PGD analysis of the heating of a composite laminate during ultrasonic compaction

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ABSTRACT

Compaction of composite layers just after placing them is a key requirement for the new out-of-autoclave in-situ curing techniques. A solution proposed for this task is the use of ultrasonic compactors. In fact, the ultrasonic vibration over the laminate induces a viscous heating of the resin that becomes less viscous and lets the air bubbles escape. The numerical study of this heat generation and distribution within the laminate implies several modeling problems because of its different dimensions (10 cm for the width of the prepreg tape and 0.01 mm for its thickness) and its two scales of time (10 seconds for the process and 10 microseconds for the vibration).

The Proper Generalized Decomposition (PGD) is a suitable technique to overcome this kind of problems. The formulation and implementation of the PGD for the problem of viscous heating inside composite laminates is presented in this work.

KEY WORDS: Composites, Ultrasonic compaction, PGD.

1. INTRODUCTION

It is well known that, especially on the aeronautic industry, usual composite manufacturing systems employed entails a large number of processes [1], most of them not automated. Because of this reason, along with the long curing times usually required, the total time of the process becomes too long and the parts very expensive. For example, an autoclave manufacturing process requires cutting the plies, lying up the plies (including intermediate compaction phases), vacuum bagging and curing [2]. The industry is looking for new processes able to circumvent these problems, and one way to do it would be to implement and automate all the steps in a single process, reducing also the curing time by using resins that can be cured almost instantaneously [3].

This is what out-of-autoclave systems are seeking for. These systems implement an automatic tape placement with a new technology curing device, as can be microwaves or electron beam. To achieve a good quality in the final parts, a compaction phase subsequent to the placement of the composite plies and previous to the curing phase is needed, in order to substitute the vacuum bag used in the autoclave manufacturing. To solve the problem of the compaction “on-the-fly”, an ultrasonic compactor [4] can be used. The ultrasonic compactor has a pressure cylinder that generates an ultrasonic vibration movement on it. When it is placed over the composite layers, it transmits the movement to the layers, thus generating heat inside the laminate. This heat contributes to the debulking of the layers liquefying the resin and letting the air bubbles to escape outside. The parameters that can be modified on the compaction device are the frequency and amplitude of the vibration of the sonotrode and the horizontal velocity of the table were the laminate is placed.

A procedure is going to be investigated: compacting the whole part before curing. In this case the machine places all the composite pre-pregs over a mould and then the ultrasonic compactor actuates, debulking all the laminate at the same time. After the whole part is laminated and compacted, it can be cured either in-situ or in an autoclave. In the way of optimizing this process, several models have been developed to study the heat generation due to viscous heating [4] and the heat distribution problem [5]. Moreover, an algorithm has been presented to couple these thermomechanical models with a resolution in a FEM commercial program [5]. A scheme of the problem under study is shown on Figure 1. Note that the fibre and resin layers of each prepreg ply are considered separated.

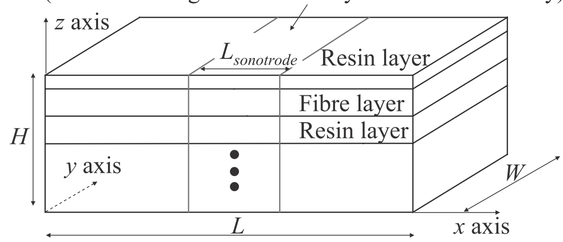

Fig. 1. Scheme of the problem

The resolution of this problem with FEM presents two main difficulties. Firstly, due to the dimensions of the problem, an accurate representation of the thickness direction becomes very expensive from the computational point of view. For this reason it’s nearly impossible to obtain a correct evolution with time of the temperature along the fibre and resin layers. Secondly, due to the process times, one concerning the ultrasonic wave and the other one concerning the real time of the process, the computing time becomes very long. Due to these facts, a different approximation to solve the problem is needed. The one chosen in this work is the Proper Generalized Decomposition (PGD), which solves the problem by decomposing the variables as a sum of products of functions of the variables involved in the problem. Using the PGD the thermomechanical problem will not be solved incrementally, it will be solved along all the process time assuming a value of the heat generation and then corrected with the value that would be obtained with the temperatures given by the calculations. The convergence of this method is very fast as can be seen, for example, on [6], [7] and [8].

An algorithm to solve the problem, the equations of the PGD and a comparison with experimental results are presented in this paper.

2. ALGORITHM TO SOLVE THE PROBLEM WITH THE PGD

The equation that defines the thermal problem is:

$$\rho C_P \frac{\partial T}{\partial t} - \nabla \cdot (\mathbf{K} \nabla T) = Q^{visc} \quad (1)$$

being $T(x, y, z, t)$ the temperature at each point, ρ the density, C_P the specific heat capacity, $\mathbf{K}$ the conductivity tensor and $Q^{visc}(x, y, z, t)$ the heat generation due to internal viscosity of the resin.

The heat conduction problem will be solved with the PGD (explained in the next section) and the right term will be solved using the algorithm and equations that describe the heat generation due to internal viscosity of the resin, presented in [5]. As shown in Figure 1, heat generation only takes place in the resin layers in the zone under the sonotrode

The heat conduction problem will be solved for every point in the laminate and for every time step. Therefore for this problem, Q^{visc} is a matrix of *n*x*m* (being *n* the number of plies –the heat generation is calculated using the mean temperature of the nodes of the ply- and *m* the number of time steps) of known values. To obtain the solution, an algorithm is presented next:

Initially, the temperature at each node and at each time step is supposed constant and equal to the room temperature. With this temperature, the heat generation induced by the ultrasonic vibration is calculated at every resin layer at every time step using the procedure described in [5]. This heat generation matrix is used to solve the heat distribution problem by solving equation (1) with the PGD. The temperatures at each node and at each time step are determined in this step and used to calculate the heat generation in the next step. This updated heat generation is compared with the one obtained in the previous step and, if the difference is smaller than a tolerance, the algorithm is finished. If not, the updated heat generation is used to solve the thermal problem again with the PGD and the algorithm continues until reaching convergence.

3. PGD SOLUTION OF THE PROBLEM

In what follows we are illustrating the construction of the Proper Generalized Decomposition of a transient model defined in a plate domain $\Xi = \Omega \times I \times \Gamma$ with $\Omega \subset \Re^2$ (where $\mathbf{x} = (x, y) \in \Omega$); $I = [0, H]$ and $\Gamma = [0, t_{\max}]$, being $t_{\max}$ the maximum time of the process. This formulation is valid for 3D and 2D problems (just assuming $\Omega \subset \Re$).

We consider that the laminate is composed of *P* different orthotropic plies each one characterized by a well defined conductivity tensor $\mathbf{K}_i$ -which is assumed constant in the ply thickness-. Moreover, without a loss of generality, we assume the same thickness for the different layers of the laminate, which we denote by *h*. Thus, we can define a characteristic function representing the position of each layer:

$$\chi_j(z) = \begin{cases} 1 & z_j \le z \le z_{j+1} \\ 0 & otherwise \end{cases} \qquad j = 1,..., P \tag{2}$$

where $z_j = (j-1) \times h$. Now, the laminate conductivity can be given in the following separated form:

$$\mathbf{K}(x, y, z) = \sum_{j=1}^{P} \mathbf{K}_j(\mathbf{x}) \chi_j(z) \tag{3}$$

The weighted residual form of Eq. (1) writes:

$$\int_{\Xi} T^* \left(\rho C_P \frac{\partial T}{\partial t} - \nabla \cdot (\mathbf{K} \nabla T) - Q^{visc} \right) d\Xi = 0 \tag{4}$$

with the test function T^* in an appropriate functional space. The equation will be solved by integrating the term involving second order derivatives by parts (and, for the sake of clarity, assuming there are no natural boundary conditions):

$$\int_{\Xi} T^* \rho C_P \frac{\partial T}{\partial t} d\Xi + \int_{\Xi} \nabla T^* \cdot (\mathbf{K} \nabla T) d\Xi - \int_{\Xi} T^* Q^{visc} d\Xi = 0 \tag{5}$$

The solution $T(x, y, z, t)$ is searched under the separated form:

$$T(\mathbf{x}, z, t) \approx \sum_{i=1}^{i=N} X_i(\mathbf{x}) \cdot Z_i(z) \cdot \Theta_i(t) \tag{6}$$

In what follows we are illustrating the construction of one such decomposition. For this purpose we assume that at iteration $n < N$ the solution is already known:

$$T^n(\mathbf{x}, z, t) = \sum_{i=1}^{i=n} X_i(\mathbf{x}) \cdot Z_i(z) \cdot \Theta_i(t) \tag{7}$$

and that at the present iteration we look for the solution enrichment:

$$T^{n+1}(\mathbf{x}, z, t) = T^n(\mathbf{x}, z, t) + R(\mathbf{x}) \cdot W(z) \cdot S(t) \tag{8}$$

The test function involved in the weak form is searched under the form:

$$T^*(\mathbf{x}, z, t) = R^*(\mathbf{x}) \cdot W(z) \cdot S(t) + R(\mathbf{x}) \cdot W^*(z) \cdot S(t) + R(\mathbf{x}) \cdot W(z) \cdot S^*(t) \tag{9}$$

Now, as the enrichment process is non-linear we propose to search the functions $R(\mathbf{x})$,

$W(z)$ and $S(t)$ by applying an alternating direction fixed point algorithm. Thus, assuming $S(t)$ and $W(z)$ known, we compute $R(\boldsymbol{x})$, and then we update $S(t)$ from previous $W(z)$ and the just updated $R(\mathbf{x})$. Finally we calculate $W(z)$ with the just obtained $R(\mathbf{x})$ and $S(t)$. The process continues until reaching convergence. The converged solutions allow defining the next term in the finite sums decomposition: $R(\mathbf{x}) \rightarrow X_{n+1}(\mathbf{x})$, $W(z) \rightarrow Z_{i+1}(z)$ and $S(t) \rightarrow \Theta_{n+1}(t)$.

4. RESULTS

A problem consisting on 8 prepreg plies has been solved with the PGD as 2D problem. The boundary conditions are: isolation under the laminate, conduction between the laminate and the sonotrode and convection between the laminate (the zones that are not in contact with the sonotrode) and the air. The mesh used consists on 100 nodes on the *x* axis (being $L = 40mm$ and $L_{sonotrode} = 20mm$), 321 nodes on the z axis (being $H = 1.04mm$) and 456001 nodes on the time axis. The convergence was reached using 25 sums of products of functions $X_i(\mathbf{x})Z_i(z)\Theta_i(t)$. The temperature distribution inside the laminate at a moment of the process is shown on Figure 2 (there is no variation in *z*).

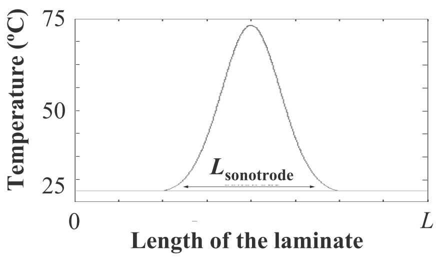

Fig. 2. Temperature distribution inside the laminate during compaction process

A comparison between the experiments and the PGD solution of the evolution of the temperature in time at the bottom of the laminate is presented in Figure 3. As can be appreciated, the agreement of the numerical solution with the experimental one is very accurate.

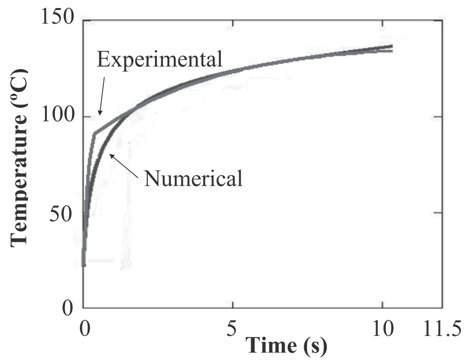

Fig. 3. Comparison of experimental and numerical temperature/time curve at the bottom of the laminate

5. CONCLUSIONS

The problem of the heat generation and distribution in composite laminates under ultrasonic vibrations has been studied from a 2D point of view.

After considering the problematic of solving the temperature distribution coupled with the heat generation in a commercial FEM problem, the whole problem has been solved using PGD solution techniques. These techniques have shown a good agreement in the results with an enormous reduction in the computing times, allowing also to obtain a more fine solution where the thickness and the time were causing problems in the FEM model. To this end, the governing equations for the PGD to solve the heat equation in laminates have been developed.

The next step is to model the thermal problem due to the movement of the sonotrode along the laminate during the compaction process.

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