PREDICTION OF THE LONG TERM MECHANICAL BEHAVIOUR OF COMPOSITE PIPES UNDER INTERNAL PRESSURE FROM SHORT TERM TESTS

Patricia KRAWCZAK, Patrick VANDEVOIR and José PABIOT

ECOLE des MINES de DOUAI,
Department of Polymers & Composites Technology,
941 rue Charles Bourseul, BP 838, F-59508 DOUAI, FRANCE
http://www.ensm-douai.fr e-mail: plastics@ensm-douai.fr Fax:+33 3 27 71 25 25

SUMMARY: The aim of the paper is the prediction of the long-term mechanical behaviour of GFRP pipes under internal dynamic water pressure with end effects from burst tests carried out on pipes. Both short-term damage and long-term dynamic fatigue damage have been characterised by damage factors with a separation of damage initiation and propagation stages. A relationship has been found between these quantities: When there is a unique structural parameter which is the main generating element of the materials degradation, the effect of an overload under an increasing pressure is similar to the effect of a number of fatigue cycles under a repeated pressure.

KEYWORDS: tubes, damage, dynamic fatigue, glass fibres, polymer matrices, interface, biaxial loading, filament winding

INTRODUCTION

Thanks to their corrosion resistance and high strength & stiffness to weight ratios, fibre reinforced plastics (FRP) are more and more used to convey pressurised liquids in the chemical industry or in the production, storage and supply of energy: pressure vessels and gas tanks for vehicles, service water piping and fire pipeworks in nuclear power plants, transportation of petrochemicals and fire pipeworks on offshore platforms, ... In particular composite pipes tend nowadays to act as a substitute of metallic products for low and high pressure applications, raising some questions about their short and long term behaviour, in terms of degradation, durability and failure when submitted to various internal pressure laws (random, increasing, repeated or constant pressures as a function of time) in various environments (aggressive liquids and temperatures). In the present state of things, the lack of data about both short-term and long-term behaviour of composite pipes subjected to the combined effects of mechanical loading, temperature and liquids considerably limits their penetration of high potential markets, such as oil industry for example.

Currently, glass/resin pipes and fittings are designed using a performance based approach, i.e., a regression curve fitted to experimental data (maximum testing time of 10 000 hours, according to ASTM D 2992). This regression curve is extrapolated, usually to 20 years, to determine the long-term strength of the pipe under internal pressure (after application of a safety factor). As testing industrial pipes under internal constant or cyclic pressure is rather expensive and time consuming, it would be interesting to dispose of a short term testing method - preferably on a flat test specimen - allowing to outline the trends and to explain the long term behaviour of more complex tubing systems. The benefit would be a quick qualification of new products (fibres, resins, sizing, structures).

Unfortunately experience shows that the extrapolation of the mechanical behaviour of laboratory flat test pieces to the behaviour of industrial structural parts such as pipes or pressure vessels is not so evident, in particular for the standardised tensile, bending, shear, static and dynamic fatigue tests. Similarly, the prediction - and even the simple prediction of the general trends - of the long term behaviour (for example under a dynamic biaxial loading) of composite tubular structures under internal pressure on the basis of short term tests is not very easy and has not been investigated extensively up to now.

Since the creation of its specific testing facilities for industrial tubular structures under increasing, constant and repeated internal pressures in 1987, the Department of Polymers and Composites Technology of the Ecole des Mines de Douai has carried out different research programmes [1,2,3]. Their general aim was to contribute to the knowledge of the damage mechanisms of such composite structures and to the prediction of their long term mechanical behaviour under biaxial loading, as did also other authors [4 to 14]. Regarding the prediction of the long-term mechanical behaviour of composite pipes under internal pressure from shorter term tests, the two above mentioned research axes have been investigated simultaneously. In the field of the extrapolation of the mechanical behaviour of flat test pieces to the behaviour of pipes under biaxial loading, some encouraging results have been obtained: It appears that mode I fracture mechanics tests performed on unidirectionally fibre reinforced flat test pieces monoaxially loaded allow the explanation of the short and long term damage mechanisms of complex composite structures under biaxial loading, and this on the basis of the participation of the fibre/matrix interface to the observed phenomena [15].Only the second research axe is going to be developed here after.

The idea is to make use of the whole stress-strain curve determined from burst tests (or so-called weeping tests) on pipes to define quantities for characterisation of the short-term damage and further to correlate these damage factors with those characterising the dynamic fatigue long-term damage under internal pressure.

EXPERIMENTALS

The experimental work is carried out on two families of composite pipes:

- Type I pipes are industrial glass/epoxy tubing systems made by filament winding by WAVIN Repox (diameter of 100 mm, winding angle of ± 55°) differing only by the nature of their sizing with : two references A and B coated with epoxy-specific coupling agents from two different suppliers and one reference C with a polyvalent one.

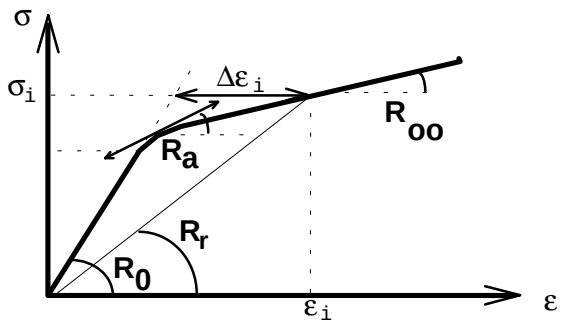
- Type II pipes are glass/resin tubing systems made by filament winding (diameter 50 mm, winding angle of ± 56°), supplied by UNION CARBIDE and differing only by the nature of the matrix : M_1 = epoxy (EP), M_2 = polyester (PE), M_3 = modified polyester (PE mod), M_4 = vinylester (VE), M_5 = modified vinylester (VE mod).

The mechanical behaviour of both types of pipes is studied under two different internal pressure loading modes with end effects: (a) Increasing pressure as a function of time (10 bars/min.); and (b) cyclic pressure with a constant amplitude and a frequency of 25 cycles/min. (All the pipes of the same type are tested in dynamic fatigue at a same pressure level).

RESULTS AND DISCUSSION

Characterisation of the short term damage

When a filament wound pipe is subjected to a burst test under internal pressure with end effects, the pressure vs. multidirectional strains curves measured show very strong nonlinearities, in particular in the axial direction: These nonlinearities (knee points) are associated with acoustic emissions and are the image of a progressive damage. If one considers the axial behaviour law as being the most representative of the damage, it is possible to define different characteristic quantities, which are likely to quantify the damage state and the damage kinetics of the material. They can be used then to try to predict the behaviour of the material under other loading modes, for example in dynamic fatigue. Three criteria are defined here, which allow to characterise and to rank the short term behaviour of the different pipes in term of damage (Fig.1).



R_0 = initial stiffness before knee point
Rr = secant residual stiffness = σi/εi
Ra = tangent apparent stiffness
Dr = residual damage factor
Dr = (Ro - Rr)/Ro
Da = apparent damage factor
Da = (Ro - Ra)/Ro
Δε = deviation from linearity

Fig. 1 : Definition of the damage factors Dr, Da, Δε

The first quantity used is defined on the basis of a residual stiffness. Indeed the slope of the secant line for a given pressure level - called residual stiffness R_r - characterises the damage state induced by this pressure: This can be verified experimentally by some repeated progressive loading tests. The damage variation is then defined by a curve running between the stiffness R_0 before the knee point and the asymptotic stiffness R_∞ after the knee point, the latter corresponding to a theoretical maximum state of damage reached under an infinite pressure. It is thus possible to define the residual damage factor Dr which varies from 0 to an asymptotic value $(R_0 - R_\infty)/R_0$.

It is possible to introduce a second quantity Δε to quantify the damage development. If one assumes indeed that an undamaged material presents a linear behaviour and that a damage creates an extra deformation compared with the linear stress/strain curve under a given load, then the deformation deviation from linearity for a given load (noted Δε) can be considered as

being indicative of a damage state. For composite materials, it is possible to consider a priori that microcracking generates an extra deformation characteristic of a certain “void” content serially coupled to the undamaged material. This reasoning has been checked for [0/90°] composite plate specimens subjected to tension as well as for filament wound pipes under internal pressure [16].

The two previous damage factors, which correspond to single points or to slopes of secants to the stress/strain curve, reflect quite well the general evolution of the crack propagation phenomenon as a function of the applied load. But on the other hand they are not very sensitive to the damage kinetics between the crack initiation at the end of linearity and the steady stage of propagation characterised by the second linear region of the pressure (or stress) vs. strain curve. Only the derivative of the phenomenon (with respect to strain) characterised by the slope of the tangent to the curves - called apparent stiffness Ra - is liable to quantify most accurately the discontinuity of this transition zone. It is then possible to define an apparent damage factor Da which varies from 0 to $(R_0 - R_\infty) / R_0$.

These damage factors make it possible to quantify for example the influence of the fibre/matrix interface (type I pipes) or of the matrix (type II pipes) on both the damage initiation and damage propagation (Fig.2). If one distinguishes damage initiation and propagation, damage level and kinetics, the results obtained on type I pipes thus show that:

- the pressure (or stress) corresponding to the sudden increase of the Dr, Da and $\Delta\varepsilon$ curves (similar in fact to the pressure at the end of linearity of the pressure/strain curve) makes it possible to characterise the damage initiation and its sensitivity to the quality of the fibre/matrix interface. Classified on the basis of these criteria, the materials A, B and C show in that way an increasing sensitivity to crack initiation;

- the post-initiation damage propagation stage can be characterised in terms of damage extent and kinetics (for example dDr/dP), features on which the interface quality has a significant influence. In that way for a given pressure level, the materials A, B and C show increasing damage levels as well as increasing damage kinetics, whatever the damage factor may be.

It appears in a same manner for type II pipes that the nature of the resin induces some differences in the crack initiation and crack propagation phenomena. The composite structure M_4 (VE) is indeed the less sensitive to damage initiation while the structure M_1 (EP) shows the highest propagation kinetics.

Characterisation of the long term damage in dynamic fatigue

In order to characterise the dynamic fatigue behaviour of the same pipes it is necessary to introduce here a notion of relative axial stiffness, defined by $R_N/R_0 = \varepsilon_0/\varepsilon_N$, where ε_0 and ε_N are the deformations at the first and at the N cycle in the axial direction (for a constant pressure P). Damage initiation is indicated by the number of cycles at which the axial stiffness of the pipe begins to decrease. Damage propagation is characterised by the slope of the stiffness loss curves. And microcracking kinetics is characterised by the slope just after initiation.

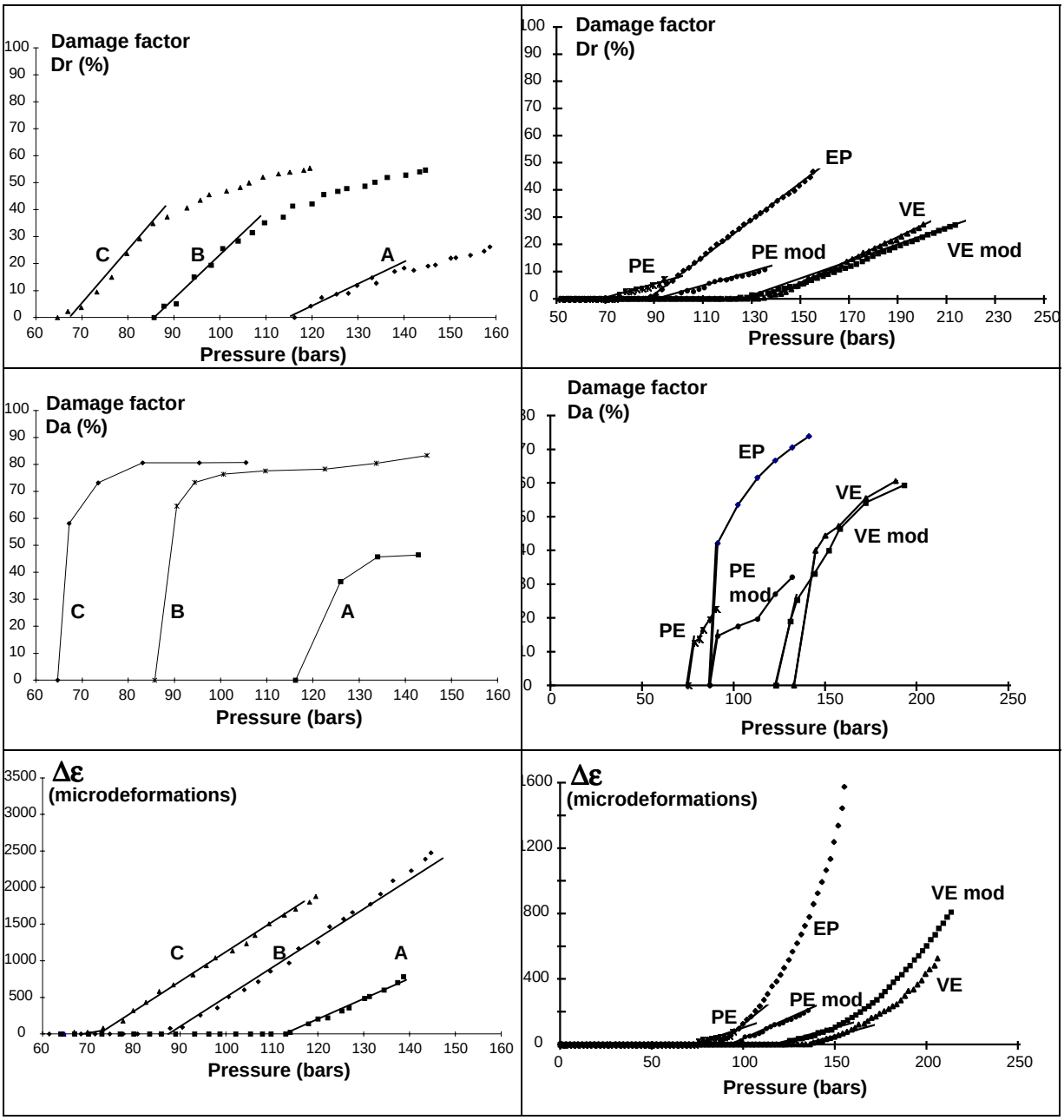


Fig. 2 : Damage factors Dr, Da and Δε for pipes of type I (left) and II (right)

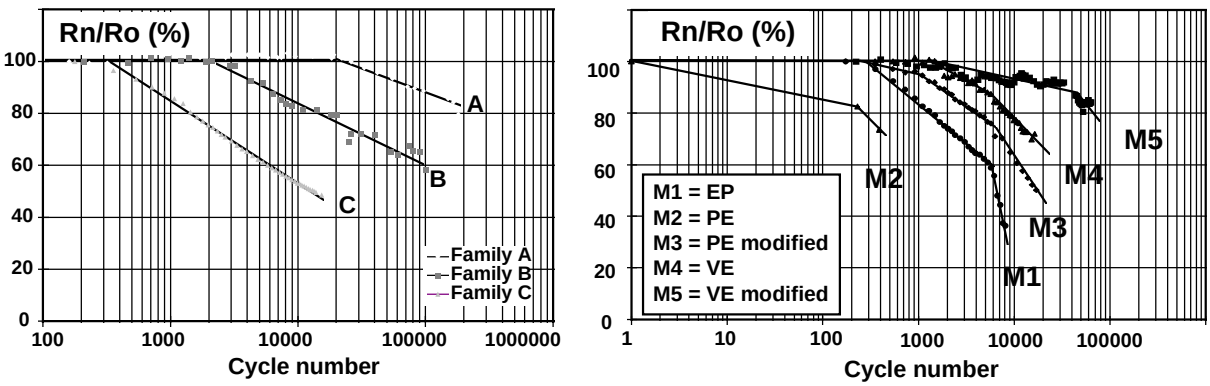


Fig. 3 : Dynamic fatigue behaviour of pipes of type I (left) and II (right)

The curves of relative axial stiffness loss in dynamic fatigue under a constant pressure amplitude are given on Fig. 3, on the one hand for the family of pipes with interfaces of different qualities (the applied pressure equals 72% of the end of linearity pressure of the pipe C, which is the most sensitive to damage initiation), and on the other hand for the family of pipes with different matrices (the applied pressure reaches 100% of the pressure at the end of linearity of the pipe M_2, the most sensitive to damage onset). As previously noted for short term tests under internal pressure, the nature of the fibre surface treatment (sizing) and of the matrix modifies the behaviour of the composite structures studied here, at one and the same time in term of damage initiation and damage propagation.

Regarding the influence of sizing, the materials A, B and C show in this order an increasing sensitivity to crack initiation under constant repeated loading. Furthermore, the materials A, B and C are also characterised by increasing damage kinetics after initiation (slopes $d(R_N/R_0)/d(\log N)$). Similarly regarding the influence of the matrix, the composite structure M_4 (VE) is the less sensitive to damage initiation whereas the highest damage kinetics after initiation is noted for the pipe M_1 (EP).

Relationship between short term and long term dynamic fatigue damage behaviour

It is finally interesting to check now to what extent the damage factors determined from the short term damage laws under increasing pressure (especially the factor Dr which appears as being the most discriminating) could be used to predict the dynamic fatigue damage of the pipes under internal pressure, for both the initiation and propagation stages. Consequently one will consider here:

- in order to characterise damage initiation:

- the hoop stress (or pressure) at the end of linearity for short term tests,
- the number of cycles at the onset of axial stiffness loss in dynamic fatigue;

- and in order to characterise damage propagation in term of kinetics:

- the ratio $d\,Dr / d\,\sigma$ (in %/bar), which corresponds to a loss of stiffness per unit of stress and is an image of the crack propagation rate during the short term loading,
- the ratio $d(R_N/R_0)/d(\log N)$ (in %/decade), which represents a loss of stiffness per decade of number of fatigue cycles and reflects the dynamic fatigue damage kinetics.

Then in order to check the existence of correlations between the different quantities characteristic of the elementary damage mechanisms related to a short term and to a long term dynamic loading, it is necessary to plot (Fig.4):

- the pressure at the end of linearity (short term value) as a function of the threshold of stiffness loss in fatigue, for crack initiation and
- the kinetics $d\,Dr / d\,\sigma$ (short term value) as a function $d(R_N/R_0)/d(\log N)$ of in fatigue, for crack propagation.

Quite good linear correlations are obtained (at least for the pressure levels applied here in dynamic fatigue), especially for the parameter “interface” for which the spreading of the data is very low. The correlation line associated with the propagation stage logically meets the origin: the stiffness loss kinetics in fatigue equals zero for a material showing no microcracking under an increasing loading (no knee point) i.e. having $d\,Dr / d\,\sigma = 0$. On the other hand, the origin of the curve associated with the initiation stage remains indeterminate, as the theoretical origin is removed to the infinite on the x-axis (material with a very low end

of linearity pressure and for which fatigue microcracking occurs at only a fraction of load cycle for an amplitude of dynamic pressure far higher than this short term linearity limit). In practice this correlation is all the more valid as the pressure level applied in dynamic fatigue is lower than the short term linearity limit, so that the genuine fatigue damage mechanisms could develop. This is confirmed by the results obtained on the second family of pipes (type II, parameter "matrix") for which the pressure applied in fatigue just corresponds to the short term limit of linearity of the composite structure M_2 (PE). Regarding now the propagation phenomenon related to this second type of pipes, a linear correlation similar to the first one is obtained, but with a largest scattering of data: This effect could be due to a coupled influence of the matrix and of the interface, as it is very difficult to separate the two parameters here.

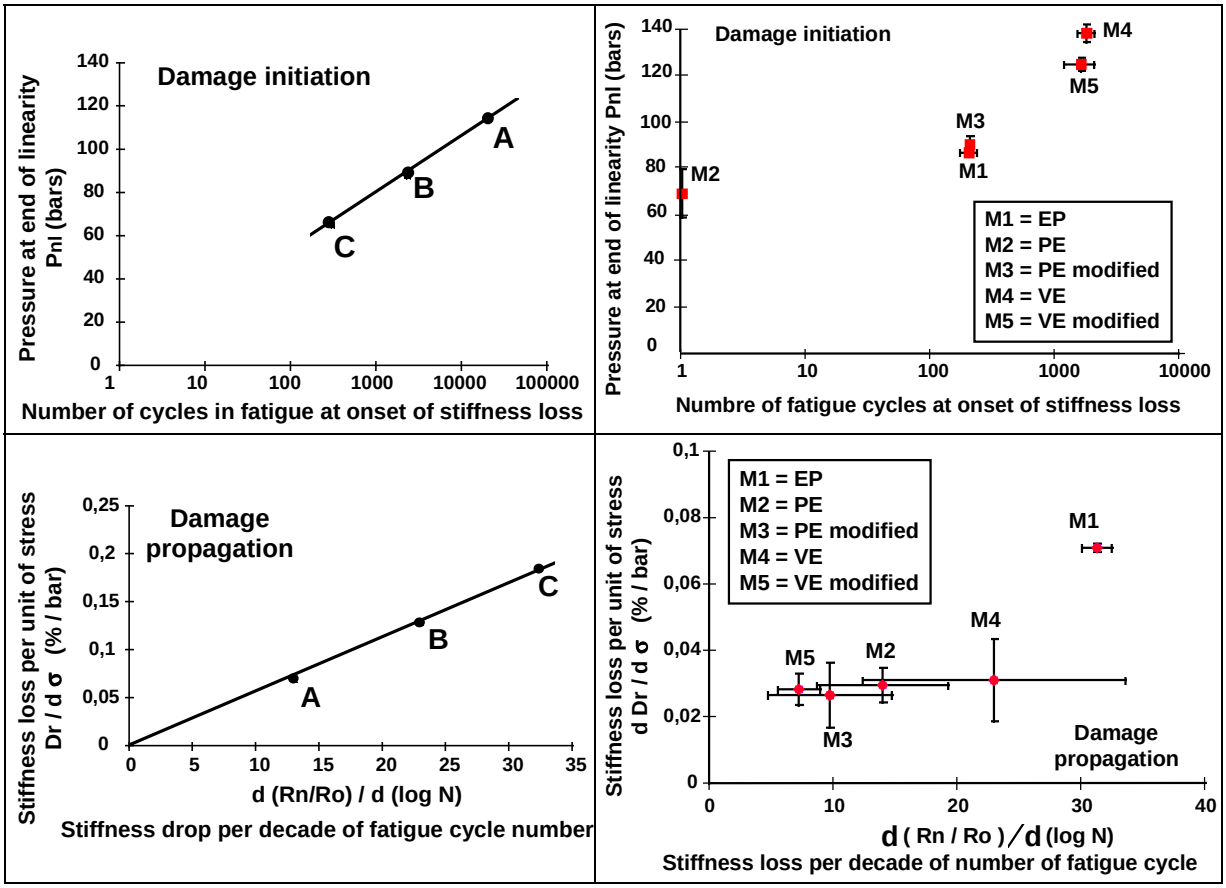


Fig. 4: Relationship between short term damage behaviour and dynamic fatigue damage behaviour in term of damage initiation (top) and propagation (bottom) for pipes of type I (left) and II (right)

CONCLUSION

In the limit of the experimentation carried out and for this specific damage mechanism which is microcracking, the obtained results make it possible to conclude the following: (1) there is a unique structural parameter which is the main generating element of the materials degradation, particularly in the case of the interface for both loading modes; (2) the effect of an overload under an increasing pressure is similar to the effect of a number of fatigue cycles under a repeated pressure. These first relationships between short term and long term damage characteristics need however to be experimentally validated further before any generalisation, among others working for example at different pressure levels. This would allow to state definitely the possibilities of prediction of the long term behaviour of such pipes from short term tests.

REFERENCES

[1] Herbeaux-Mourin M., Etude de l'influence de l'interface sur le comportement à long terme de tubes en composites verre/époxy soumis à une pression interne, PhD report, Université de Lille / Ecole des Mines de Douai (F), 1990.

[2] Jeannetaud P., Etude paramétrique du comportement de coudes en composites sou spression interne - Prévision et mécanismes d'endommagement, PhD report, Université de Lille / Ecole des Mines de Douai (F), 1995.

[3] Monnier C., Influence de la température et de la constitution du composite sur les mécanismes d'endommagement de tubes et réservoirs en composite sous différentes lois de pression, PhD report, Université de Lille / Ecole des Mines de Douai (F), 1996.

[4] Legg M.J., Hull D., Effect of resin flexibility on the properties of filament wound tubes, Composites, 10/1982, p. 369-376.

[5] Mieras H.J.M.A., Irreversible creep of filament wound glass reinforced resin pipes, Plastics ans Polymers, 04/1983, p. 84-89.

[6] Hull D., Spencer B., Effect of winding angle on the failure of filament wound pipes, Composites, 10/1987, p. 263-271.

[7] Soden P.D., Kitching R., Tse P.C., Experimental failure stresses for ±55° filament wound glass fibre reinforced plastic tubes under biaxial loads, Composites, Vol. 20, N°2, 03/1989, p. 125-135.

[8] Soemardi T.P., Etude du comportement mécanique et de l'endommagement de tubes en composites verre/époxy soumis à des sollicitations axiales et biaxées en statique et en fatigue, PhD report, Ecole Centrale de Paris (F), 1990.

[9] Ghorbel I., Mécanismes d'endommagement des tubes verre-résine pour le transport d'eau chaude: Influence de la ductilité de la matrice, PhD report, Ecole des Mines de Paris (F), 1990.

[10] Soden P.D., Kitching R., Tse P.C.,Tsavalas Y., Hinton M.J., Influence of winding angle on the strength and deformation of filament-wound composite tubes subjected to uniaxial and biaxial loads, Composite Science and Technology, Vol.46, 1993, p. 363-378.

[11] Frost S.R., The fatigue performance of glass fibre/epoxy matrix filament wound pipes, Proceedings of 9th Int. Conf. on Composite Materials (ICCM 9), Vol.5, Madrid, 1993, p. 684-691.

[12] Frost S.R., Cervenka A., Glass fibre reinforced epoxy matrix filament wound pipes for use in the oil industry, Composite Manufacturing, Vol.5, N°2, 1994, p. 73-81.

[13] Perreux D., Varchon D., Lebras J., The mechanical and hygrothermal behaviour of composite piping: notes on the methodology of dimensioning and structural design, Proceedings of Int. Conf. on Composite Materials and Energy (ENERCOMP'95), Montréal, 1995, p. 819-826.

[14] Bai J., Hu G., Bompard P., Micromechanical modelling of the damage initiation and the competition between different mechanisms of ±55° filament wound glass fibre / epoxy resin tubes, Proceedings of 11th Int. Conf. on Composite Materials (ICCM 11), Vol.5, Gold Coast, 1997, p. 540-551.

[15] Krawczak P., Benteyn M., Pabiot J., Fracture mechanics applied to the analysis of the degradation of anti-corrosion glass/resin pipes as a function of the fibre matrix interface quelity, Revue de l'Institut Français du Pétrole, Vol.50, N°1, Jan-Fév. 1995, p. 105-112.

[16] Krawczak P., Pabiot J., Quantification de l'endommagement instantané de composites à fibres continues et matrice thermodurcissable et application à la prévision du comportement à long terme de tubes sous pression interne, Composites 17, 1996, p. 7-14.