CURING OF THICK ANGLE-BEND THERMOSET COMPOSITE PART: CURING PROCESS MODIFICATION FOR UNIFORM THICKNESS AND UNIFORM FIBER VOLUME FRACTION DISTRIBUTION

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Summary: Thermoset composite parts with angle-bend are more difficult to cure as compared to straight parts. The curvature at the bend usually creates fiber micro-buckling, non uniform fiber distribution across the thickness, non uniform fiber distribution along the length of the part, existence of voids, etc. The procedure normally used for the manufacturing of straight composite parts therefore needs to be modified for parts with angle bend. This paper presents the work done in the development of modified procedures for the manufacturing of good thermoset parts with angle bend. The work consists of two aspects: numerical modeling and experimental. For numerical modeling, finite difference method was used to model the governing equations and the curved geometry. A special boundary condition was also developed to handle the effect of bleeder materials. Modified procedures were developed from the results of the numerical model. Samples were manufactured using the modified procedure. AS4/3501-6 graphite/epoxy materials were used. Parts with much improved quality, as compared to parts made using the manufacturer's recommended procedure, were obtained. Uniform thickness distribution and uniform fiber distribution in the parts made with modified procedure were obtained.

Keywords: angle-bend, thermoset, curing process modification, uniform fiber distribution, uniform thickness.

INTRODUCTION

Autoclave processing is a manufacturing method used to produce high performance composite parts. Varying temperature, pressure and vacuum cycles in the autoclave leads to different cure processes which will end up with different final part quality: (1) The degree of cure and the fiber volume fraction affect the mechanical properties of the final composite part. (2) The pressure distribution affects the compaction of the laminate and the void formation. (3) Temperature gradients can introduce residual stresses and strains. (4) Finally, for cost-effective process, the duration of the processing cycle should be short.

There have been many studies on the curing of thick thermosetting composite materials. In References [1,2], researchers developed cure simulation models that predict temperature and degree of cure distributions within the part as a function of the autoclave temperature history. Researchers who considered the resin flow model include Hojjati [3] who studied curing of thick flat section parts, and Johnston et al [4] who showed, for curved sections, that resin flow was uneven resulting in non-uniform part thickness. Also, [4] found that springback angle is influenced by two factors: choice of tool material, and surface friction condition. Many other workers as in [5,6] also performed studies to come up with optimized curing cycles for their composite parts. In a previous work [7], we showed how the recommended curing cycles resulted in thickness and fiber volume fraction variations along the length and thickness of an angle bend composite part (Fig. 1). In this work, a modified curing process was developed that minimizes the spatial variations in thickness and fiber volume fraction along with the gradients in temperature and degree of cure. 2-step and 3-step curing cycles were implemented experimentally and theoretically to study the variations in thickness and fiber volume fraction of an angle-bend piece made from 50 layers of graphite/epoxy Hercules AS4/3501-6 prepreg (ply thickness is approximately 0.16 mm and has 36% resin content by weight).

THICKNESS AND FIBER VOLUME FRACTION VARIATION

To get a final part that has a consistent quality in terms of thickness and v_f distributions, the curing process itself should be altered. Reference [8] was the only one found that mentioned how they controlled the fabrication conditions to achieve uniform thickness in the corner of a flange-web. The specimens were manufactured using hard tools on both sides. The configuration of our lay up is shown in Fig. 2. In our case, since the lowest v_f value was found to be present at the curved bend adjacent to the mold surface, then inserting a bleeder layer between the mold and the composite part prior to processing would allow resin to escape at that surface and hence increase the v_f value. Consequently, this will result into a lower variation in thickness from section to section. (This case will be referred to as Case (I).) Alternatively, adjusting the number of perforated release films on the upper surface will allow controlling the amount of resin flow out of the part. However, this will produce a uniform thickness but will not give a uniform v_f distribution. (This case will be referred to as Case (II).)

To simulate the presence of the lower bleeder layer and/or the upper perforated release films, a generalized boundary condition formulation in terms of a Robin pressure boundary condition was imposed. Formulating pressure boundary conditions for the Dirichlet or Neumann case is a straight forward procedure. When pressure values at the surface boundaries P_s are known, their values are directly applied. Also, when no flow occurs at a surface boundary that has outward unit normal $\hat{n}$, then $\frac{\partial P_s}{\partial \hat{n}}$ is set equal to zero. However, when flow proceeds through different media (as in the case for resin flow out of the laminate through the perforated release film, bleeder and breather layers) and the pressure value at this boundary changes with resin build-up, neither Dirichlet nor Neumann cases will succeed in representing the real situation. Therefore, a generalized boundary condition formulation for pressure must be derived for the following reasons:

1. to avoid the assumption of "free bleeding", i.e. $P_s = 0$ that is associated by excluding the effect of the bleeder on the resin flow behavior[1],

2. to overcome difficulties in modeling the detailed flow at the perforated release film, bleeder and breather layers where resin would bleed out of the laminate freely at first, and then will be restricted when the different cloths are filled with resin[2], and

3. to quantify the combined resistance of release, bleeder and breather materials to flow at that boundary.

To formulate a generalized boundary condition for pressure as well, Darcy's law of permeability will be used. Resin flow rate at the laminate surface according to this law, is written as [10,11]:

$$q_n = -\frac{S_p}{\mu}\frac{\partial P_s}{\partial \hat{n}} = -\frac{S_b}{\mu}\frac{\partial P_s}{\partial \hat{n}} \tag{1}$$

where S is the permeability in the $\hat{n}$ direction, and subscript p and b refer to the prepreg material and the bagging materials (perforated release film, bleeder and breather layers), respectively, as shown in Figure 3.

The second term in Equation 1 can be approximated by:

$$\frac{S_b}{\mu}\frac{\partial P_s}{\partial \hat{n}} = -\frac{S_b}{\mu}\frac{P_s - P_g}{\Delta} \tag{2}$$

$$\begin{gathered} or \quad \frac{S_b}{\mu}\frac{\partial P_s}{\partial \hat{n}} = -\bar{f}_c\left(P_s - P_g\right) \\ where \quad \bar{f}_c = \frac{S_b}{\mu \cdot \Delta} \end{gathered} \tag{3}$$

$\bar{f}_c$ is an average flow coefficient that is analogous to the average heat transfer coefficient h.
Δ is the thickness of the different bagging materials. Hence, combining equations 1 and 3, resin flow can be written as:

$$\frac{S_p}{\mu}\frac{\partial P}{\partial \hat{n}} = \bar{f}_c\left(P_s - P_g\right) \tag{4}$$

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[1] A procedure followed by most researchers.

[2] A situation that was addressed in Reference [9], and solved by setting $P_s = 0$ at the laminate top surface and $P_s = 0.5MPa$ at the edges.

$$or \quad \frac{\partial P}{\partial \hat{n}} = (F_c)_{eff} \left(P_s - P_g\right)$$
$$where \quad (F_c)_{eff} = \frac{S_b}{S_p \cdot \Delta} \tag{5}$$

$(F_c)_{eff}$ is an effective flow coefficient that is analogous to $\left(\frac{h}{k}\right)_{eff}$ used in heat flow equations. When the value of $(F_c)_{eff}$ is small, then the resistance to flow from laminate to boundary layer is high, and vice versa. Now using equation 5 will enable us to formulate a generalized boundary condition for pressure, the same as temperature. This is expressed as follows:

$$a\frac{\partial P}{\partial \hat{n}} + bP_s + cP_g = 0 \quad for \quad P(x,z)\, on\ D \tag{6}$$

The three different boundary conditions that may be enforced on the boundaries are summarized in Table 1 below.

Coeff.	a	b	c
Dirichlet	0	1	-1
Neumann	1	0	0
Robin	1	$(F_c)_{eff}$	$-(F_c)_{eff}$

Table 1: Generalized Boundary Condition Coefficients

Figure 4 shows the implementation of the generalized temperature and pressure boundary conditions for the kind of lay-up that was shown in Figure 2. For Case (I), the boundary conditions will be:

1. Temperature:
   - Top surface: $\left(\frac{h}{k}\right)_{eff} = 10m^{-1}$
   - Bottom surface: $T = T_a(t)$
   - Side surfaces: $T = T_a(t)$

   where $T_a(t)$ is the autoclave temperature (cure cycle).

2. Pressure:
   - Top surface: $(F_c)_{eff} = 1000$ for 1 perforated release film,
     $(F_c)_{eff} = 100$ for 2 perforated release films

- Bottom surface: $\dfrac{\partial P}{\partial \eta} = 0$
- Side surfaces: $\dfrac{\partial P}{\partial \eta} = 0$

where the autoclave pressure was $P_a = 0.584\,MPa$ and the bag pressure was $P_g = 0\,Pa$.

Figure 5 shows the model results of applying this pressure boundary on the bottom surface Case (I). As shown, the thickness variation was controlled and kept to a negligible value. Also, as expected, the v_f variation was negligible for Case (I) $\left(v_f \approx 68\%\right)$ as shown in Figure 6.

COMPARISON WITH EXPERIMENT

Experiments were done in order to investigate the modified cure process suggested above. A 50 layers sample was prepared from Hercules AS4/3501-6 prepreg and cured using the 2-step modified curing process. Two (2) perforated release films were laid at the top surface of the laminate. Two bleeder layers were laid at the top surface of the mold (under the laminate). One covers the mold surface from $\phi = 20\circ$ to $\phi = 70\circ$, the other one covers the whole surface. The final thickness after curing was almost 7mm as shown in Figure 7.

CONCLUSIONS

This research demonstrated the ability of getting a uniform fiber distribution across the thickness of a part with a curved angle-bend shape. By introducing a generalized pressure boundary condition in the simulation model, the real behavior of resin flow was modeled. Thickness variations over the part length were negligible and a uniform thickness was obtained. This was possible though modifying the curing process by incorporating bleeder layers at the lower surface between the mold and the sample. This extra layer was able to absorb the resin and hence decrease the thickness and increase the fiber volume fraction. However, the surface finish was not of the same appearance as that of a part processed without this extra layer.

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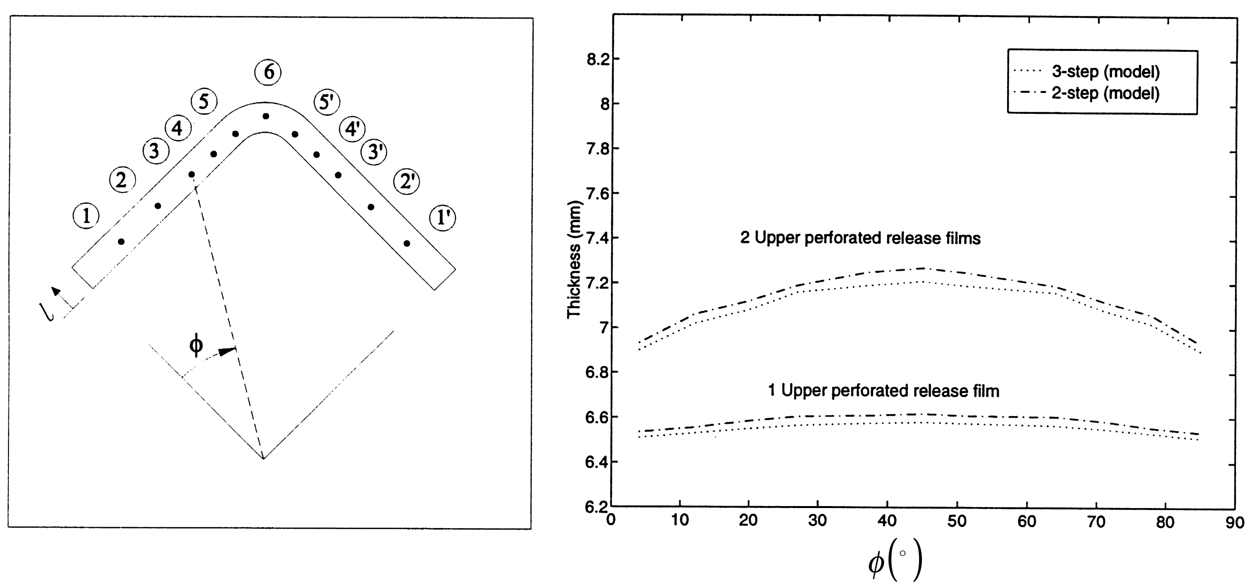

Figure 1: Thickness variation along curved parts processed with the recommended 2-step and 3-step cure cycles [7].

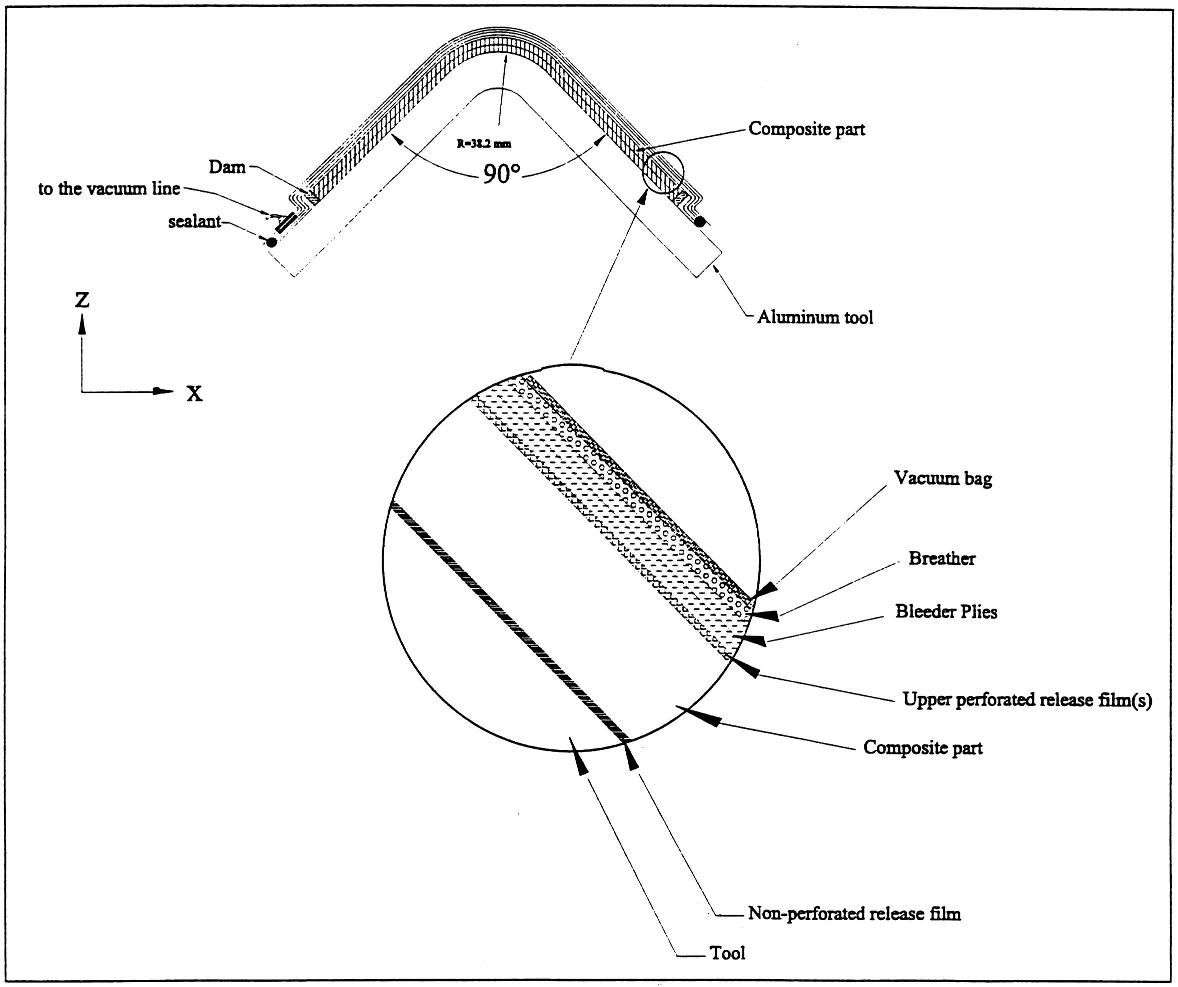

Figure 2: The laminate geometry and lay-up sequence used.

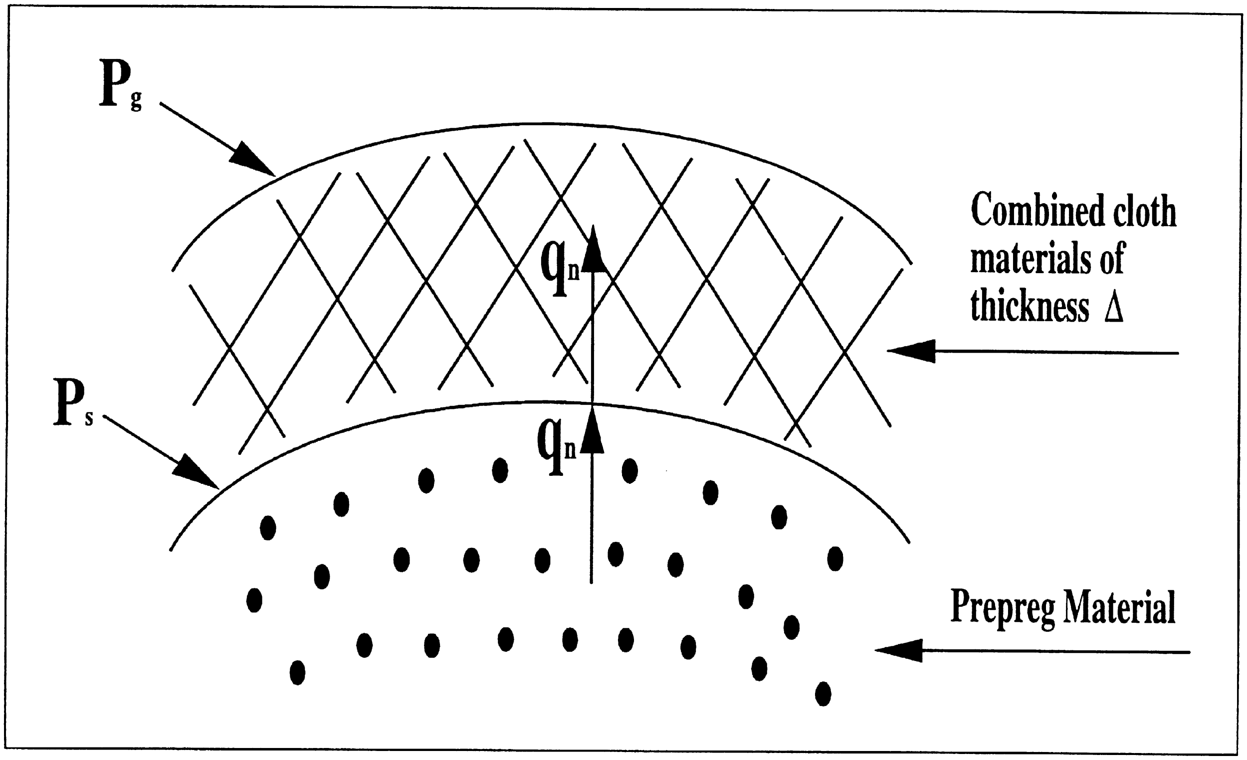

Figure 3: Resin flow out of the laminate through the combined release, bleeder and breather materials.

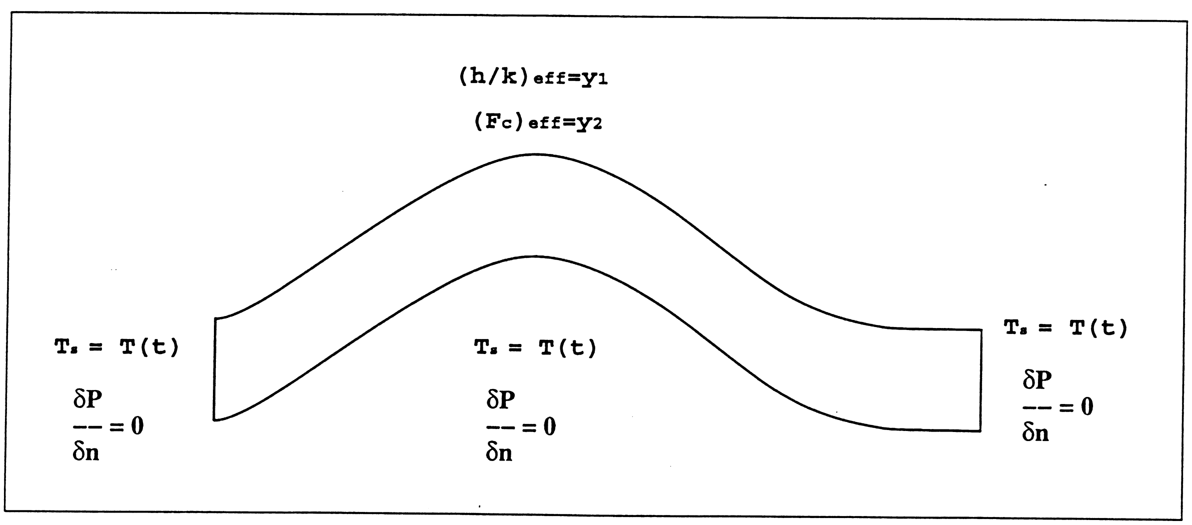

Figure 4: Temperature and pressure boundary conditions.

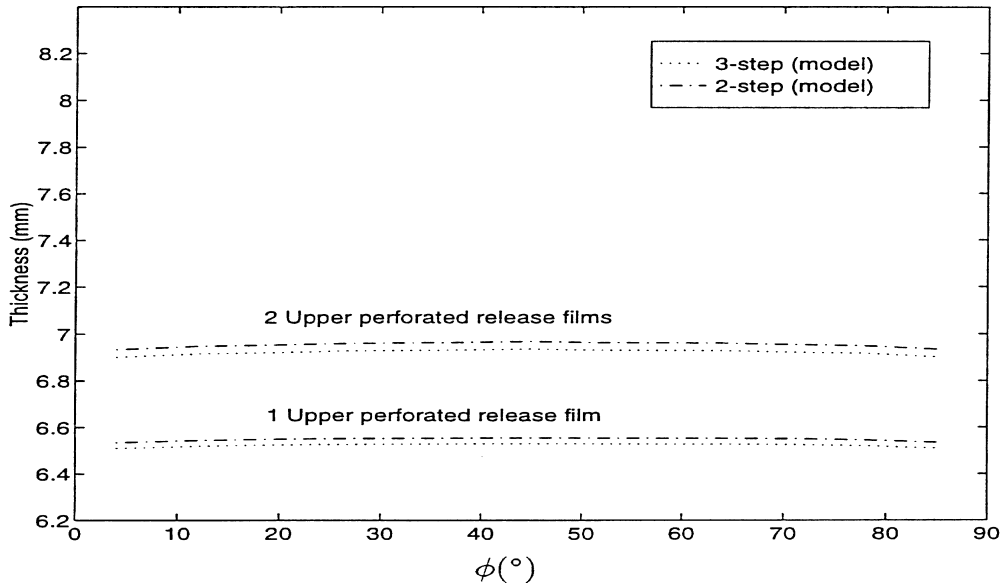

Figure 5: Thickness variation along the curved part for Case (I).

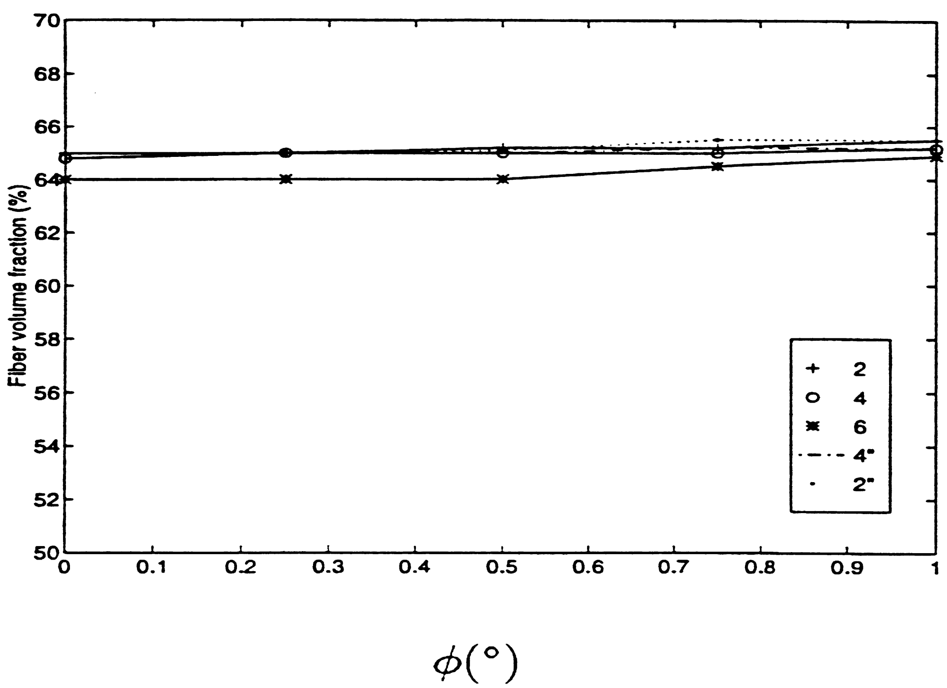

Figure 6: v_f variation across the thickness obtained from experiment for the 2-step modified process.

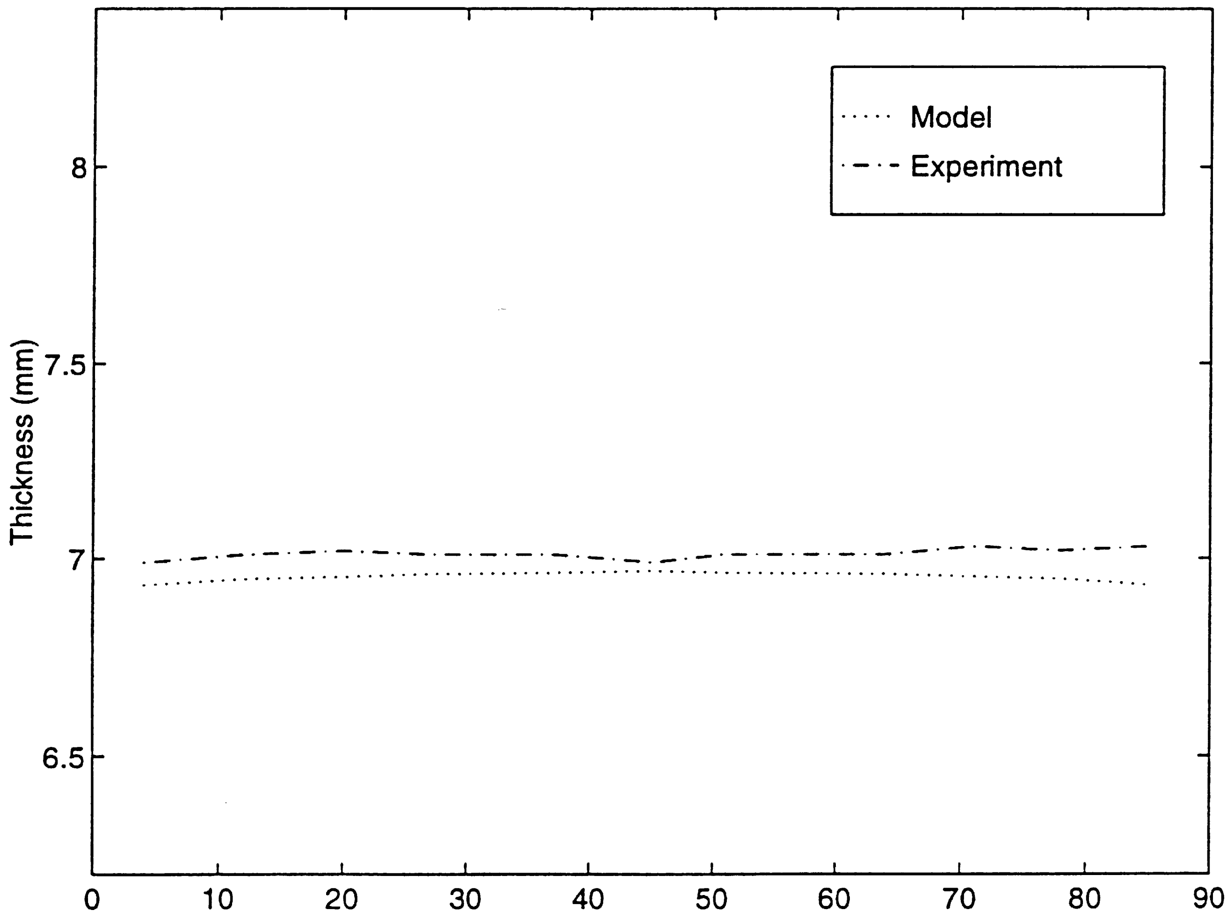

Figure 7: Thickness variation along the laminate length obtained from the 2-step modified. cure process Case (I) experiment.