PROOF TESTING AND LIFETIME RELIABILITY OF CARBON FIBRE REINFORCED COMPOSITE PRESSURE VESSELS

C.Devilliers¹, A.R.Bunsell²*, A.Thionnet², ³, H.Y.Chou², S.Joannès²

¹ Air Liquide, 1, chemin de la Porte des Loges, 78354 Jouy-en-Josas Cedex, France
² Mines ParisTech, BP 87, 91003 Evry Cedex, France
³ Université de Bourgogne, Mirande, BP 47870, 21078 Dijon, France
* Corresponding author (anthony.bunsell@gmail.com)

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1 General Introduction
The three year HyCOMP research programme began in January 2011 and followed earlier studies, also funded by the European Commission, into the reliability of storage systems for hydrogen and other gases at high pressures, up to 70 MPa. The programme encompasses the work of eleven partners in eight European countries and aims to place the design of such vessels on an objective and quantitative footing based on an understanding of the failure processes which can occur in carbon fibre composites when used in pressurised filament wound structures over long periods of time. Such pressure vessels are destined to store hydrogen at high pressures for use in ground transportation and other applications. Reliability is an absolute necessity but over designing should be avoided for reasons of cost. Existing testing standards are based on metal structures. The most intuitively obvious technique is the hydraulic test in which the pressure vessel is briefly subjected to one and a half times the maximum in-service pressure. After all if the vessel does not fail at a higher pressure why should it fail at a lower one? If the vessel survives this test it is deemed safe to continue in service. This is not only intuitive but can be justified by an understanding of failure processes in metals, which occurs by crack propagation. Any incipient crack or defect will provide a site for a stress concentration, as shown by Inglis (1) and if failure does not occur, the plastic deformation created ahead of the crack will impede its development at lower pressures. Composites do not fail in this way! Carbon fibres are elastic and wound on geodesic paths to make the pressure vessel so that, under pressure, they experience above all tensile loads and support up to 99% of the load. The carbon fibres ensure the integrity of the pressure vessel and if it is to fail catastrophically the fibres must break. Carbon fibres are elastic with no evidence of fatigue or time dependent failure processes (2). Composite pressure vessels do not fail by simple crack propagation and there is no simple plastic deformation process which inhibits damage. This means that the standards for testing metallic pressure vessels are unsuited to composites so that new means of evaluating composite pressure vessels based on their particular processes of damage accumulation are required. Failure models have been developed which simulate damage accumulation under sustained loads and have been validated by experimental tests on plate and filament wound specimens.

2 Simulation of failure

2.1 Development of models of damage accumulation

As reinforcing fibres in filament wound structures are wound on geodesic paths they are subjected primarily to tensile loads when the vessel is under pressure. It is also clear that the fibres have to break for the pressure vessel to fail. This observation has been used to develop models in which the scatter in fibre strengths, obtained experimentally and quantified using Weibull statistics, is introduced into Representative Volume Elements (VER) containing, initially, thirty two intact fibres but which can fail during monotonic or sustained loading; see Figure 1. Fibre failure is seen as the primary failure
mechanism causing the composite structure to break. A data base quantifying the effects of fibre breaks in the VERs is established as an essential step in the multi-scale model. Previous studies have addressed the kinetics of fibre failure by considering the influence of the material components (3, 4). An ideal unidirectional composite, made up of a regular array of fibres embedded in a viscoelastic matrix and containing no defects, has been considered and the failure processes evaluated when it is under load. At this scale the physical process of fibre failure and associated phenomena such as decohesion of the fibre-matrix interface, load transfer lengths around broken fibres, load transfer between fibres and the viscoelastic behaviour of the matrix, can all be included in the behaviour of the RVE. The viscoelastic nature of the matrix is seen to control long term behaviour of the composite structure (5). It should be noted that some variations in the composites, such as local variations in fibre volume fraction have been considered but the results will not be discussed here. In addition the experimentally observed increase in elastic modulus and strength in carbon fibre composites under sustained load, due to relaxation of the matrix allowing improvements in fibre alignment, has been ignored.

The VERs making up the structure, are summed so as to obtain an overall behaviour. Initial simulations have been on the behaviour of unidirectional composites and successfully compared to the results of damage accumulation detected using acoustic emission. Later studies have applied this approach to both models of pressure vessels and to experimental studies to various types of carbon fibre pressure vessel. The experimental results show agreement with the model, which is able to calculate not only failure stress but also the experimental scatter which can be expected from apparently similar vessels.

However this ideal view of the material is incomplete when considering a real structure as it then becomes necessary to include the effects of imperfections on the behaviour of a real rather than an ideal structure. By referring to a data base of the effects of fibre failure on the characteristics of the RVE it becomes possible, through a multi-scale simulation to scale up to the full structure, including imperfections, so as to finally predict failure of the complete structure. This approach has already been compared favourably with the results obtained with acoustic emission (AE). Nevertheless the analysis of the AE is not sufficiently detailed for the kinetics of failure of a unidirectional composite to be determined with precision (6). In addition the AE technique requires interpretation and analysis, which is open to doubt. For this reason the simulations have been compared directly to results obtained using high resolution tomography to reveal fibre failure as a function of applied load. In order to do so the simulation model has been used to examine behaviour in the material having the same resolution as in the high resolution tomographic experimental technique. The comparison has revealed very similar results between the simulation and high resolution tomography during tensile loading to failure of notched cross-plied specimens and this has lent confidence in applying the simulation to examine the behaviour of composite pressure vessels under more complex loading conditions (7, 8).

The difficulties of experimentally observing the accumulation of damage at the level of individual fibres are considerable and require means that are not readily available, such as using high resolution tomography. However the above results have lent confidence in applying the simulation model. For this reason, the logical process adopted in the HyComp study is to use simulations to refine the understanding of the fibre break phenomenon based on relevant modelling.

It is therefore assumed that it is possible to examine, a priori, in a complete composite structure, the kinetics of fibre failure events. This has been shown to consist of an initially random fibre failure process, which if it occurs in a RVE has no effect outside the remaining 31 intact fibres. However, as loading is increased, or time increases as in a constant loading situation, clusters of fibres begin to be created. Whilst low numbers of fibres in the clusters lead to still random distributions of damage, higher levels of numbers of broken fibres in clusters lead to a concentration of damage which eventually precipitates failure of the structure.

The possibility that failure occurs with no warning, by a sudden-death type scenario, can be examined. The study has examined this process in simple composite laminated plates which were; unidirectional; cross-plied and angle-plied. This will be extended to more complex industrial structures, such as, composite pressure vessels.
3 Results

3.1 Consequences of the model

The model is sufficiently robust to allow different scenarios to be examined. For example the possibility that measurements of residual strength could be an indicator of remaining lifetime, as can be the case for metal structures. The model is able to demonstrate how the fibres in the VERs making up the composite structure fail during monotonic or sustained loading. It is observed that damage in the form of fibre failure is largely random during most of the lifetime of the composite but that failure occurs rapidly after the fibre breaks begin to cluster. The numbers of broken fibres in a RVE are described using the term i-plet in which i represents the number of broken fibres. Figure 2 reveals how this is described in the model.

3.2 Monotonic loading

At the point of failure, during a monotonic tensile test, it is seen that most (75%) of the RVEs contain no broken fibres and are in their initial state, as can be seen from Fig. 3. Just before failure only approximately 7% of the VERs contain thirty-two broken fibres. This explains previously published observations of flat SN curves of carbon fibre composites and the lack of warning of imminent failure which is observed with these materials. The model allows a closer examination of the kinetics of fibre failure in the composite while it is being loaded monotonically to failure, as shown in Figure 4.

The simulated tensile test allows a close examination of the kinetics of fibre failure; in this case for a unidirectional composite loaded parallel to the fibres. At the point of non-linearity, I, announcing imminent failure, approximately 5% of all fibres are broken and only 2% of these are in the form of 32-plet RVEs, however, almost immediately, at J, around 7% of the broken fibres are as 32-plts and an instantaneous extension occurs during fibres in lower order i-plets are broken until point C is reached after which deformation is controlled by the remaining intact matrix before complete failure occurs at D.

It is clear that residual strength tests of composite structures, including pressure vessels, are not suitable for the purpose intended in the case of these materials.

3.3 Steady loading

Under constant steady loading conditions, or cyclic loading up to a constant maximum load, damage accumulates as fibre breaks due to relaxation of the matrix within the RVEs. This leads to progressive increases in intact fibres neighbouring fibre breaks and some eventually fail. As this mechanism continues some RVEs begin to accumulate several fibre breaks and clusters of breaks are created. In extreme conditions this can lead to failure as shown by the experimental results in Figure 5 (9).

These results show how several unidirectional composites loaded in the fibre direction to 96% of mean breaking load, failed after some time under steady loads. The specimens were nominally identical and showed times to failure ranging from less than two hours to 14 hours. Simulations of this type of test reveal that fibre break clusters develop throughout the loading but eventually lead to failure. It could be envisaged to do numbers of tests under steady loading at progressively lower loads so as to determine the possible existence of a threshold load below which failure was very unlikely to occur. The difficulty is that times to failure rapidly become very long as the loads are reduced. Simulated tests allow this behaviour to be assessed, as is shown in Figure 6. It can be seen from this figure that times to failure increase rapidly as the load level is reduced. In addition it can be seen that, as the load is reduced, the scatter of time to failure increases. This is again evidence of the effect of the viscoelastic relaxation of the resin surrounding fibre breaks and resulting in increased loading, locally, on neighbouring intact fibres. The effect becomes more marked as loading times to failure increase. It can be seen that the time to failure increases in such a way as to become asymptotic to a threshold time representing an indefinitely long time to failure.

4 Intrinsic limits based on component behavior

4.1 Damage Threshold and Intrinsic Safety Factors

Failure has been shown to occur when a threshold of damage is reached, at which point the breaks are
seen to be no longer random but to be grouped in clusters. However, the rate at which this happens and its exact level is a function of the defects and their distribution within the fibre population. Simulations and experimental studies on plate specimens have shown that the time to reach this critical threshold can vary considerably but can be determined from the nature of the composite constituents. In this way the probability curve of failure for a given structure, subjected to sustained loadings, can be drawn and the time to reach the damage threshold can be calculated. This has been possible due to the development of simulations of composites behaviour which have been compared favourably to experimental results. Experiments in which plates or pressure vessels would be held under steady loads until they failed could be conceived but the large scatter in lifetimes would involve a prohibitively high number of tests, and costs, which would last for very long periods. The simulated results however allow this behaviour to be investigated and a threshold level of load or pressure determined below which failure will not occur in any reasonable expected in-service lifetime. In this way, a minimum safety factor based on the intrinsic properties of the composite, but not taking into account possible defects due to manufacture or handling, has been calculated. However, it is unreasonable to conclude that there is no probability of failure however long the pressure vessel is under load. This inherent in the probabilistic analysis and that the curve shown in Fig. 6 is plotted on log scales for the life times. This means that there is no real asymptote of lifetime at which it is considered to be infinite. For this reason the model has been used to calculate the load level at which a probability of failure of one in a million over fifteen years and also over one hundred and fifty years. These results are shown in Table 1. Based on the above understanding of damage accumulation in carbon fibre composite pressure vessels, two means of arriving at these results have been used and will be discussed elsewhere. The results are similar and show lower risk factors than those previously proposed by other authors. In this way the minimum safety factor can be quantified, rather than being guessed at or being based on the behaviour of metal structures. Using the values for a probability of one failure in a million over 150 years, which has to be conservative, a value for the intrinsic safety factor of 1.4 becomes reasonable. However, in order for a realistic safety factor to be assessed other damaging events should be considered such as manufacturing difficulties and the risk of accidental or deliberate damage occurring during the in-service life of the pressure vessel. Nevertheless quantifying the intrinsic safety factor goes a long way to allowing more realistic factors to be established which should both reduce costs whilst not reducing reliability and together these factors should encourage the industry to grow.

5 Long term failure probability

5.1 Determination of Reliability

For composite pressure vessels to be widely used with confidence it is necessary to be able to determine long term reliability and also to be able to assess damage during in-service use. The model which has been developed and justified experimentally allows this to be done. A master curve of damage accumulation is drawn for the type of pressure vessel considered, taking into account the intrinsic safety factor described above. Any of the pressure vessels can then be compared to the master curve throughout its in-service life. It is possible to determine a threshold for a given lifetime but more useful is the threshold for indefinite in-service lifetime, as is shown schematically in Figure 7. Loading which does not take the pressure vessel above this level of damage can be considered to be acceptable and this threshold defines the minimum intrinsic safety factor. Unforeseen events could accelerate damage, such as overheating and other mechanisms but if the pressure vessel is seen to fall below the master curve which would be asymptotic to this threshold level, it can returned to service with confidence.

6 Conclusions

The aim of this study has been to understand how damage accumulates during the in-service lifetimes of carbon fibre composite pressure vessels. It has been shown that fibre breakages determine failure and that these can be modelled using a multi-scale simulation of the composite behaviour. This simulation has been compared to experimental
results both on composite plates and pressure vessels and shown to be realistic.

Monotonic loading to failure of such composites produces random fibre failures all over the specimen until clusters of fibre breaks occur. This is very near final failure. Up until this point very little macroscopic effect is seen on failure strength, so that any measurements of residual strength show no marked change. Failure occurs with no warning in a sudden death manner. A close examination of the kinetics of fibre breaks shows that even immediately before failure most fibres in the structure are intact. Clustering of breaks occurs due to the effect of the matrix.

Under steady loading, less than the failure load, clusters of fibre breaks do accumulate due to the effects of the viscoelastic relaxation of the resin around breaks. This produces a gradual increase in stress, locally, in intact fibres neighbouring breaks and some of these can undergo delayed failure, even though the fibres are themselves purely elastic and insensitive to time effects.

Experimental results have revealed that delayed failure can occur in the most stable form of the composite, which is a unidirectional plate loaded in the direction of the fibres. This has been successfully simulated and used to determine lifetimes at different load levels. It is seen that lifetimes tend to indefinite lengths of time as the load is reduced. In this way an intrinsic safety factor can be determined by dividing the mean breaking load by the threshold level. When a probability of failure of one in a million over different time scales is considered, it has been shown that a safety factor of 1.4 is more than adequate, based on the intrinsic properties of the composite’s components. In this way the intrinsic safety factor can be quantified for the structure. For real structures other factors would have to be factored in to determine a realistic safety factor and this would inevitably be higher than the intrinsic factor.

References


Scatter of carbon fibre strength

Fig. 1: The stochastic nature of fibre failure is introduced into the RVE.

Fig. 2: The properties of the RVE are calculated as a function of increasing numbers of broken fibres.
Fig. 3: Percentages of fibres in VERs with no breaks (0-plets) and those with all fibres broken (32-plets) during tensile loading.

Fig. 4: A simulated monotonic tensile test.

Fig. 5: Damage accumulation & end of life under static load.

Fig. 6: Times to failure as a function of applied steady load.
Fig. 7: Curves of damage accumulation for pressure vessels showing thresholds determining lifetimes of twenty years and indefinite in-service lifetimes.

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<th>Lifetime = 15 years</th>
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<tr>
<td>Finite element analysis</td>
<td>78.8% of mean burst pressure (SF = 1.28)</td>
<td>75.5% of mean burst pressure (SF = 1.32)</td>
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<tr>
<td>Analytical study</td>
<td>71.9% of mean burst pressure (SF = 1.39)</td>
<td>71.4% mean burst pressure (SF = 1.40)</td>
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Table 1: One in a million probability of failure of composite pressure vessels in periods of fifteen and one hundred and fifty years taken as an acceptable risk factor.