Experimental and numerical analysis of interply porosities in composites thermoforming

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ABSTRACT: Effective forming of Continuous Fiber Reinforced Thermoplastic Composites requires a detailed understanding and modeling of the forming mechanisms and the development of computational techniques for process simulation. A re-compaction stage is performed at the end of the process in order to avoid interply porosities. The through the thickness behaviour of the composite during forming and consolidation is analysed by a shell finite element with pinching degrees of freedom. This element avoids a locking due to pinching by a modification of the constitutive relation.

Key words: Thermoplastic composites, re-consolidation, shell finite elements

1 INTRODUCTION

The CFRTP (composites with continuous fibres and thermoplastic matrix) forming starts from flat laminated plates made of several unidirectional or textile reinforcements which have been consolidated by a thermoplastic matrix in an autoclave. After heating at a temperature higher than melting (figure 1.1), the forming is made with a punch and die process usually using a rubber on the die (figure 1.2). Finally a reconsolidation is obtained by applying a pressure on the punch (figure 1.3). The objective is to avoid all residual porosity at the interface of the plies. This last stage is important and critical because the health requirements for loaded aeronautical parts are severe. If the use of CFRTP is increasing in the manufacturing of new aircrafts [1][2] because the processing cycle is shorter than those of thermoset composites, there is an important need of simulation codes of the forming operations in order to define the forming conditions for a given shape and a given stack of plies. The present paper is focused on the experimental and numerical analysis of the compaction stage. Micrographs made on specimens formed at different moment of the process show the evolution of the porosity during forming. They show the porosities are large and consequently the importance of the compaction stage in order to guarantee compaction.

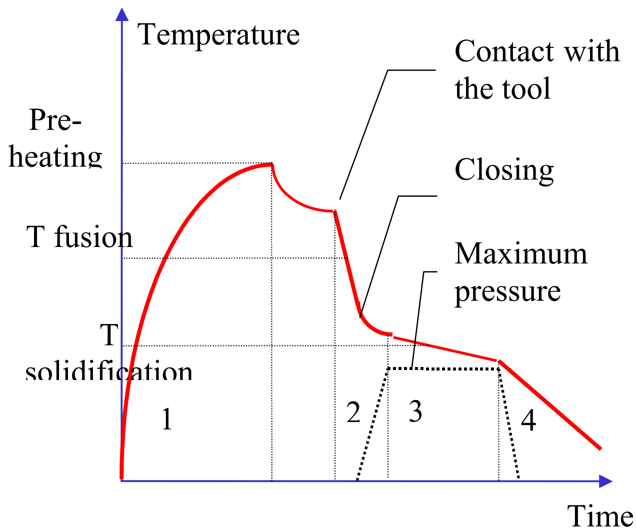

Figure 1: Pressure and temperature during the manufacture
1. Heating of the CFRTP plate
2. Forming with punch and die
3. Reconsolidation phase
4. Release of the final part

Concerning the reconsolidation, porosities only disappear if a sufficient normal stress is achieved in the ply. In order to model this compaction, a new shell element is defined in which a through the thickness strain degree of freedom is introduced. The stress through the thickness is taken into account and the element can model the compression during the re-compaction stage within a shell finite element analysis.

2 ANALYSIS OF THE RE-CONSOLISATION STAGE

2.1 Experiments

Z-shaped parts were manufactured at CCR EADS Suresnes (figure 4 & 5) in order to analyse the generation and resorption of porosities during the different stages of the process. The material is APC2 (carbon fibers and peek matrix). Micrographs were made in a flat and in a curved part of the specimen in different stages of the manufacturing process.

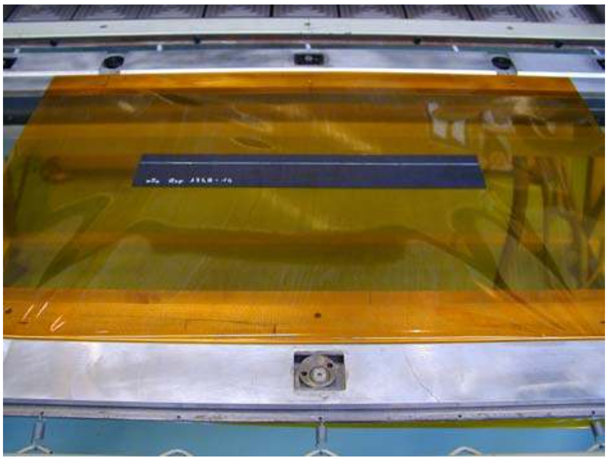

Figure 4. Initial position of the part on a thermalimid film

Figure 5. Punch and die (and final shape)

Before forming, no voids are present in the part (Figure 6). After one minute heating, many voids and porosities can be observed in the part (Figure 7).

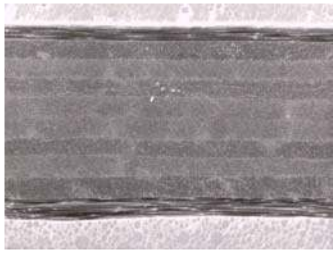

Figure 6 : Composite before heating

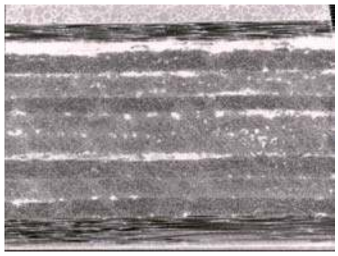

Figure 7 : Composite after heating

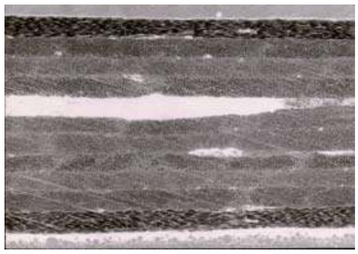

Figure 8 : Composite in flat part for H=5.3mm

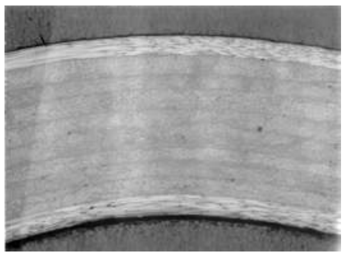

Figure 9 : Composite in curved part for H=5.3mm

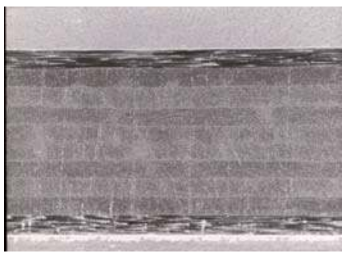

Figure 10 : Composite in flat part for H=0

Figure 8 and 9 correspond to H= 5.3 mm (H is the height before the end of forming. Chocks have been used to stop the process). There are still voids in flat parts but there is no porosity in curved parts of the reinforcement. For H=0 (complete process), (figure 10) all the voids have disappeared. This last stage corresponds to the end of the re-consolidation phase where a pressure is applied on the tools. That shows that this stage is very important for the final quality of the part. In the curved zones of the part, the re-consolidation is done during the forming accounting for the geometrical effect that leads to transverse stresses during forming.

2.2. Shell Element with stress and strain through the thickness

The re-consolidation has been studied in [3] and some models have been proposed for the local consolidation. Some studies on consolidation have shown that it depends on the stress state in the laminate and mainly on the normal stress in the consolidation stage. This stress is not present in classical shell theory. Some finite elements with stress/strain through the thickness have been proposed [4][5][6][7]. In the present work a new shell element is used where a through the thickness strain degree of freedom is introduced [8].

The displacement is obtained in subtracting the initial position from the current position.

$$u = (\bar{x}^t - \bar{x}^0) + \tilde{z}^t \hat{X}^t - \tilde{z}^0 \hat{X}^0 \tag{1}$$

with $\bar{x}$ the projection of this point on the midsurface and $\tilde{z}$ the position of this point on the normal $\hat{X}$.

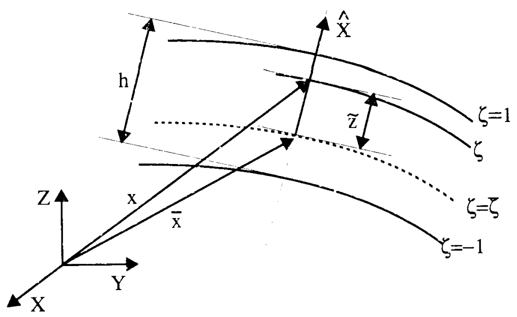

Figure 11. Geometry of the shell

Let $\Delta h = \tilde{z}^t - \tilde{z}^0$ the displacement of the point in the thickness and define β as the strain in the thickness, $\beta = \frac{\Delta h}{\tilde{z}^0}$. In the case of small rotations between two states the displacement expression becomes:

$$u = \bar{u} - \tilde{z}^0 \hat{X}^t \times \theta + z\beta \hat{X}^t \tag{2}$$

In contrast of classical shell, a sixth degree of freedom appears to describe the displacement in the thickness..

If β =0 equation (2) leads to the classical shell kinematics without pinching. We consider β constant thought the thickness. β is an additional pinching degree of freedom.

The strain tensor $\varepsilon(u) = \frac{1}{2}\left[\nabla(u) + \nabla^T(u)\right]$ can be derived from the displacement (2).

In an orthogonal frame ($\hat{e}_1, \hat{e}_2, \hat{e}_3 = \hat{X}$) the membrane and bending strain components are:

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ 2\varepsilon_{12} \end{Bmatrix} = \begin{Bmatrix} u^m_{x,1} \\ u^m_{y,2} \\ u^m_{y,1} + u^m_{x,2} \end{Bmatrix} + z \begin{Bmatrix} \theta_{y,1} \\ -\theta_{x,2} \\ -\theta_{x,2} + \theta_{y,1} \end{Bmatrix} \tag{3}$$

The transverse shears are :

$$\begin{Bmatrix} 2\varepsilon_{13} \\ 2\varepsilon_{23} \end{Bmatrix} = \begin{Bmatrix} u^m_{z,1} + \theta_y \\ u^m_{z,2} - \theta_x \end{Bmatrix} + z \begin{Bmatrix} \beta_{,1} \\ \beta_{,2} \end{Bmatrix} \tag{4}$$

and the through the thickness strain (pinching) is :

$$\{\varepsilon_{33}\} = \beta \tag{5}$$

The transverse shear strains are modified by the pinching. In contrast of classical shell, the normal stress through the thickness is not zero. It is deduced from ε_{33}=β using the compaction behavior law.

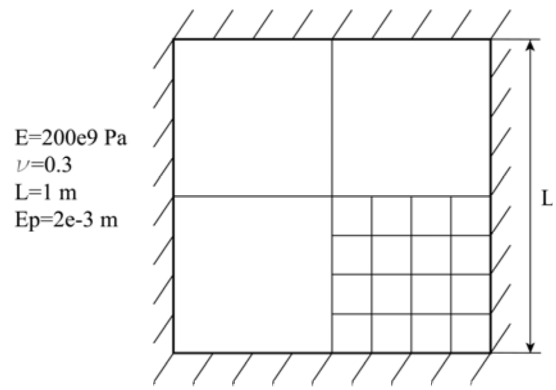

Figure 12. Clamped square plate under pressure

It has been shown [8][9] that this element exhibits a "pinching" locking. To avoid this locking it is necessary to modify the constitutive relation in order to remove the coupling between pinching and bending [8][9].The example presented figure 12 and 13 (Clamped square plate under pressure) shows the pinching locking with is obtained with a complete behaviour law and the accurate result if pinching and bending are not coupled.

This element is used in order to compute the through the thickness stress during the forming stage as well as in the proper compaction phase. As an example the through the thickness stress computed after compaction of a cylindrical shell is shown in figure 14. The radius of the shells is 10 mm, the width is 3 mm and the thickness of each ply is 0.2 mm. In each of the two plies, the thought the thickness is proportional to the projection of the normal on the compaction direction. The simulation of a Z forming and the computation of the through the thickness stress and its comparison with experimental results can be found in [10].

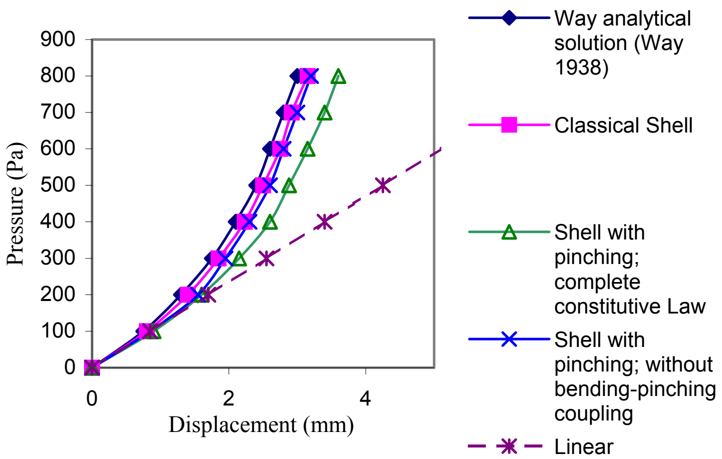

Figure 13. Displacement at the center of a plate under pressure.

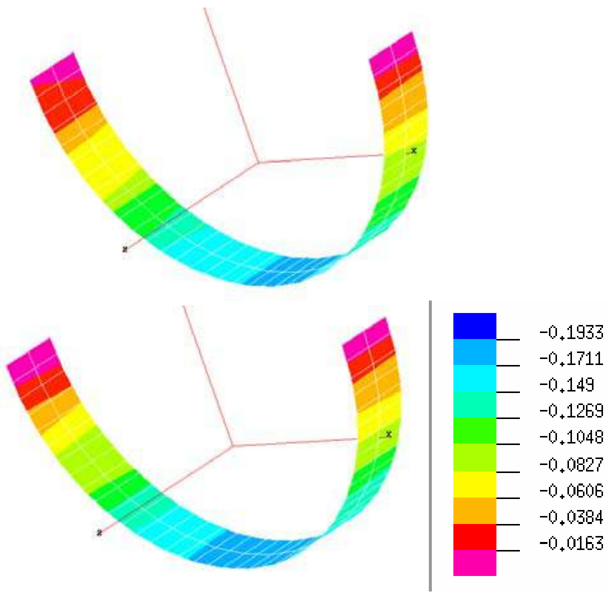

Figure 14. Through the thickness stress in a cylindrical shell compaction

CONCLUSION

A shell element with pinching is used to simulate the compaction during forming of thermoplastic composites. It has been shown by experimental analysis of the forming that porosities induced by the process are important and must be suppressed. This finite element has a degree of freedom in the thickness and give the stress and strain through the thickness. The further work will be focused on the definition and the identification of the compaction constitutive relation.

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