Optimization of filament wound parts based on non geodesic winding

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Abstract

The composite materials are well known by their excellent combination of high structural stiffness and low weight. Their inherent anisotropy allows the designer to tailor the material in order to achieve the desired performance requirements. However, during the filament winding process the desired fibre orientations can not be freely chosen: process restrictions as fibre slipping and fibre bridging should be taken into account in order to get feasible fibre paths. This paper presents a methodology for the optimization of filament wound parts based on non-geodesic fibre paths. Basically, the methodology tries to place the fibres in the most appropriate directions in such a way that the failure indices can be kept as constant as possible along the part. In order to implement such a methodology, one complete integrated environment encompassing CAD system, Finite element analysis and fibre path calculation has been developed. An application of the proposed methodology is also presented and the results discussed.

Keywords : composite design, filament winding, design optimization

1 Introduction

The design of composite structures requires an integrated procedure between different phases like selection of material, preliminary design and definition of the manufacturing process. Within this integrated procedure the designer should be able to make the optimization of the material in an iterative way: changes in the angles of certain layers imply changes in the structural stiffness, which affect the load distribution and require again changes in the fibre orientations. This process is repeated until the best lay-up is obtained.

The basis of the filament winding process is the high-speed precise lay-down of continuous reinforcements in prescribed patterns. In the ideal case the fibres should be placed in the maximum load directions. However, the trajectory of the fibre path can not completely free be determined : in order to obtain an accurate fibre placement, the fibres may not slip on the surface during winding and also, depending on the geometry of the part, problems of fibre bridging can arise. The use of geodesic paths simplifies the calculation of fibre paths but it is much more restrictive: once the starting position and the starting angle of the fibre path have been chosen, the whole trajectory of the fibre is defined. This is an obstacle to get the optimized composite lay-up, since the designer has the control of the fibre orientation only in the starting position. Although non geodesic paths require more elaborated calculations, use of them gives much more flexibility : deviations from the geodesic allow a more appropriate placement of the fibre path. Optimum fibre paths that result from iterative finite element calculations can be approximated much better using non geodesic lines than with geodesic lines.

2 Computer Integrated Design of Filament wound parts

The highly directional nature of continuous fibre reinforcement requires that the fibres are precisely placed along carefully chosen directions, which can be calculated by an appropriate analysis of the stress distribution along the part and throughout the different layers. When designing filament wound parts, use of an integrated strategy is recommended in order to make use of all composite benefits in spite of the restrictions imposed by the process [1 2]

Following this methodology, we have :

- **Design.** The process starts with the design of the part in the CAD system. This CAD-surface model can also be used to fabricate the mandrel on a CNC-machine.
- **Preliminary Finite Element analysis.** In order to provide a starting-point for building up the laminate, a simulation of the loaded geometry with an isotropic material is performed. From this simulation the ideal fibre orientations can be derived to be used in the path generation.
- **Fibre path generation.** The geometrical data of the part are also used to calculate the possible fibre paths. Unfortunately, due to the restrictions imposed by the winding process (section 3.1), the ideal fibre angles cannot always be achieved. Suitable software is required to consider these restrictions in order to get feasible fibre paths. It produces a family of fibre paths that can really be wound in practice.

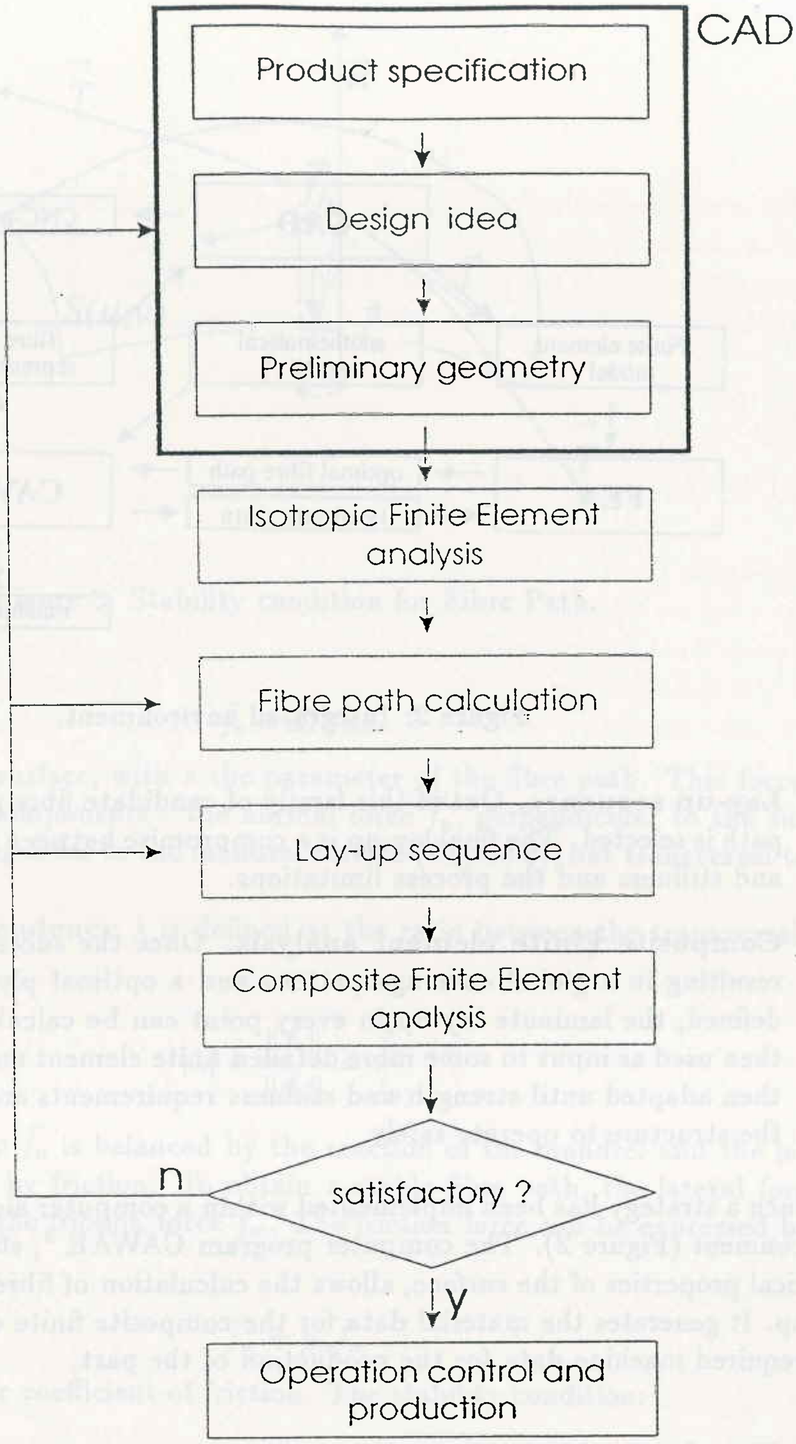

Figure 1: The design methodology for filament winding

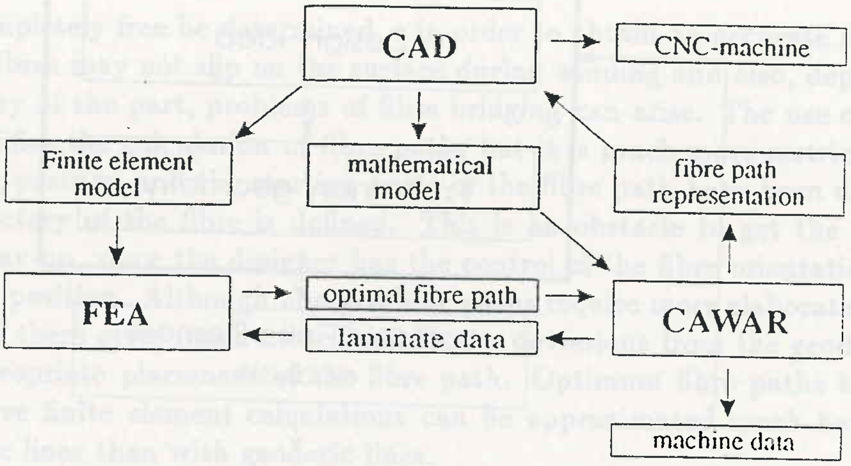

Figure 2: Integrated environment.

- **Lay-up sequence.** Out of this family of candidate fibre paths, one particular path is selected. The final lay-up is a compromise between the optimal strength and stiffness and the process limitations.
- **Composite Finite element analysis.** Once the successive winding steps, resulting in a global coverage pattern and a optimal ply stacking have been defined, the laminate lay-up in every point can be calculated. This lay-up is then used as input to some more detailed finite element analysis. The lay-up is then adapted until strength and stiffness requirements are achieved to permit the structure to operate safely.

Such a strategy has been implemented within a computer aided filament winding environment (Figure 2). The computer program CAWAR [2], starting from the geometrical properties of the surface, allows the calculation of fibre paths and laminate lay-up. It generates the material data for the composite finite element analysis and the required machine data for the production of the part.

3 Basic concepts

3.1 Calculation of fibre paths

As mentioned before not every path can be wound. To obtain a stable fibre path the fibre may not slip on the surface. This means that the transversal force acting on the fibre should be less than the friction force.
The winding tension $\vec{T}$ makes equilibrium with tangent component $\vec{t}$ and a normal component $\vec{f_r}$. This component is given by [2] [3] :

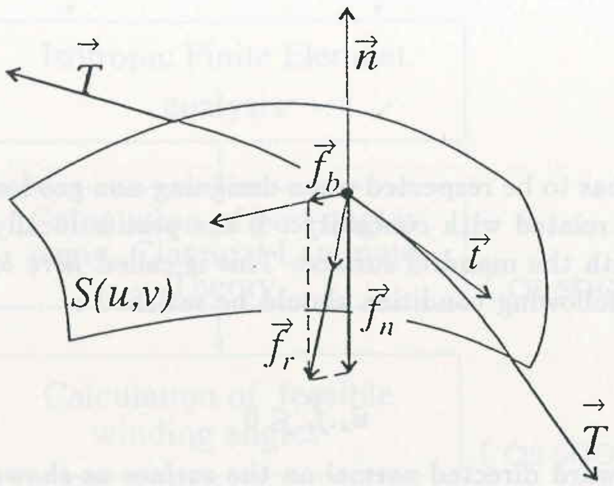

Figure 3: Stability condition for Fibre Path.

$$\vec{f_r} = d\vec{T}/ds \tag{1}$$

on the mandrel surface, with s the parameter of the fibre path. This force can be resolved in two components : the normal force $\vec{f_n}$, perpendicular to the surface and the force $\vec{f_b}$, tangential to the mandrel surface (Figure 3), but transversal to the fibre.

The slippage tendency λ is defined as the ratio between the transversal and the normal force :

$$|\lambda| = \frac{\|\vec{f_b}\|}{\|\vec{f_n}\|} = \frac{f_b}{f_n} \tag{2}$$

The normal force $\vec{f_n}$ is balanced by the reaction of the mandrel and the lateral force $\vec{f_b}$ is balanced by friction. To obtain a stable fibre path, the lateral force $\vec{f_b}$ should be less then the friction force $\vec{f_w}$. The friction force can be expressed by:

$$\vec{f_w} = \mu_s \vec{f_n} \tag{3}$$

with μ_s the static coefficient of friction. The stability condition:

$$\|\vec{f_b}\| \leq \|\vec{f_w}\| \tag{4}$$

can then be written as :

$$|\lambda| \leq \mu_s \tag{5}$$

This condition has to be respected when designing non geodesic trajectories. Another restriction is related with concavity : if the part is locally concave, the fibre will lose contact with the mandrel surface. This is called *fibre bridging.* To prevent fibre bridging, the following condition should be satisfied :

$$\vec{n}_s.\vec{f}_r \leq 0 \tag{6}$$

with $\vec{n}_s$ the outward directed normal on the surface as shown in Figure 3.

Geodesic lines connect two points along the shortest distance over the surface. In this case no friction force is required to keep the fibre from slipping, since it follows a self-stable trajectory [4]. A geodesic line can be defined also as the curve for which the second order derivative is perpendicular to the surface. This calculation can be done mathematically by solving the system of two second order differential equations which describes the fibre path over the surface [5] .
Also a simplification can be made for surfaces of revolution, using the law of *Clairaut*:

$$R.sin\alpha = constant \tag{7}$$

that relates the fibre angle α with respect to the meridian curve in a point of the fibre path, to the radius R of the surface in that point. [4].

The calculation of non geodesic lines can be done by a similar procedure, but in this case the slippage tendency should be checked with relation to the friction coefficient for every point of the fibre path calculated.

4 Proposed methodology using non geodesic windings

The following methodology is proposed for the optimization of the filament wound part (Figure 4).

Starting from a given geometry, an isotropic Finite Element Analysis is performed, revealing internal forces in each of the elements. These loads are then used as input to an Angle Ply Analysis, taking into account the angle dependence of the laminate thickness in filament winding, to yield the optimum angle combination, giving minimum failure index (see appendix for a description of the failure index used) for a given number of windings along the circumference. From all elements, the most critical element (**m.c.e.**) is sought, considering maximum Von Mises stress. For this element the necessary number of windings to get the desired failure index is then calculated. Once the number of windings has been defined the

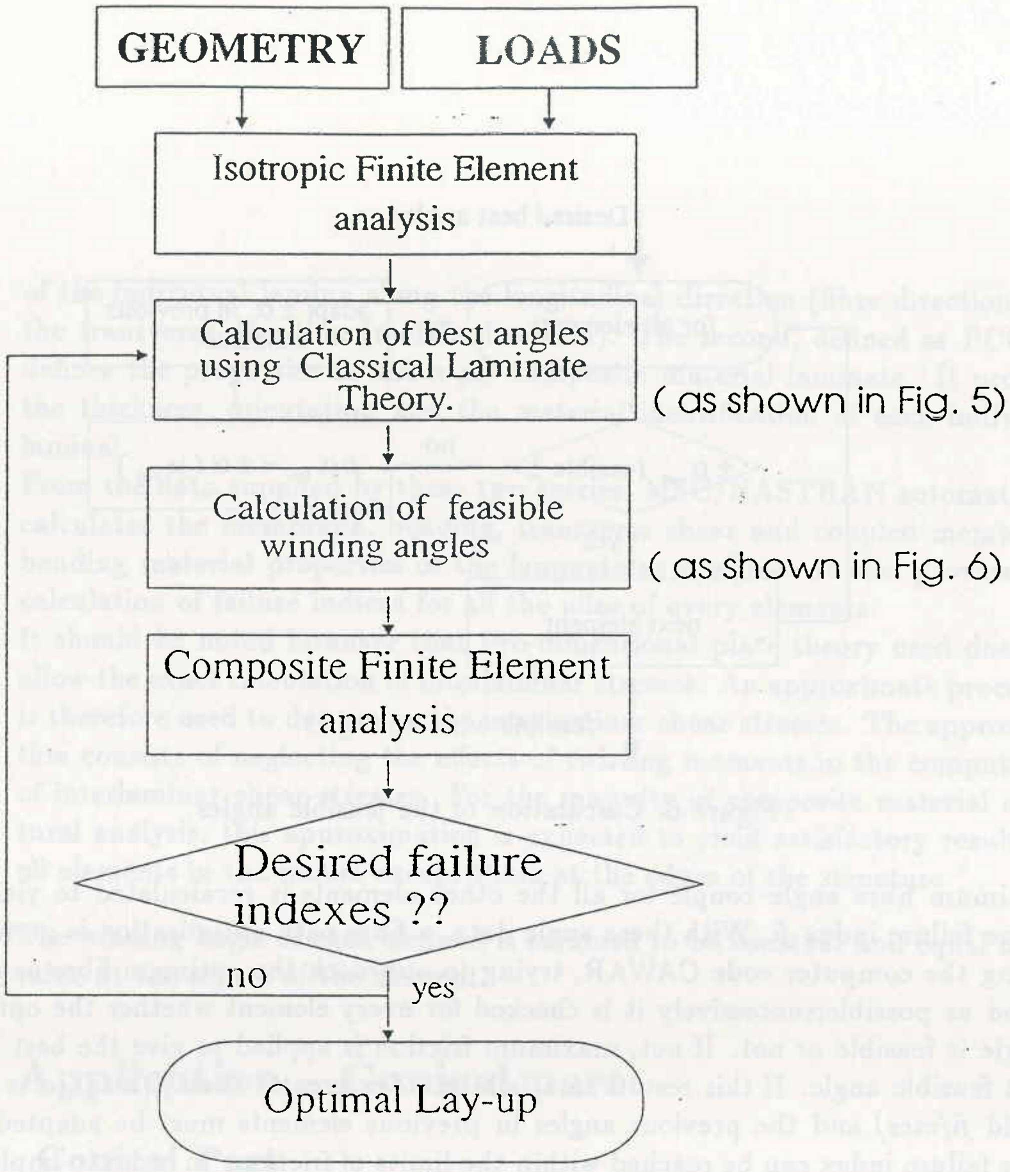

Figure 4: Proposed methodology.

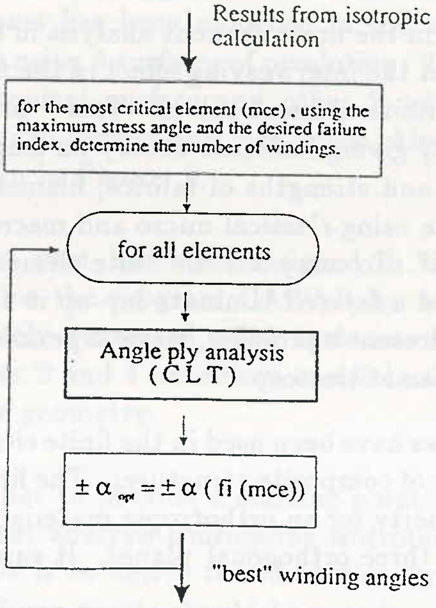

Figure 5: Calculation of the "best" angles.

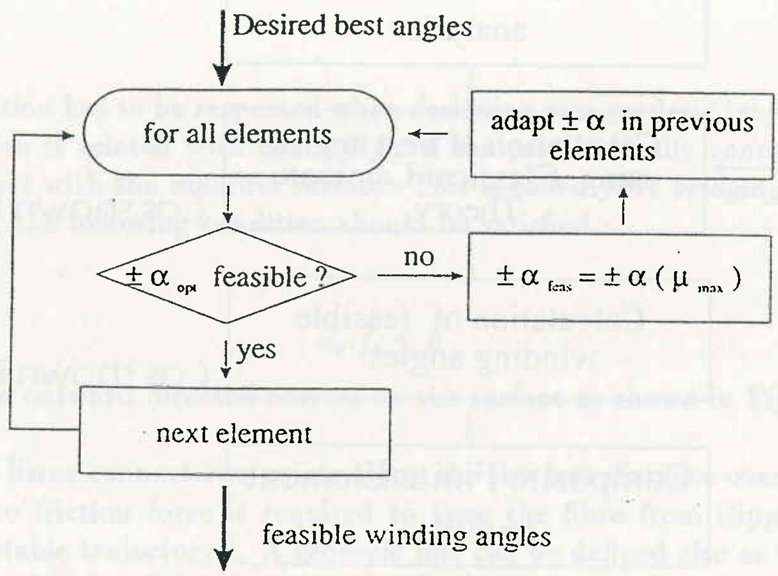

Figure 6: Calculation of the feasible angles.

optimum fibre angle couple for all the other elements is recalculated to yield the same failure index *fi*. With these angle data, a fibre path optimization is performed using the computer code CAWAR, trying to approach the optimum fibre angles as good as possible;successively it is checked for every element whether the optimum angle is feasible or not. If not, maximum friction is applied to give the best suited but feasible angle. If this results in a failure index greater than *fi(mce)*, α is set to yield *fi(mce)* and the previous angles in previous elements must be adapted until this failure index can be reached within the limits of friction. In order to implement such methodology, following assumptions have been made:

- In order to perform the finite element analysis in filament wound parts it must be considered that the interweaving effect of the fibres usually cannot be modelled within the finite element solver. Tsai [6] proposes to solve the problem of interweaving by giving laminate theory an empirical hand: " predictions of elastic constants and strengths of fabrics, filament wound and braided structures can be made using classical micro and macromechanics with appropriate correction factors". To carry out the finite element analysis in the wound part it will be assumed a layered laminate lay-up in the material properties entry. This does not represent a problem, since experimental results have shown that this assumption is satisfactory [4].
- Two special entries have been used in the finite element code (MSC/NASTRAN) for the modelling of composite structures. The first , defined as MAT8, defines the material property for an orthotropic material. That material has symmetric properties in three orthogonal planes. It supplies the material properties

of the individual lamina along the longitudinal direction (fibre direction) and the transverse direction (matrix direction). The second, defined as PCOMP, defines the properties of the n-ply composite material laminate. It provides the thickness, orientation and the material identification of each individual laminal.
From the data supplied by these two entries, MSC/NASTRAN automatically calculates the membrane, bending, transverse shear and coupled membrane-bending material properties of the laminate as a whole. It also provides the calculation of failure indices for all the plies of every elements.
It should be noted however that two-dimensional plate theory used does not allow the exact calculation of interlaminar stresses. An approximate procedure is therefore used to determine the interlaminar shear stresses. The approximation consists of neglecting the effects of twisting moments in the computation of interlaminar shear stresses. For the majority of composite material structural analysis, this approximation is expected to yield satisfactory results for all elements in the model except those at the edges of the structure [7].

- The winding angle of each element is assumed to be constant and equal to the value at the centre of the element.

5 Application - Conical part

5.1 Conical Part

To illustrate the proposed methodology, a conical filament wound part has been studied (Figure 7). This part has been modelled in the the design module of the CAD system (Unigraphics) using 5 surfaces of revolution: 2 related to the cylindrical surface, 1 related to the conical surface and other 2 related to the fillet in the transition cylindrical to conical surface and vice-versa. Also the finite element mesh has been generated as shown in Figure 8.

Preliminary design The part has been designed in the CAD system and its geometry made accessible for the program CAWAR by using the IGES file. The geometry has been completely generated using surfaces of revolution. The curves used to generate the surfaces 2 and 4 have been created using fillet curves, so there are no discontinuities in the geometry.

Isotropic analysis In order to provide a starting-point for building up the laminate, an initial finite element analysis considering isotropic material has been performed. The main objective is to derive the ideal fibre orientations to be used in the fibre path generation. Some points should be noted:

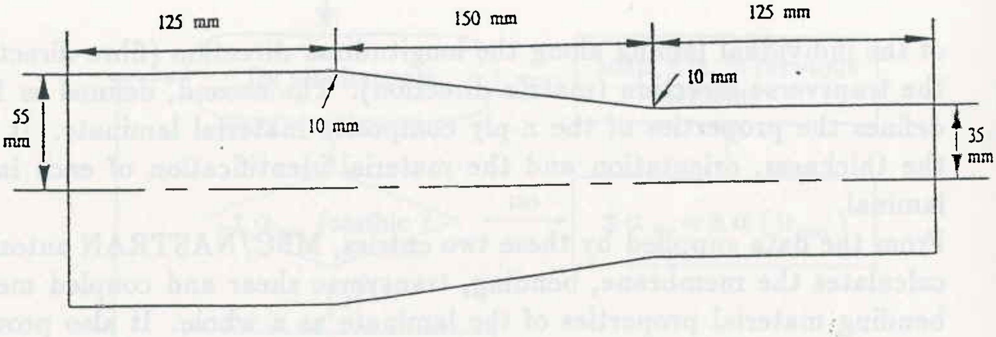

Figure 7: The conical part.

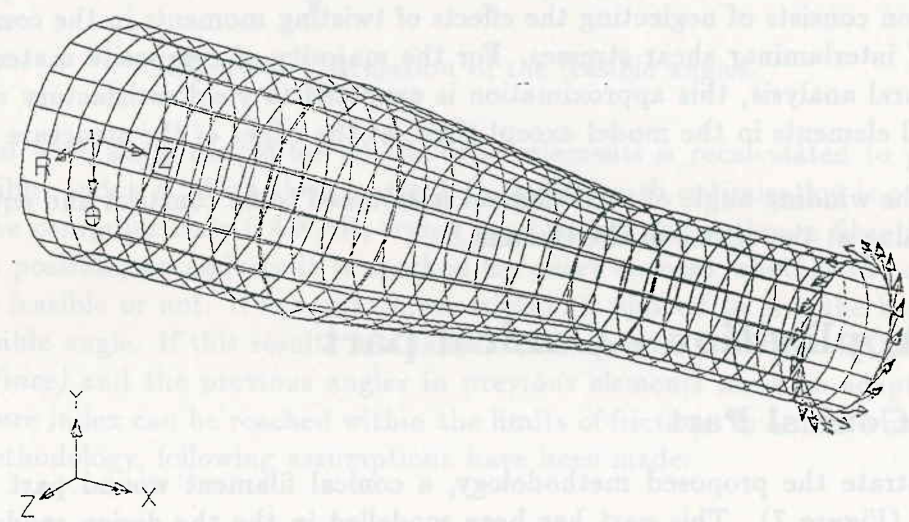

Figure 8: Loading conditions and constraints

- **Generation of the Model** The CAD system allows to generate the finite element mesh onto the designed geometry. As the part will be loaded with single static load the standard quadrilateral plate element has been used. The resulting finite element model is composed of 640 finite elements.
- **Loading conditions and constraints** The part is loaded with torsion, as shown in Figure 8. The other extremity of the part is constrained in all six degrees of freedom.
- **Some other data** necessary for the finite element simulation are:
  - *Loading conditions:* As described before a single loading in torsion is used (load = 3500 N.m).

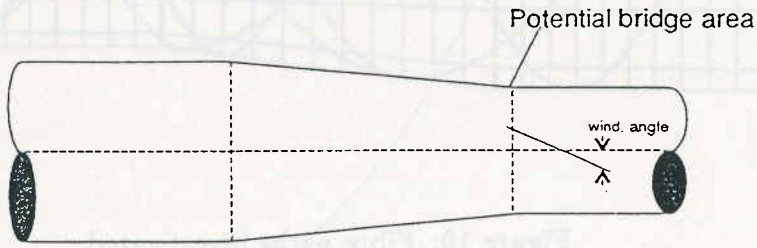

Figure 9: Fibre bridge area.

– *Material Choice:* The material used is the Scotchply (E - glass + epoxy).The cross section of the wet fibre equals to 1.57 mm^2

It is known from basic beam theory that principal stresses in pure torsion are directed along lines inclined by 45° to the meridian. Finite element analysis confirms this inclination.

Generation of the fibre paths The resulting angle of maximum stresses, calculated before, was then used for generating the fibre path in the program CAWAR. Some options have been initially tested:

- **Geodesic line:** The geodesic line was generated considering the starting winding angle of 45° at the origin (the extremity with the bigger radius). On the cone, this angle increases up to 90° and the fibre is returned without reaching the smaller cylinder. (Figure 10). Therefore, the coverage of the whole mandrel is impossible using geodesic trajectory.

- **Constant winding angle** The fibre path was generated considering a constant winding angle of 45° However, problems of fibre bridging arise in the surface 4, and the desired geometry of the part cannot be achieved by this way (Figure 9).

To solve this problem, three possibilities are proposed (Figure 10) :

- **Part 1:** first, using constant winding angle. In this case the angle in which the fibre bridging does not occur can be determined after successive trials. This procedure has been used, resulting in a constant angle of 62°.

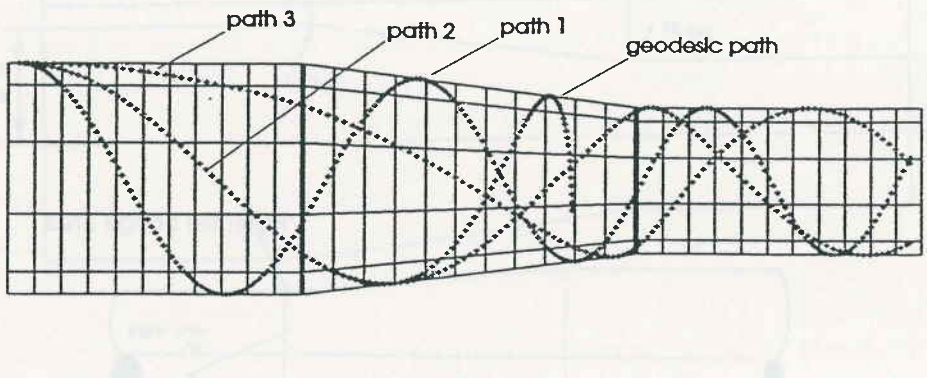

Figure 10: Fibre paths investigated

- **Part 2:** second, using initially a constant angle of 45° (maximum stress angle) and deviating to 62° in the fibre bridging area. After avoiding the fibre bridging the angle returns to 45°
- **Part 3:** third, using the proposed methodology. In this case one start angle of 21° has been calculated (for the largest diameter of the part). Anyway due to the fibre bridging it has to deviate to 62° at the end of the cone. After that the angle of 45° is restored.

6 Results

In order to compare the different parts the following procedure has been used:

- First, the thickness (and consequently the number of windings) required to get the maximum allowed failure index is calculated for the part wound with constant angle. The total weight of the part is also calculated.
- Second, for the other parts, the thickness (and number of windings) necessary to get the same value of the failure index is calculated. The weight is then calculated and compared to the other parts.

The results obtained, considering one maximum Tsai-Wu failure index equals to 0.70 are shown below:

- Part 1

  number of windings: 500
  thickness: 4.89 to 7.69 mm
  weight: 1214 g

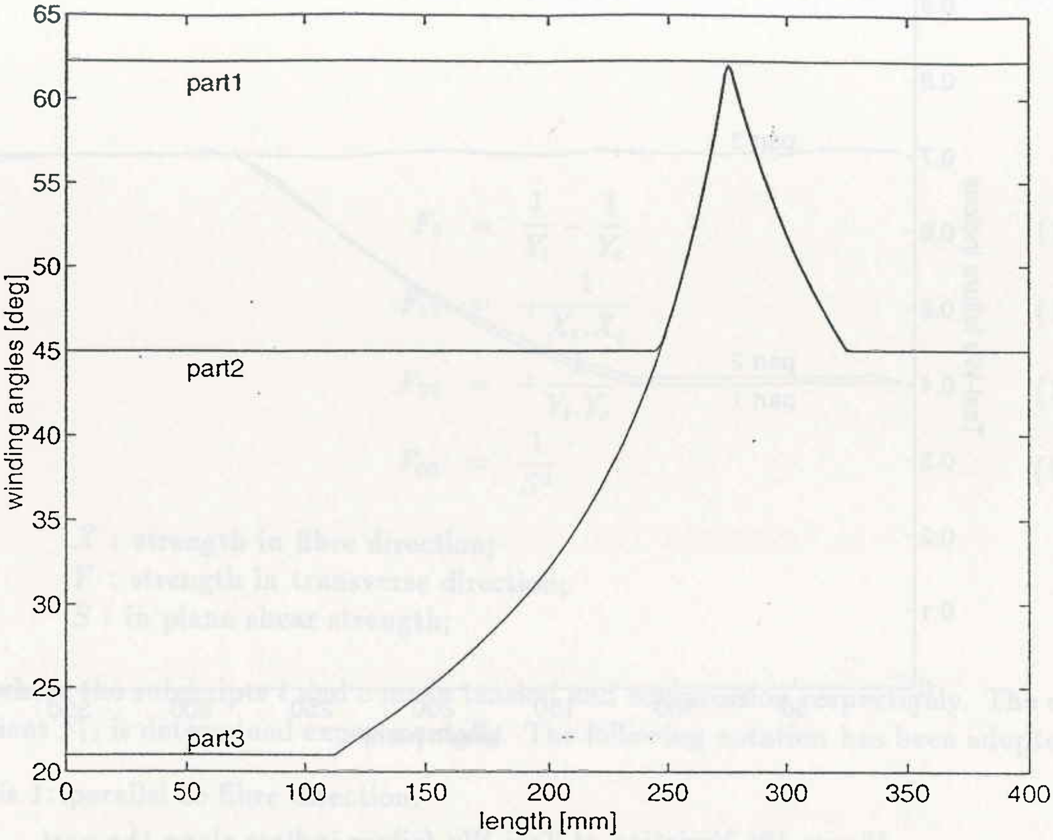

Figure 11: Variation of the winding angles.

- **Part 2**

  number of windings: 668
  thickness: 4.35 to 10.1 mm
  weight: 1106 g

- **Part 3**

  number of windings: 668
  thickness: 3.27 to 10.1 mm
  weight: 982 g

The variation of the failure indices along the part is shown in Figure 12 .

7 Conclusion

The results obtained in the example are very satisfactory and prove the validity of the methodology. However, some points should be considered:

- The part presented is loaded with a simple torsion moment. In this case the effect of bending moments can be neglected during the calculation. This simplifies the application of the methodology since the final optimum fibre path can be obtained after a few iterations. For more complex cases additional number of iterations may be required.

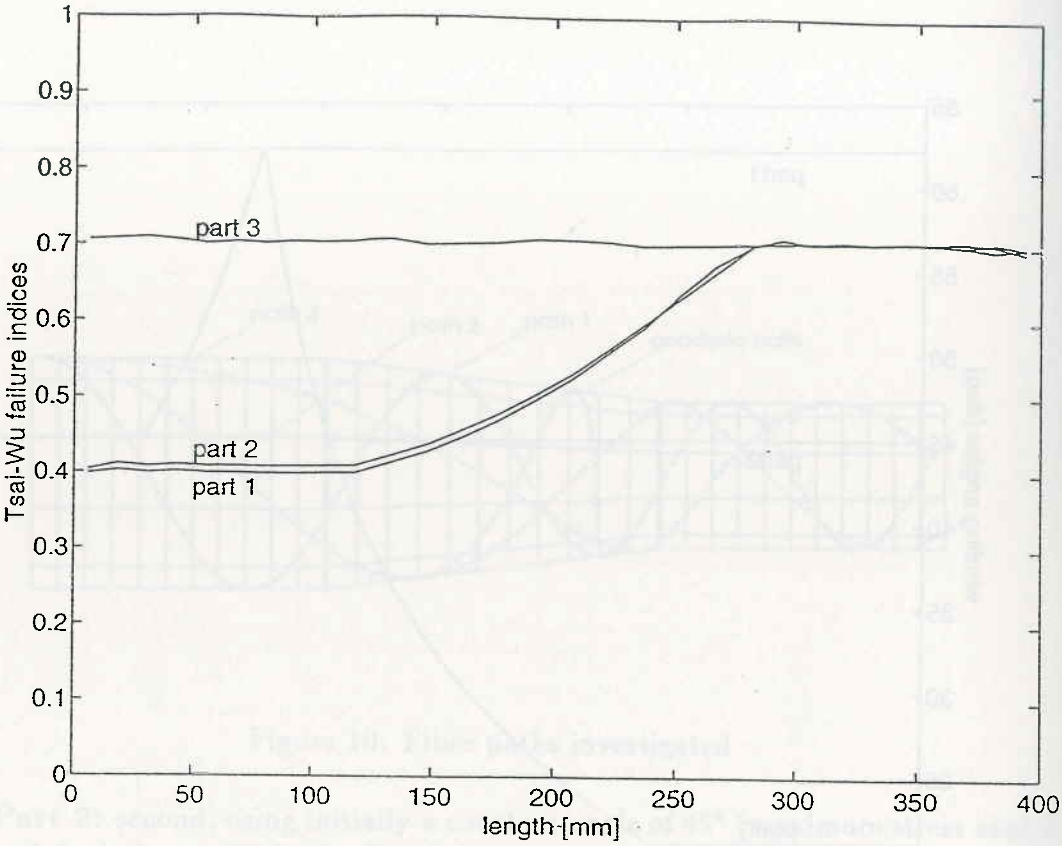

Figure 12: Variation of Tsai-Wu failure indices along the part

- The final laminate has been modelled as a layered laminate lay-up, whereas in the real filament wound part the fibres are interwoven. This interweaving of the fibres cannot be modelled in the available finite element code, but experimental results have proven that a layered laminate lay-up is a good approximation (as mentioned before).

Appendix - Tsai-Wu failure index

The number of failure criteria for composite materials is very large. This is not really surprising, given the complexity and range of materials that they attempt to model. Following there is a short description of the failure criteria used. Tsai and Wu specialized to the case of an orthotropic lamina in a general state of plane stress is:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + 2F_{12}\sigma_1\sigma_2 + F_{66}\sigma_{12}^2 = fi \qquad (8)$$

where:

fi : Tsai-Wu failure index.

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c} \qquad (9)$$

$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c} \tag{10}$$

$$F_{11} = +\frac{1}{X_t . X_c} \tag{11}$$

$$F_{22} = +\frac{1}{Y_t . Y_c} \tag{12}$$

$$F_{66} = \frac{1}{S^2} \tag{13}$$

X : strength in fibre direction;
Y : strength in transverse direction;
S : in plane shear strength;

where the subscripts t and c mean tension and compression respectively. The coefficient F_{12} is determined experimentally. The following notation has been adopted:

Axis 1: parallel to fibre direction.

Axis 2: perpendicular to fibre direction.

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