DAMAGE RESPONSE OF FILAMENT WOUND PRESSURE VESSELS

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Abstract

A theoretical and experimental analysis of the prediction of failure envelopes for filament wound composite vessels under biaxial loads is presented. A spectrum of biaxial stress conditions have been experimentally produced by applying different combinations of internal pressure and axial loads to several carbon fiber and glass fiber specimens tested up to failure. The experimental results have been compared with theoretical predictions obtained by numerical analysis with three-dimensional finite elements and thin shell analysis, applied using different failure criteria. Moreover, the computer program developed in this work takes into account the non linear characteristics of the shear behavior. A statistical comparison between experimental and theoretical results have been carried out to establish the more realistic failure envelopes.

Introduction

Advanced composites for high performance applications are characterized by high strength matrix and fibers, with the interface between fiber and matrix showing a different behavior than that of the two components. Moreover, the prediction of the failure of the composite part is further complicated by several phenomena including filament breaking, micro-buckling, matrix cavitation and crack propagation. Most of the mechanical properties of composite materials reported in literature have been generated in uniaxial stress tests(1-3), but practical applications involve multiaxial stresses.

Filament winding provides the best method of manufacturing fiber reinforced plastic components and structures in which the fibers are aligned in preselected directions to support the applied loads. Practical filament winding structures (pressure vessels, pipes, shafts, rocket motors, etc.) are usually subject to complex loads involving biaxial stress systems.

Composite cylinders have been used in aerospace and industrial applications where light weight and corrosion resistance are needed. Fabrication and testing of small size cylinders having various thickness and ply angles have shown potential for high performance with low weight-to-displacement ratios. Rocket motor cases have the longest history of production and represent the greatest share of manufacturing experience and capacity.

Filament wound pressure vessels have been produced for many years and are used in a number of service conditions and pressure ratings. They range from air-breathing backpacks to missile accumulator systems where light weight is important. In particular, pressure vessels made of filamentary composites have had a strong impact on high performance applications where efficiency and reliability are important requirements. For example, filamentary composite vessels are used in applications of Space Shuttle tankage, as well as for the storage of fluids in various commercial applications.

Although their wide range application, limited experimental data on the complex strength of filament wound cylindrical tubes and vessels are available(4-9), and this lack reflects the difficulty of performing multiaxial stress tests on well characterized specimens. The aim of the present work is to provide experimental data on the strength of simple filament wound glass and carbon fiber reinforced tubes under wide range of biaxial loading conditions, and compare them with theoretical data coming from a finite element modeling of the specimens taken into account.

In order to analyze the failure behavior, a study is performed to determine the influence of the winding angle on the damage response of filament wound pipes by comparing the stress-strain response with the predictions of the classical lamination theory. A number of empirical failure criteria, both on the laminate and lamina level, are applied to the total set of data. Of particular interest is the consideration of a non-linear model for the shear either in a close form or in a finite element program.

Experimental

Tubular specimens

Tubular specimens have obvious advantages in that loading of internal pressure, axial load, and torsion can be applied to produce a wide selection of stress conditions. Filament wound tubes, supplied by WEST of Finmeccanica Group, were manufactured either from continuous E-glass fiber (Owens-Corning, 1200 tex), or from continuous standard modulus carbon fiber (Tenax HTA 5331, 800 tex); both with an epoxy resin matrix (Shell Epikote 828 resin cured with 32 phr of Texaco Jeffamine D-230 hardener). For carbon fiber specimens a simple ±J helical pattern angle was employed and complete coverage of the tube (one cover) resulted in at least one +J and one -J layer of fibers at each point on the tube surface. For glass fiber specimens two covers have been applied.

All the tubes were 250 mm long and had 42 mm nominal diameter. The wall thickness was measured at 30 points in the middle of the tube. The following average values have been obtained:

_ glass fiber tubes, t=1.93 mm

_ carbon fiber tubes, t=1.24 mm

Carbon fiber cylinders showed a better thickness uniformity than glass fiber cylinders.

For all 18 glass fiber specimens two ±55° covers have been used. This angle value has been chosen following the recommendation suggested by netting analysis that this is the best angle for use in cylindrical pressure vessels where the ratio of applied circumferential to axial stress is two. A same number of carbon fiber specimens have been tested (4 with one ±75° cover, 2 with one ±35° and 12 with a ±55° cover). All specimens have been protected against the leakage of the pressurized oil (up to 700 bar) with an internal liner, made with an elastic epoxy band cured with different amounts of hardener, positioned around the mandrel before starting the filament winding.

Testing equipment

The simultaneous application of internal pressure and axial load allowed the generation of a variety of biaxial stress combinations. Experimental tests have been carried out using a Schenk M100 testing machine to apply axial loads, while a simple hydraulic circuit has been used to apply internal pressure. The hydraulic system contained an electrical pump (up to 120 bar) and a hand pump (up to 700 bar). No hydraulic accumulator, to damp out pressure fluctuations, has been used and particular care has been taken in applying the hand load. The pressurized fluid was Mobil DTE oil.

Special grips have been designed and manufactured for loading the specimens with the principal goal to avoid sliding when axial load is applied.

Displacements in the specimen length have been measured using electrical strain gauges, while stresses have been computed from experimentally measured loads.

Strength and failure of composites

A composite lamina exhibits an anisotropic strength behavior, that is, the strength is directionally dependent. Moreover its tensile and compressive strengths can be very different one from the other. In addition, the orientation of the shear stresses with respect to the fiber direction in the lamina has a significant influence on its strength. Then, the final fracture depends not only on a number of interactive failure modes occurring but also on the particular mode which dominates the failure process. While we are able to describe the failure of an isotropic material by an allowable stress field associated with its ultimate tensile, compressive and/or shear strength, the corresponding anisotropic material requires the knowledge of at least five principle stresses (longitudinal tensile and compressive stresses, transverse tensile and compressive stresses and shear stresses). Basic milestones for a correct approach to anisotropic lamina failures(1-3) are a stress dominated theory (maximum stress), strain dominated theory (maximum strain) and interactive theories (Tsai-Hill, Tsai-Wu, Hoffman) .

In a broadest context of a laminate strength analysis, if the loads are known, the design has to be tested using a first ply failure approach (FPF) and extending the analysis to the behavior after this point. If the applied load exceeds the FPF, a laminate may or may not be able to sustain an additional load. To rationalize the limit and ultimate strengths a matrix degradation model must be used to distinguish intact plies from those which gradually crack up to the global failure (Last Ply Failure)(10).

All the above mentioned failure theories have been used in this work to compare experimental data with numerical predictions.

Shear behavior

The complete characterization of a composite structure needs the determination of its shear behavior. Load conditions applied in this work (axial load and internal pressure) introduce, due to orthotropy, a shear stress in each lamina. When layers with different angles are combined in a laminate, strains are constrained and shear stresses are produced in addition to direct applied stresses. The presence of this combination of shear stresses, strongly influences the stress distribution along the laminate thickness.

Most composite materials have a non-linear stress-strain behavior in at least one of the principal directions. Generally, in a unidirectionally reinforced lamina, the stress-strain curve, in the direction of the fibers, is linear also for high stress levels. In the orthogonal direction non-linearity is obtained at high loads. On the other hand the shear response is strongly non-linear (Fig. 1)(1). This is a complex phenomena that originates from different mechanisms (damage accumulation, matrix crack, debonding, fibers rotation, and, above all, the non-linear behavior of the matrix).

Numerical approach

The aim of the present work is the determination of the influence of coupling biaxial stresses and strains on the material failure. The experimentally imposed biaxial state of stresses causes in the cylindrical specimens a general stress condition that includes also the interlaminar shear. The resulting stress state can be then verified using the different failure criteria mentioned above.

In order to perform the numerical analysis, the classical lamination theory was applied in a finite elements model.

The non-linearity was taken into account and small linear increments of the external load were considered to determine the failure envelopes. For each increment of the external load the lamina stiffness matrix was updated substituting the shear modulus corresponding to the actual state of stress. Once the lamina stiffness matrix is known, the laminate and the global stiffness matrices of the cylindrical specimen can be determined. At each step stresses (or strains) drawn for each lamina and suitably rotated in a global coordinated system were compared. with the lamina failure criteria to establish the occurrence of the first ply failure. Then, continuing the application of the same procedure of small linear increments, considering a progressive ply degradation, the conditions for the last ply failure were defined.

The step-by-step linear computation method allows the convergence when the number of steps increases or the step width decreases. Intrinsically the method tends to diverge when applied loads increase. In this case a correct choice of the step dimension is mandatory to get precise numerical results. This problem was addressed by starting from a very small step, close to zero, then increasing it till two subsequent results values differed in a fixed small difference.

The numerical investigation was carried out using the CEA's (Commissariat à l'Energie Atomique) finite element program CASTEM 2000. The discretization of the specimens for the definition of the finite elements was accomplished using DKT thin shell elements. Figure 2 shows the flow chart of the program.

Discussion of results

Figure 3 shows the burst strength calculated for carbon fiber specimens as a function of the winding angles using the Tsai-Wu criterion considering both, linear and non-linear behaviors, compared with experimental results obtained on specimens with three different winding angles (± 35°, ± 55°, ±75°; load ratio = 2). For all the curves the maximum strength, as expected, is in the range of the winding angle included between 50° and 60°. The lower experimental values with respect to numerical results can be attributed to the lack of end reinforcements in the specimens which favor crack initiation. Figures 4 to 7 show failure envelopes for the carbon fiber specimens, obtained with the four failure criteria mentioned above considering both linear and non-linear behaviors.

Generally, experimental data tend toward the netting analysis solution which result is also shown in Figs. 4 to 7. This theory, which allows the prediction of the strength for only one load ratio for a fixed winding angle, gives rough results but useful to have a good idea about the order of magnitude of the material strength(11).

When the non-linear shear behavior is considered, also the predicted failure envelopes show a tendency toward the netting analysis point, as in the case of the experimental data. These similarities suggest that, excluding the quantitative differences due to end effects, non-linear models give a better description of the real behavior.

Table 1
Predicted compressive strengths

Tsai-Hill:	204.8 MPa
Tsai-Wu:	230.9 MPa
Max. stress:	246.9 MPa
Hoffman:	228.2 Mpa

The predicted compressive strength of the tubular specimens, computed accordingly with the applied failure criteria, are reported in Table 1. The possible effects of buckling on the compressive resistance have been also considered by computing the corresponding critical stress value ($\sigma_{cr} = 838.3$) applying Love's theory(12). This value, compared with Table 1 results indicate that the specimens should brake without going on buckling. These results were confirmed by the reported experimental observations.

While the Hoffman criterion gives the highest strength prediction, the maximum stress criterion, in linear field, gives the best approximation to experimental points. All other criteria lead to less conservative estimates. However, as expressed above, the premature failure observed in the specimens as a consequence of the absence of end reinforcements must be also considered. With these considerations, the maximum stress criterion with non-linear shear behavior, probably gives the best prediction of the damage response of biaxially loaded tubular specimens.

Figure 8 shows two different failure envelopes (linear Tsai-Wu and maximum stress criteria) for glass fiber specimens. As a consequence of a higher thickness-to-radius ratio the thin shell theory is no longer valid in this case. Moreover, the non-linear behavior was not considered in the numerical analysis. These two reasons are responsible for the position of most of the experimental data outside the computed failure envelopes.

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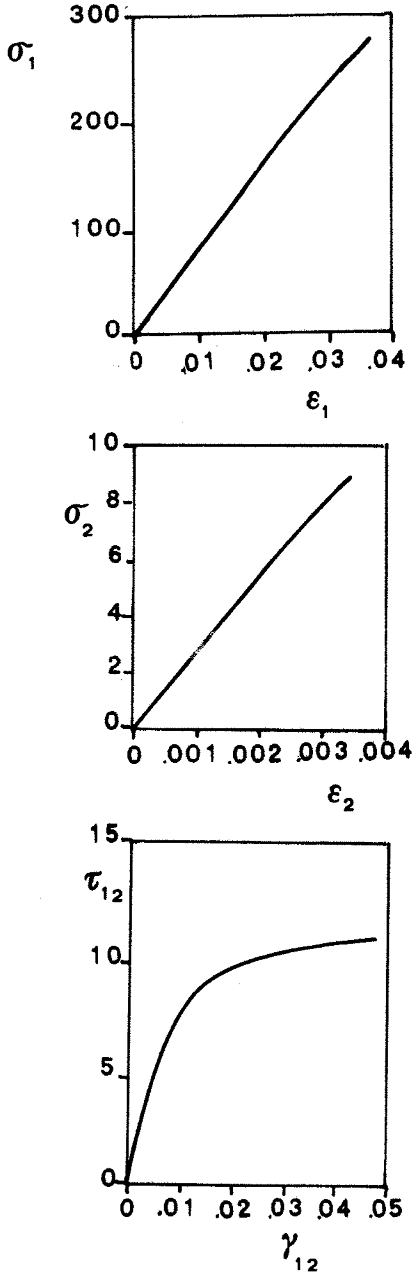

Figure 1: Stress-strain curves for an orthotropic carbonfiber/epoxy matrix composite laminate(1)

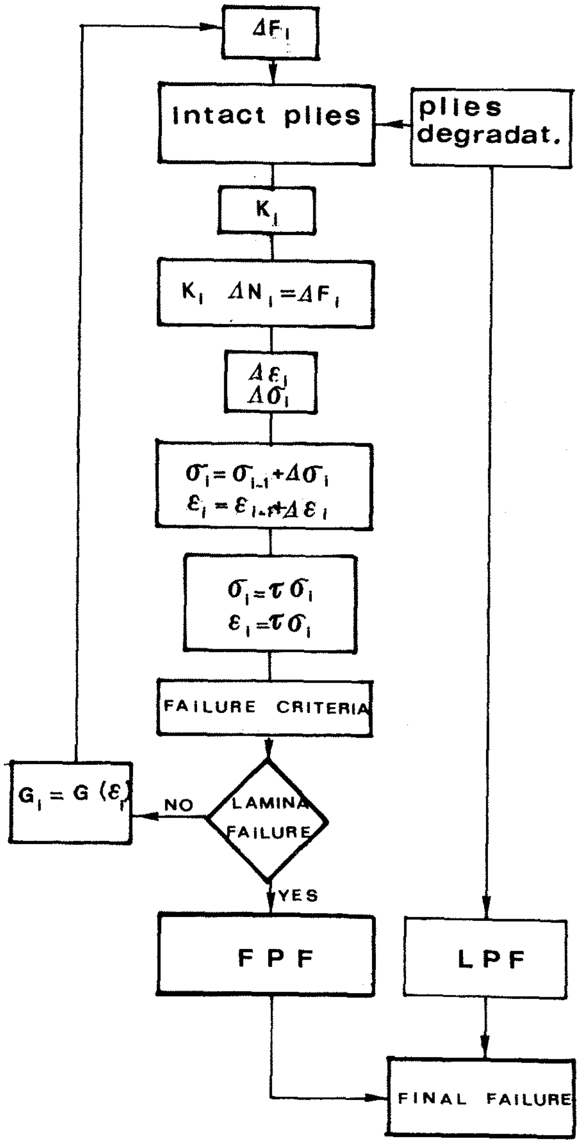

Figure 2: Flow chart of the computing program

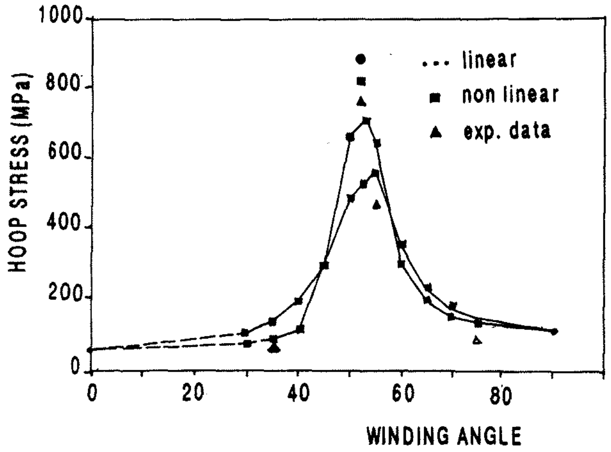

Figure 3: Experimental burst strength compared with predicted values computed as a function of the winding angle according with the Tsai-Wu criterion.

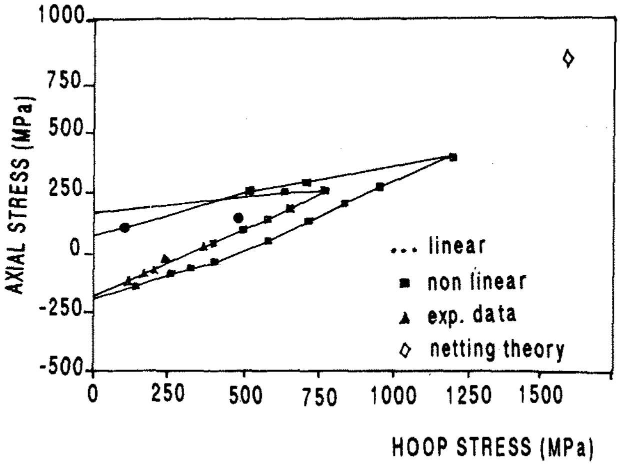

Figure 4: Failure envelope of carbon fiber specimens calculated with the maximum stress criterion

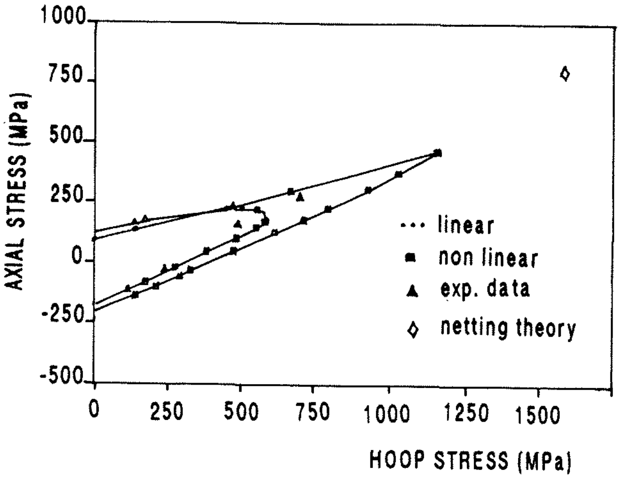

Figure 5: Failure envelope of carbon fiber specimens calculated with the Tsai-Hill criterion

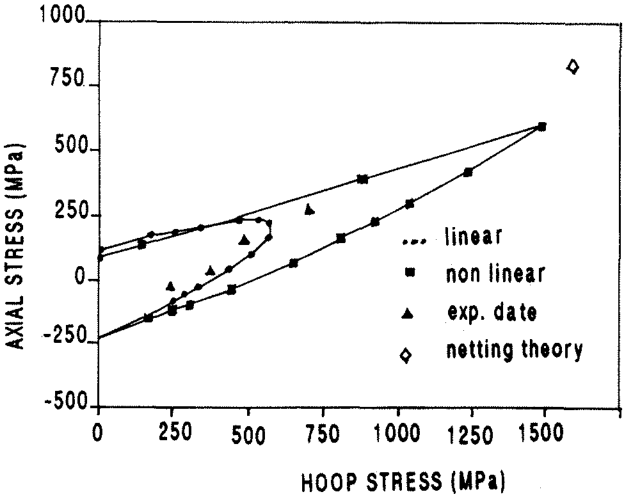

Figure 7: Failure envelope of carbon fiber specimens calculated with the Hoffman criterion.

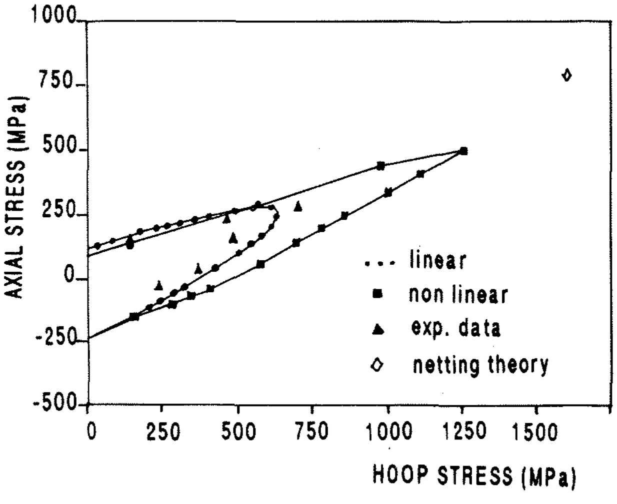

Figure 6: Failure envelope of carbon fiber specimens calculated with the Tsai-Wu criterion

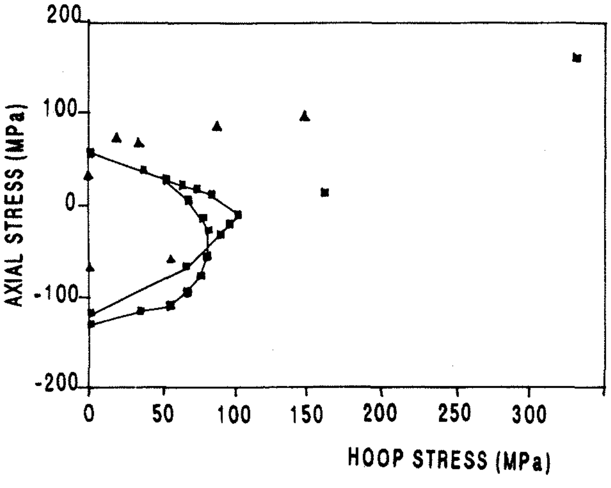

Figure 8: Failure envelope of glass fiber specimens calculated with the Tsai-Wu criterion