mentioned. However the failure processes in metals are very different from those which control the behaviour of composites. Nevertheless operators are reluctant to face this fact and are applying methods of control which are entirely inappropriate for composite pressure vessels. At present the high pressure composite vessels which are in service rely entirely on being over dimensioned for their long term reliability. This situation is clearly unacceptable as any failure would put into danger the lives anyone in the vicinity. Even if the probability of failure is low the numbers of pressure vessels now in service and likely to enter into service in the next few years is in the millions so that a means of determining minimum lifetimes based on a thorough understanding of damage accumulation in these vessels is needed with some urgency.

Their high performance properties, which dominate the properties of any carbon fibre reinforced composite and their elastic behaviour, have led many to conclude that, in the direction of the fibres, such composites behave as a purely elastic body. That is to say, that

carbon fibre composites are considered by these authors as being insensitive to time effects. This assumption is not justified at the microscopic level but is a reasonable approximation for short term applications [1]. However, the increasing use of these composites in structures for which lifetimes, under load, measured in tens of years, has meant that, as a matter of some urgency, a closer examination of time dependent damage processes at the microscopic level which can eventually accumulate over many years and eventually cause failure of the structure need to be examined and understood. It is only through a thorough understanding of these processes that reliable lifetime estimates, of such structures as composite pressure vessels, can be achieved and so permit the development of large composite markets for this type of product.

The use of acoustic emission techniques to detect damage in composites has been suggested for many years, as has the possibility of using the technique for proof testing [2]. The difficulty has been the lack of another, independent, technique to verify the interpretation of damage accumulation detected by acoustic emission. Faced with this lack of technique it was decided that it was necessary to be able to model the macroscopic behaviour of the composite starting at the level of the individual fibres and introducing the viscoelastic behaviour of the matrix material.

Fortunately computing power, now available, allows a multiscale approach to modelling damage accumulation in composites. This paper will demonstrate that it is possible to predict macroscopic behaviour of composite structures based on damage processes occurring at the microscopic level and so to predict minimum residual lifetimes of composite pressure vessels.

DAMAGE ACCUMULATION IN COMPOSITE PRESSURE VESSELS

Composite pressure vessels can be made with a number of different reinforcements, carbon, aramid or glass fibres. Aramid composites are used, for example, for some rocket motors as they are lighter than the other fibres and when used in such a pressure vessel are subjected only to tensile forces so that their inherent anisotropy is not a problem. However these types of pressure vessels are not expected to be used repeatedly over periods of many years. Glass fibres suffer from delayed failure under load as microdefects in the fibres grow slowly and can become critical for the load applied. Carbon fibres are the reinforcement of choice for most high performance containers. The carbon fibres possess high strengths and stiffness and are perfectly elastic. They show no signs of creep or fatigue behaviour at room temperature so that their inherent stability is seen as an attractive characteristic for pressure vessels destined for long term use.

The fibres are first impregnated with epoxy resin before being filament wound over a mandrel which determines the shape of the pressure vessel. Gas permeability is of course a concern so that the mandrel is used to ensure gas tightness. The mandrels are of aluminium or polyethylene for natural gas containers but, for very high pressure systems, can be steel. Carbon fibre pressure vessels are being used on vehicles at present and typical vessels are shown in Figure 1.

A filament wound structure in which the fibre bundles are wound onto a mandrel and are placed, as a consequent of the manufacturing process, along geodesic paths. This means that, at the scale of the fibres and in the absence of any stress concentration due to the geometry of the structure, the material can be considered to behave as a unidirectional composite as the fibres are subjected only to tensile forces when the vessel is pressurised.

A simple calculation will show that the stiff and strong carbon fibres support 99% of the pressure in a typical pressure vessel. It is therefore axiomatic that for the pressure vessel to

burst the carbon fibres have to be broken. As with all types of pressure vessel, damage can accumulate by a variety of means. Impacts due to mistakes in handling when being mounted on a vehicle or unloading or damage during use or mistakes in manufacture can occur. Such damage leads to localised regions of damage which can be detected by a number of NDE techniques such as ultrasonic inspection, tapping, radiography and others but none address the problem of composite deterioration, caused by over pressurisation or ageing, due to the combined effects of the pressure and time which lead to the continuous failure of the carbon fibres.

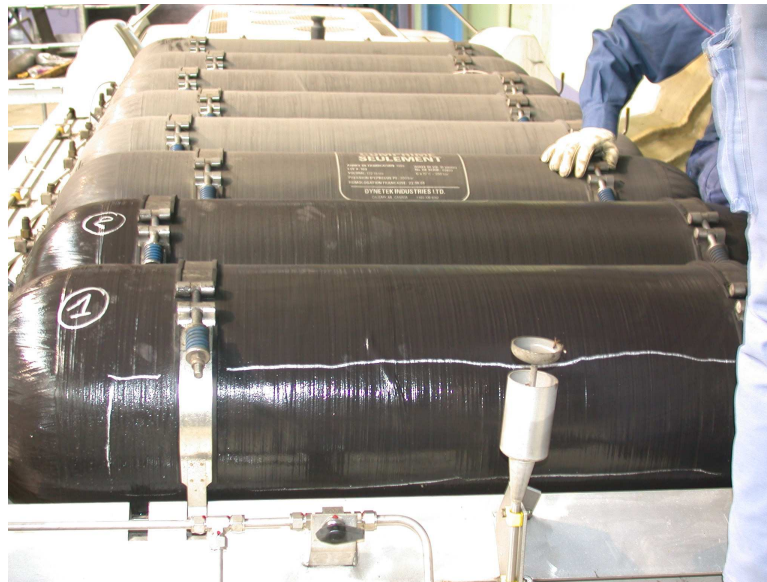


Figure 1 : Carbon fibre pressure vessels.

The most elementary level of any composite material is that of a fibre embedded in a matrix. The role of the matrix is to transfer load, through its shear deformation, between the reinforcing fibres. If subjected to loads in the direction of fibre alignment, it is the response and possible failure of all such fibres in the composite and the consequences this has on fibres neighbouring the breaks that will govern overall composite degradation. This degradation may not be detectable at the macroscopic level because of the great numbers of fibres involved and the random nature of failure but an increasing number of breaks will eventually lead to instability in the composite and ultimately failure.

Theoretical Models

Theoretical approaches to predicting the failure of unidirectional composites have been generally based on : an understanding of the stochastic nature of fibre strength, which is often modelled by a Weibull distribution; the calculation of stress transfer coefficients on intact fibres neighbouring a fibre break; and the development of a critical size of defect comprising broken fibres or the coalescence of areas of broken fibres so as to make the composite unstable. The probability of fibre failures within a bundle is shown schematically in Figure 2. It can be seen that any increase in load on a composite, such as in a standard proof test, inevitably causes fibres to break.

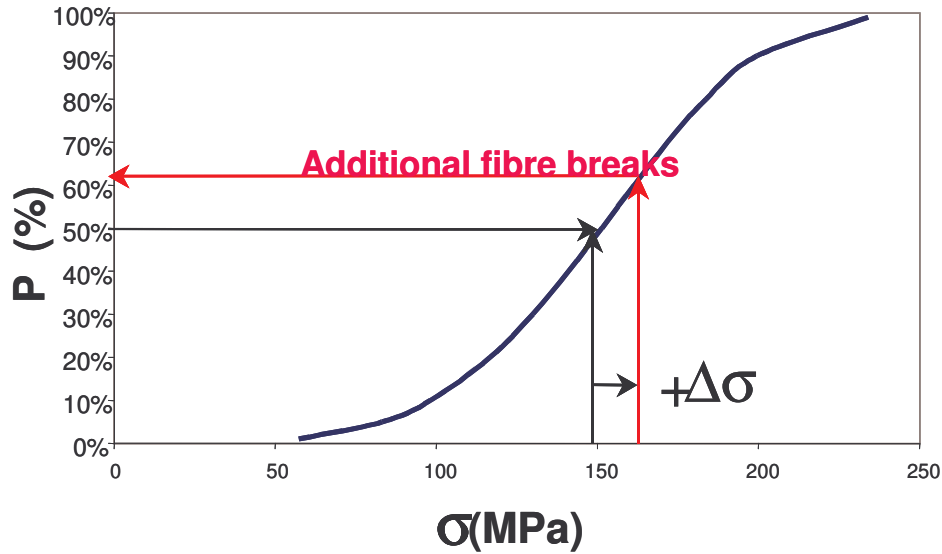


Figure 2 : Probability of fibre failure in a population of fibres as the stress is increased.

Rosen and Zweben [3, 4] were the first authors to propose a model of unidirectional composite failure based on an understanding of the effects of the scatter, inherent in fibre strengths. In this model the average stress supported by the m fibres reinforcing the composite before first fibre failure was given the value, σ_{f0} . The shear of the matrix, around a fibre break, was seen to be the mechanism which resulted in load being transferred back to the broken fibre, up to a given fraction, ϕ , of σ_{f0} . Rosen therefore could divide the composite into N links, analogous to links in a chain. The length of these links was related to the critical load transfer length, δ , which resulted in the broken fibre continuing to contribute to the support of the applied load away from the point of failure. Within the link, the remaining intact fibres were considered to take on the additional load originally supported by the broken fibre. The distribution of this additional load was considered to be uniform amongst the intact fibres in the composite section. The calculation of the parameters of Rosen's model was possible using Cox's analysis of a single short fibre embedded in a cylinder of matrix and which had introduced the concept of "shear lag", or load transfer, through the shear of the matrix around the fibre break. The calculation of the failure stress of the composite, σ_{cR} , required the use of the function $G_m(\sigma_c)$ describing the distribution of fibre strengths in a bundle of m fibres of length δ . The model developed an expression for the most probable failure stress of the composite, which was $\sigma_{cR} = \sigma_0(\delta\beta e)^{1/\beta}$, in which β is the Weibull modulus. This model was found to overestimate composite failure strengths and considers far fewer fibres than that which is generally the case.

Zweben (3) extended Rosen's model and introduced the concept of stress concentrations in fibres neighbouring the break rather than a uniform redistribution amongst all intact fibres in the plane of the break. Zweben was able to calculate the effects of several adjacent fibre breaks on the probability of composite failure. This model introduced the concept of a critical defect size, corresponding to the number of adjacent fibre breaks, which determined composite failure. The model, however, underestimates the strength of unidirectional composites. The complexity of the physical processes involved in composite failure encouraged Kong [6] to propose a numerical approach to estimate the strength of unidirectional composites. Kong introduced a Monte Carlo simulation in a Rosen type model for calculating fibre failures in the composite. The model was an important step in the understanding of composite failure. Nedele and Wisnom [7, 8] used a finite element approach

to calculate the three dimensional state of stress around fibre breaks. Their results were consistent with those using a shear lag model. Composite failure was seen to implicate the localised failure of between 4 and 15 fibres.

In the present study a multi-scale modelling approach has been adopted in order to understand the failure processes in a pressure vessel. Multi-scale modelling using finite element analysis employs the concept of a “representative elementary volume” or R.E.V. which is the smallest volume, or cell, which can be considered to contain all the physical mechanisms which govern the composite behaviour. At this scale, all of the different phases, in the present case, fibres, matrix and interfaces, are considered and each is considered to be homogeneous. If the microstructure is periodically organised, the periodicity is also represented in the R.E.V. The calculation consists of applying the macroscopic stress or strain field to the R.E.V. at each point in the macroscopic structure so as to determine any changes which occur within the cells. This being carried out, the next step is one of homogenisation in which the response of the composite structure is calculated by summing the effects at each R.E.V. in the structure. In this way it is possible to pass from the microscopic to the macroscopic scale. The calculation of the overall behaviour of the composite structure is therefore iterative. The first step is to calculate the macroscopic behaviour of the unidirectional material. The finite element analysis gives access at each Gaussian point to the localised stresses and strains in the R.E.V. The values calculated of stresses on the fibres allow their probability of failure to be assessed. In order to evaluate the local stresses on the fibres within a R.E.V. for a given uniaxial macroscopic tensile stress state, an analytical procedure has been adopted. In this way it is possible to determine the variation of stress in intact fibres neighbouring a broken fibre by smoothing the values out which are calculated at points along the fibres. In this way it becomes possible to construct a data base for the localisation step which is directly useable in the multiscale analysis.

The study undertakes a three dimensional analysis of the unidirectional composite material loaded in the fibre direction. In order to do so, the analysis, at the macroscopic scale, considers the material to be homogeneous and represented by a three dimensional R.E.V. However at the microscopic scale the R.E.V. is taken to consist of two homogenous constituents: the carbon fibres and the matrix. The analysis has made the assumption that the composite can be considered to be analogous to a periodic three dimensional continuum in which the carbon fibres are distributed as a square array. The two dimensional R.E.V. used by Baxevanakis [9] gave a constant average unidirectional composite failure stress and consisted of 6 parallel fibres of 8mm in length. This implies that the unidirectional composite considered was transversely isotropic. By comparison with Baxevanakis this means that the number of fibres to be considered in the present analysis should be around thirty six, depending on the numbers of fibres considered broken. For reasons of convenience the number of fibres considered in the array was chosen to be thirty two. The degrees of damage were modelled considering six levels of failure in the R.E.V. representing levels of damage from one broken fibre in thirty two fibres, which has been shown to give exactly similar results as if single fibre failures were randomly distributed in the composite and isolated from one another due to the shear of the matrix, to a critical state of one in every two fibres broken. The original state in which it is considered that no fibres are broken is described as the C_{∞} damage state. Figure 3 illustrates various states of damage considered.

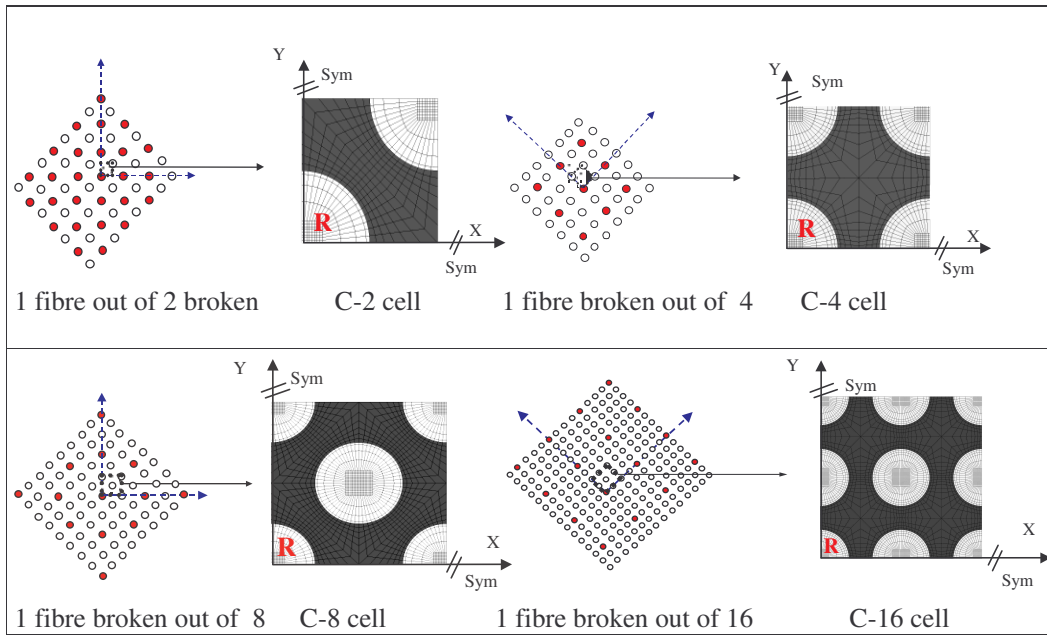


Figure 3 : Representative elementary volumes for the damage states and geometries of the periodic elementary cells (R represents the broken fibre)

The analysis of the microscopic phenomena is a necessary preliminary step in this multiscale model as the results are required to be able to determine the variations of the states of stress and strain in each elementary cell, and so of the R.E.V., so as to be able to sum their average values over the whole of the composite structure and determine its macroscopic response.

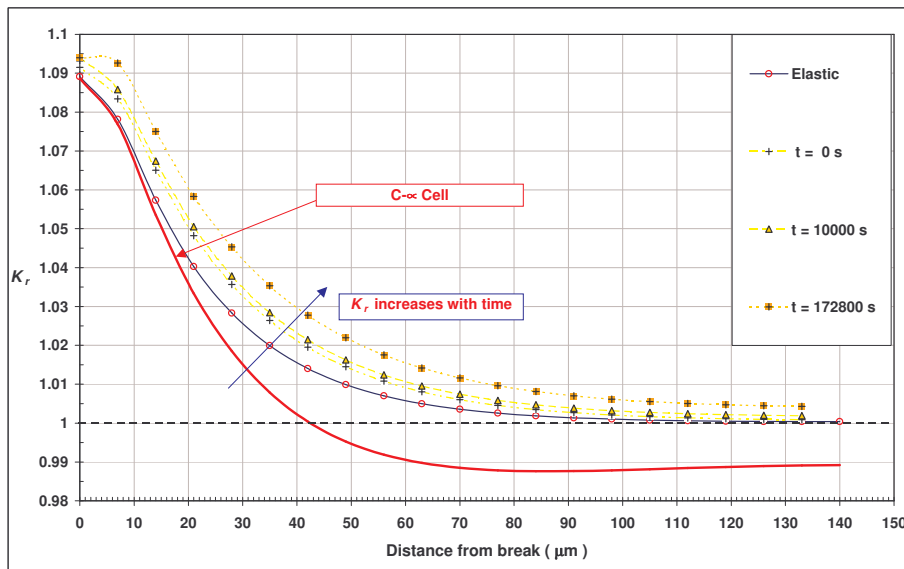


Figure 4 : Variation of the stress concentration coefficient, K_r , in the nearest intact neighbour to the broken fibre in the case of a viscoelastic matrix without debonding and a comparison with the $C-\infty$ cell

Figure 4 shows the effect on the stress concentration, K , on intact fibres neighbouring a fibre break due to the relaxation of the matrix. It can be seen that the lengths of intact fibre

subjected to raised stress increase with time so increasing the probability of additional fibre breaks. The detailed model shows that this effect is exacerbated by the debonding which occurs around the fibre break. This is contrast to the results obtained by classical shear lag theory.

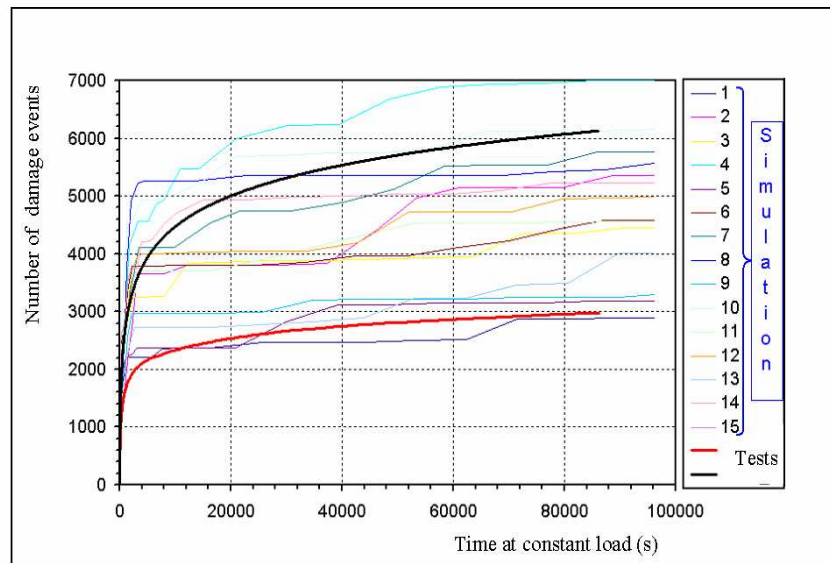


Figure 4 : Curves of fibre failures as a function of damage refinement for a load equivalent to 85% of failure load

The introduction of the statistical failure characteristics of the fibres and the viscoelastic properties into the matrix makes possible the simulation of damage accumulation in unidirectional specimens. This is shown in Figure 4 which also shows experimental curves. It can be seen that the experimental behaviour falls in the range of the results predicted by the model.

Application of the model to composite pressure vessels

The model shows that even perfectly elastic fibre reinforcements which have no time dependent properties, at room temperature, but do show a range of strengths, will continue to break when the composite is subjected to a constant load. This is because of the relaxation of the matrix leading to overloading of fibres neighbouring fibre breaks. The model predicts damage accumulation under a steady load as shown in Figure 4 and that instability occurs when the density of damage sites reaches a critical level at which they begin to interact. The use of composite pressure vessels involves their repeated pressurisation followed by depressurisation as the gas is used up. This means that two processes could be involved in provoking fibre failure under these cyclic conditions. The model described succinctly above considers the effects of the viscoelastic properties of the matrix which is the only process which can be involved in damage accumulation under steady conditions. Under cyclic conditions however it is possible that the plastic, time independent, behaviour of the matrix could also contribute to damage accumulation. This effect has been considered in the model and found to be significant during the early life of the pressure vessels but to stabilise as cycling continues. The protocol which is proposed however makes no assumptions as to the origins of the damage before the test. It is proposed that pressure vessels should be subjected to steady pressures equal to the maximum value reached in service [10]. Under these conditions the rate of damage accumulation is described by the model. The rate of damage is

a function of the applied pressure, the density of damage accumulated before the test, by any process and time. The damage accumulation from a typical pressure vessels is as shown in Figure 5.

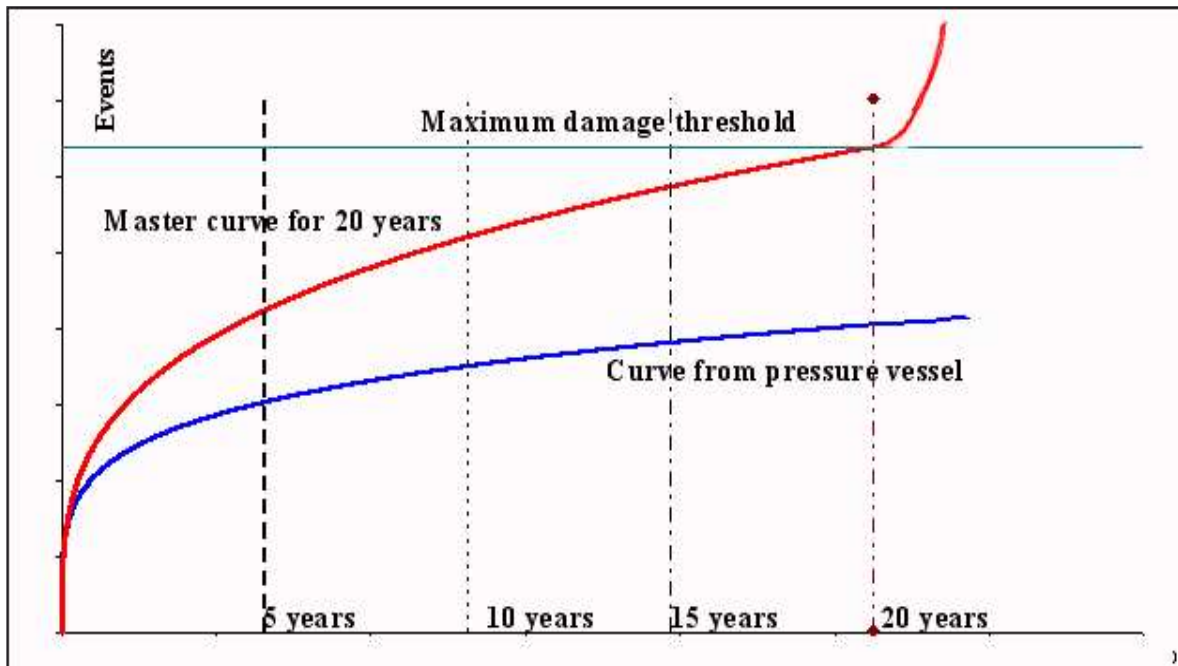


Figure 5: Comparison of acoustic activity from an in-service test on a pressure vessel compared to the master curve for a vessel which would reach instability after twenty years.

It can be seen that the curves are very similar to those shown in Figure 4. They are found to obey the following equation ;

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

- In which;
- N is the number of events
 - T the time from steady loading
 - T a time constant
 - A a factor which only depends on the applied stress level
 - n a factor less than 1.

A master curve is shown in Figure 5 corresponding to a pressure vessel which will last twenty years which corresponds to the needs of one application of interest but could be any duration. A threshold level for damage is determined by preliminary tests on the type of pressure vessel being used. The lower curve represents the experimentally determined damage pressure curve as a function of time for a pressure vessel which will last longer than the twenty years required. It can be seen that at 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.

It now becomes possible to draw curves which can be used in a practical tests. The numbers of emissions expected from the master curve depends 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

6 shows curves for a control period of 24 hours corresponding to pressure vessels which have been in service for different periods of time.

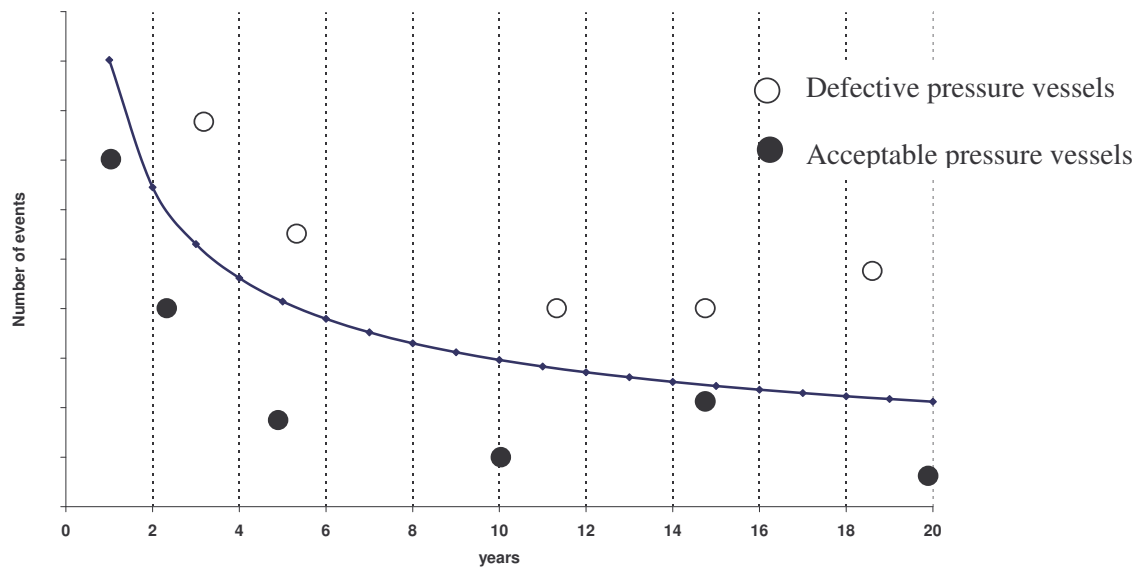


Figure 6: Numbers of events predicted by the master curve after different periods in service.

The result of the test is a number of damage processes are detected during a given period and this number is compared to those predicted by the master curve. If the number is less than the maximum defined by the master curve the pressure vessel can continue in service. It is clearly possible to incorporate safety coefficients into this comparison so that the test can be made as conservative as is required. The practical implications of testing pressure vessels are important as the technique allows the control to take place without removal of the pressure vessels which not only saves time but avoids any possible additional damage occurring to the piping system associated with their use.

CONCLUSION

A practical and cost effective means of predicting minimum lifetimes for carbon fibre reinforced composite pressure vessels has been proposed. The processes which determine the ageing of such structures have been determined and modelled. The mechanisms involved are delayed fibre failure induced by the relaxation of the resin matrix around fibre breaks. The model takes into account the dispersion in fibre properties and the viscoelastic behaviour of the matrix. The model accurately predicts the type of damage accumulation curves which are obtained by monitoring of the pressure vessels by acoustic emission.

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