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Paper Title: **VARTM Process Modeling of Aerospace Composite Structures**

Authors: Xiaolan Song[†], Brian W. Grimsley[††], Pascal Hubert[†††], Roberto J. Cano[††], and Alfred C. Loos[†]

[†] Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

[††] NASA Langley Research Center, Hampton, Virginia 23681

[†††] McGill University, Montreal, Quebec H3A2K6

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ABSTRACT

A three-dimensional model was developed to simulate the VARTM composite manufacturing process. The model considers the two important mechanisms that occur during the process: resin flow, and compaction and relaxation of the preform. The model was used to simulate infiltration of a carbon preform with an epoxy resin by the VARTM process. The model predicted flow patterns and preform thickness changes agreed qualitatively with the measured values. However, the predicted total infiltration times were much longer than measured most likely due to the inaccurate preform permeability values used in the simulation.

Keywords: VARTM, resin flow, compaction, simulation

INTRODUCTION

Vacuum assisted resin transfer molding (VARTM) has shown potential to significantly reduce the manufacturing cost of aerospace composite structures. Recent studies have demonstrated that carbon fiber preforms can be resin infiltrated by the VARTM process and cured to produce void free structures with fiber volume fractions approaching 58%.

The manufacture of composite structures by the VARTM process requires the specification of a vast array of molding and processing parameters. Use of experimental trial-and-error methods to determine these parameters would be both time consuming and costly. Over the years, process simulation models have been shown to be cost-effective tools for analytically determining the molding and processing variables that will result in the fabrication of well consolidated and void free composite structures that are cured to the desired fiber volume fraction. In the present investigation, a finite element simulation model of the VARTM process was used to assess the effects of material properties, molding conditions and processing variables on resin infiltration. The model contains one, two and three-dimensional elements, which can be assembled to describe the geometry of a complex shape composite structure. For a specified temperature-pressure-time processing cycle, the model can be used to predict the resin flow front position, resin pressure distribution and thickness changes in the preform during infiltration, and the total infiltration time.

Carbon fiber preforms were resin infiltrated in an instrumented tool, which contained sensors to measure pressure and displacement during the VARTM process. Preforms with different layer

† Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
†† NASA Langley Research Center, Hampton, Virginia 23681
††† McGill University, Montreal, Quebec H3A2K6

thicknesses were infiltrated to examine the effects of compaction. For all experiments, the resin pressure and the total panel thickness were monitored at different locations in the preform during the infiltration process. The flow front positions on the top and bottom surface of the preform were also measured.

Resin infiltration of the preforms was simulated using the VARTM process simulation model. To assess the accuracy of the model, the predicted flow patterns and the changes in preform thickness during resin infiltration are compared with the values measured in the experiments.

VARTM SIMULATION MODEL

Previous Work

The resin infusion process in VARTM is similar to the mold filling process in RTM, but the following two issues must be considered: the effect of high-permeable distribution medium on the resin flow field, and the compaction and relaxation behavior of the preform.

Tari et al. [1] developed a closed-form solution for the location of the flow front as a function of time. This study showed that the use of distribution medium creates a transverse flow in the fiber mat and thus greatly reduces mold filling time. The importance of the distribution medium in mold filling was also estimated by Sun et al. [2] using experiments. The experimental results showed that the use of the distribution medium reduced the filling time by 85%. Sun et al. employed a 3D control volume/finite element model for the numerical simulation of the resin infusion process. The numerical results for the filling time compared well with the experimental measurements. Neglecting the in-plane resin flow in the preform, the authors presented a leakage flow model to consider the flow as a 2D in-plane flow in the distribution medium with a sink term to account for the resin leaking into the preform. The leakage flow model reduced the computational cost significantly and yet provided reasonable estimate of the mold filling time.

Due to the flexible nature of the vacuum bag used in VARTM process, there is no direct control over the thickness or fiber volume fraction of the composite part, which is governed by the compaction and relaxation of the preform. Williams et al. [3] performed a preliminary experimental study of fabric compression during VARTM process. The compaction of the reinforcement was found to be very complex. An initial reduction in thickness under the vacuum was observed. The presence of the flowing resin appeared to have a lubricating effect and resulted in a further compaction. However, since the net pressure on the laminate fell after the passage of the resin, the preform thickness subsequently increased. Detailed knowledge about the response of reinforcing fabrics subjected to compressive forces is very important to investigate this dynamic compaction behavior of the preform. However, the research works in reinforcement compaction were mainly carried out for the RTM process where the compaction pressure goes up to 1 MPa, and only a few investigations [4, 5, 6] about compression behavior of the reinforcement during VARTM, i.e., under low compaction pressure ($\leq$ 1 atm) were published. It was found that by mechanically loading and unloading the preform, a maximum fiber volume fraction may be attained prior to applying vacuum pressure for resin infusion. Under the same pressure, the fiber samples saturated with resin are compacted more than the dry reinforcements due to the lubrication effect of the resin. Hammami and Gebart [6] proposed a 1-D model to simulate the VARTM process considering both the resin flow and the compaciton of the preform. In this model, Darcy's law and continuity equation were used to model the resin flow, and an equation of transverse equilibrium was introduced to take into account the compaction of the preform under the vacuum force. Compared with the infusion experiments, the model obtained a good estimate of the total filling time for VARTM process. However, the authors did not present any results about the thickness change of the preform during infusion process.

VARTM Model Formulation

The VARTM process consists of two important mechanisms: flow of the resin through the preform, and compaction and relaxation of the preform under the vacuum force. Correspondingly, flow model and compaction model are developed to simulate the VARTM fabrication process of the composites.

The flow model is developed to track the flow of the resin through the distribution medium and the preform. Both the high-permeable distribution medium and the preform can be modeled as heterogeneous and anisotropic porous media. The resin fluid is assumed to be Newtonian and incompressible. Assuming that the flow is quasi-steady-state, the governing equations for the flow problem are the continuity equation for an incompressible fluid, and Darcy's law of flow through a porous medium:

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

$$\vec{v} = \frac{\vec{q}}{\phi} = -\frac{S}{\phi\mu}\nabla P_r \tag{2}$$

where $\vec{v}$ is the interstitial velocity vector of the resin, $\vec{q}$ the superficial velocity vector, ϕ the porosity of the porous preform, μ the viscosity of the fluid, S the permeability tensor of the preform, and P_r is the resin pressure.

The boundary conditions necessary to solve the governing equations are:

- A flow front pressure condition: $P_{r_{flow\ front}} = 0$
- A constant pressure condition at the inlet: $P_{r_{inlet}} = \hat{P}_r$
- The velocity normal to the mold wall is zero: $\vec{v} \cdot \vec{n} = 0$, where $\vec{n}$ is the vector normal to the boundary wall.

In addition to the governing equations deriving the flow model, i.e., Darcy's law and the continuity equation, a new equation is introduced to account for the transverse equilibrium inside the mold cavity during impregnation:

$$P = P_r + P_n \tag{3}$$

where P is the total compaction pressure ($\approx 1\text{atm}$), P_r is the resin pressure, and P_n is the net pressure applied on the preform.

At each time step, after the calculation of resin pressure distribution, the net pressure applied on the preform is computed using eqn. 3. Then the normal strain in the transverse direction, ε, could be obtained from the curves of strain .vs. compression pressure, which are the results of the compaction test. With the initial fiber volume fraction of the preform (V_{f0}) and thickness of the panel (t_0) given, the fiber volume fraction V_f and displacement (w) could be found by the eqn. 4 and 5, respectively.

$$V_f = \frac{V_{f0}}{1+\varepsilon} \tag{4}$$

$$w = \varepsilon \cdot t_0 \tag{5}$$

The flexible nature of the vacuum bag coupled to the varying pressure inside the mold cavity results in the fiber volume fraction change of the preform during the impregnation process.

Accordingly, the permeability of the preform changes and influences the resin flow in the preform. The resin flow model and the compaction model are coupled together as a comprehensive VARTM simulation model.

Compaction Test

The relationship between the strain in the preform and pressure applied was obtained by fitting the compaction test data. In this study, compaction tests were conducted to develop an understanding of the response of the SAERTEX fabric under the low pressure experienced during VARTM process. The test results are shown in Fig. 1. Because of the resin's lubrication effect, the compression response of the wet fibrous preform was found to be quite different from that of the dry fiber mat. The hysteresis phenomenon was observed during unloading process. During the VARTM infusion process, before the flow front passes by, the dry reinforcement is under the vacuum compression and the strain of the preform can be calculated from the compaction response of the dry preform during loading process. After the resin passes by, the local net pressure applied to the preform decreases as a result of increasing resin pressure. This is equivalent to an unloading process. Accordingly, the strain in the wet preform is determined by compaction response of the resin saturated preform during unloading process. The equation of preform strain as a function of pressure for 4-stack of SAERTEX unstitched multiaxis warp knit fabric is shown in equation 6.

$$\varepsilon = \begin{cases} 0.22(1-\exp(-0.026P_n)) & \textit{dry compaction, loading} \\ 0.028 + 0.20\dfrac{P_n}{1.87+P_n} & \textit{wet compaction, unloading} \end{cases} \qquad (6)$$

where ε is the strain of the preform, and P_n is the net pressure applied to the preform.

SIMULATION RESULTS

In this study, the VARTM of composite panels using SAERTEX multi-axial non-crimp carbon fiber fabric and the SI-ZG-5A epoxy resin was studied. Two flat panels (60 cm by 30 cm) with different thickness were fabricated. Panel 1 contained one stack of fabric while Panel 2 contained four stacks of fabric. The resin viscosity was 0.23 $\mathrm{Pa \cdot s}$. Three layers of nylon mesh screen were laid on the top of the preform to serve as the distribution medium. The media was cut smaller than the preform allowing a 1.3 cm gap between the edge of the media and the edge of the preform along the length. The distribution medium ended at a distance of 2.5 cm before the end of the preform. These gaps prevent the race-tracking of the resin as it flows through the media and the preform. In the experiments, Linear Variable Displacement Transducers (LVDT) were installed to monitor the thickness change of the panels at three different locations: 3.8 cm away from the end near inlet, center of the panel, 3.8 cm away from the end near the outlet. Details of the experimental study are given in reference [7].

The numerical model, 3DINFIL was used to simulate the fabrication process. Fig. 2 and Fig. 3 show the flow front shapes on the top and bottom surface of the thin and thick panel, respectively. Note that the flow is much slower along the edges of the panel because there is no distribution medium. The flow front positions as a function of time are presented in Fig. 4 and Fig. 5. The flow front on the top surface leads the resin front on the bottom surface. Larger lag was observed for the thicker panel. The model predicted that Panel 1 and Panel 2 should be filled at 394 and 657 seconds, respectively. However, the experimental measurements of the infiltration times were 134 and 239 seconds for Panel 1 and Panel 2, respectively. The difference is attributed to two factors. First, the infiltration time was difficult to measure accurately in the experiment. Second, the values of the preform permeability used in the simulation were measured at constant flow rate which may not truly

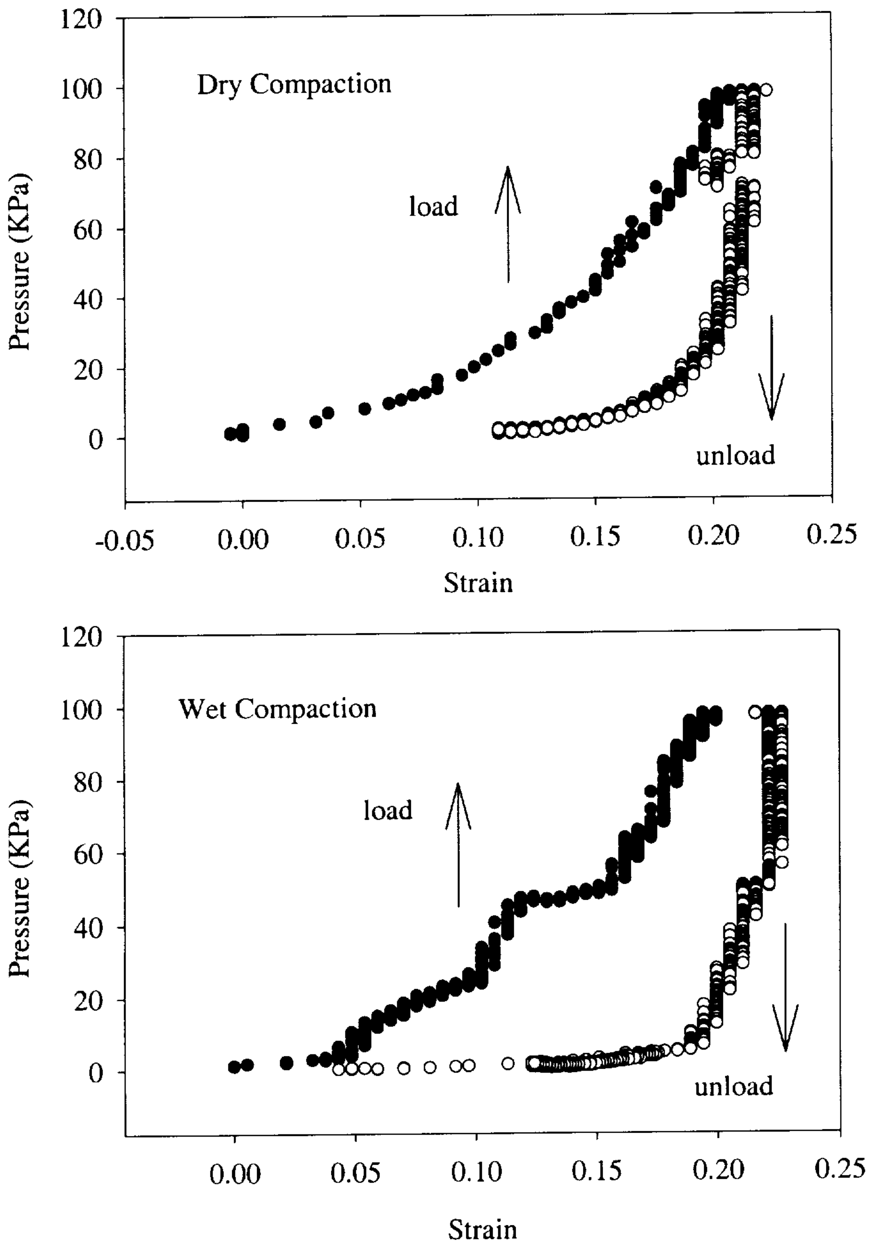

Figure 1 Compaction test results for SAERTEX fabric.

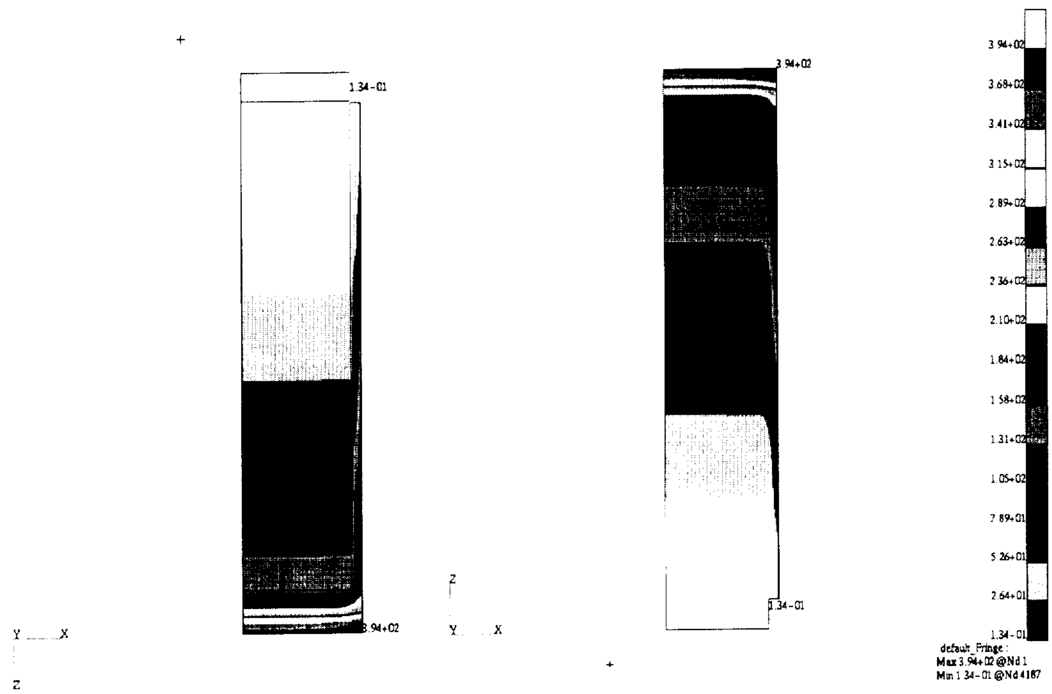

Figure 2 3DINFIL predictions for flow along the top (left) and bottom (right) surfaces of Panel 1.

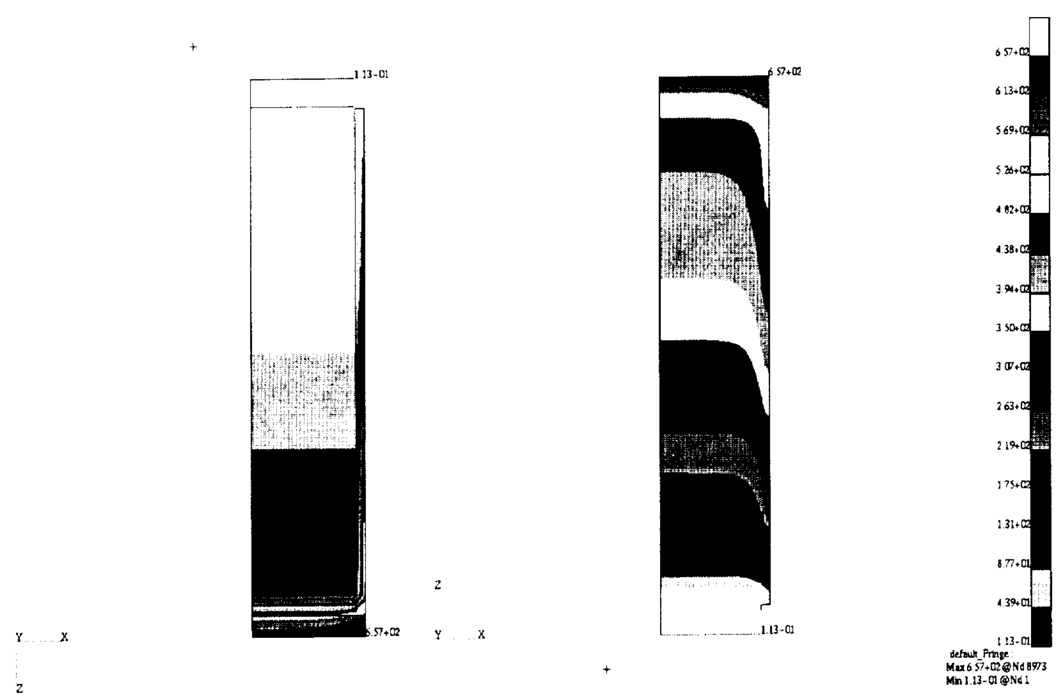

Figure 3 3DINFIL predictions of flow along top (left) and bottom (right) surfaces of Panel 2.

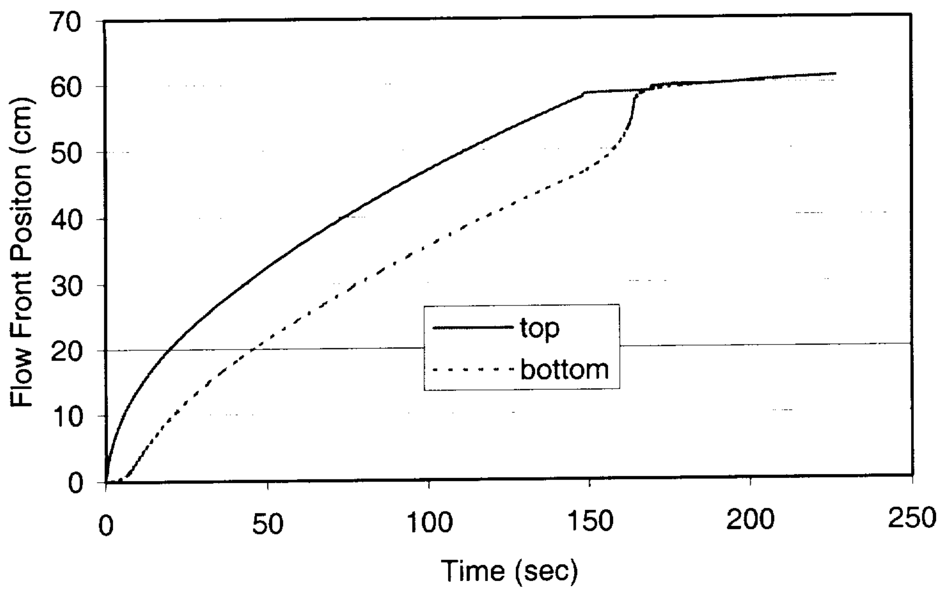

Figure 4 Predicted flow front position as a function of time for Panel 1.

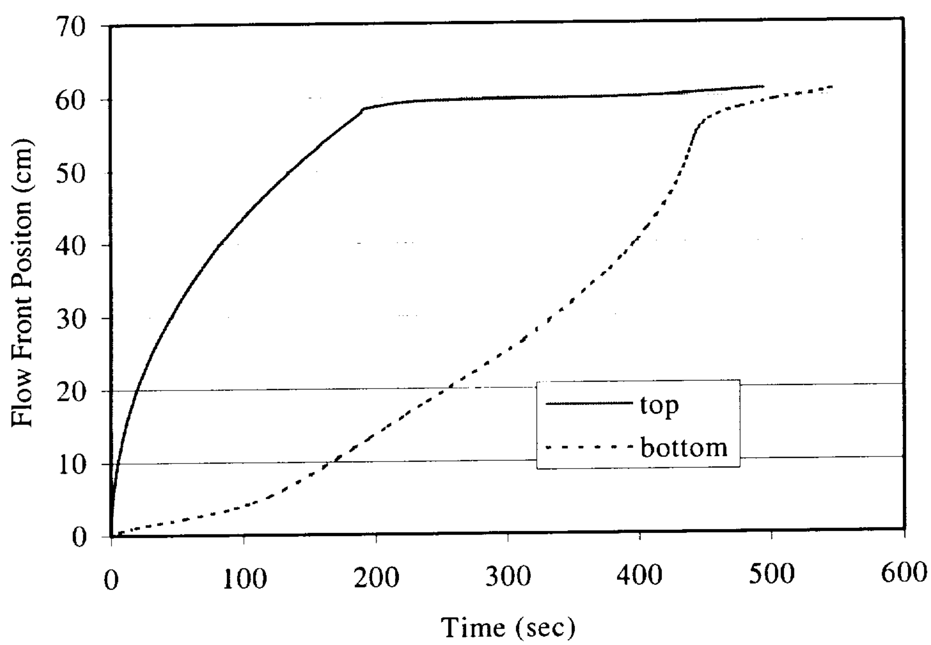

Figure 5 Predicted flow front location as a function of time for Panel 2.

represent the VARTM flow conditions. The preform permeability varying with the preform thickness change during impregnation is the subject of further investigation. Fig. 6 shows the predicted transverse displacement of Panel 2 during the infusion process. The thickness change of the preform was tracked at the three LVDT positions. It was found that the amount of the displacement increases when it approaches the end near the outlet. This indicates that the panel is less compacted on the resin inlet side and more compacted on the vacuum side. This phenomenon was also observed in the experiment. The measured displacement of Panel 2 using LVDTs is shown in Fig. 7. The predicted thickness change agrees well with the experiment measurement qualitatively. Before the resin flows into the mold, the dry preform is compacted under the vacuum pressure. After the flow front approaches, the preform becomes wet and is further compacted due to the lubrication effect of the resin. On the other hand, the local resin pressure increases with the progression of the flow front. This leads to the decrease of net pressure applied to the preform. Therefore, after the maximum displacement is reached, the displacements decrease as a result of decreased compression force.

CONCLUSION

In this study, a comprehensive model was developed to simulate the VARTM process. The model can be used to simulate the resin flow in the distribution medium and preform, track the thickness change of the preform, and predict the infiltration time and final thickness of the composite parts. Using the simulation model, the VARTM of two flat panels was investigated. The model predictions for the flow pattern and the thickness changes of the preforms were qualitatively accurate although the predicted total infiltration times were much larger than measured. This can be attributed to the inaccurate input of preform permeability value. The investigation of the preform permeability is under progress.

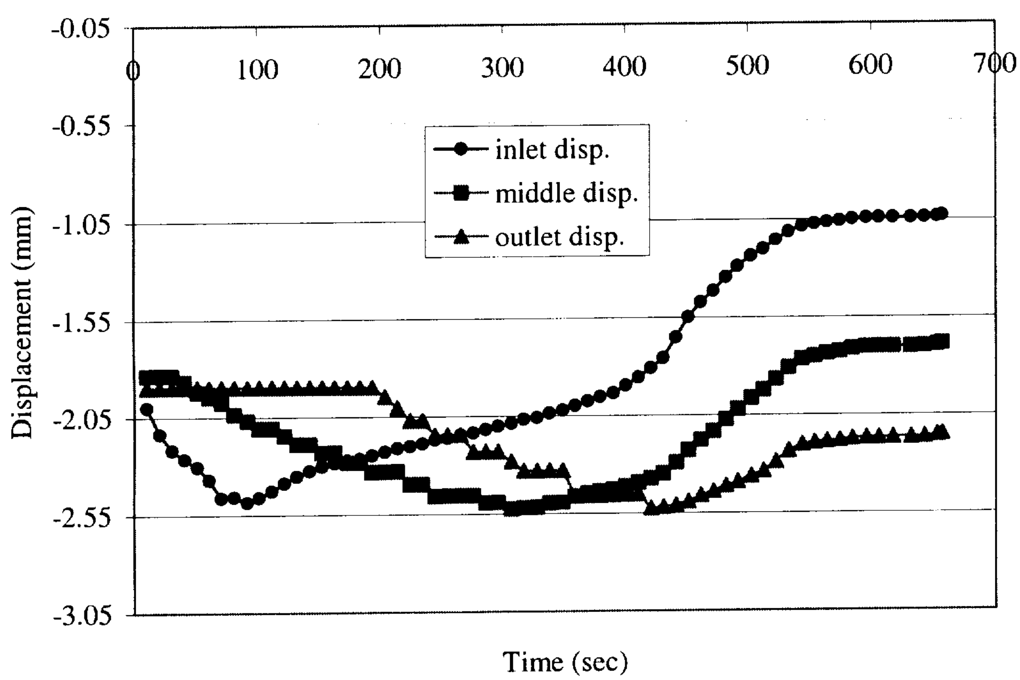

Figure 6 Predicted transverse displacement for Panel 2.

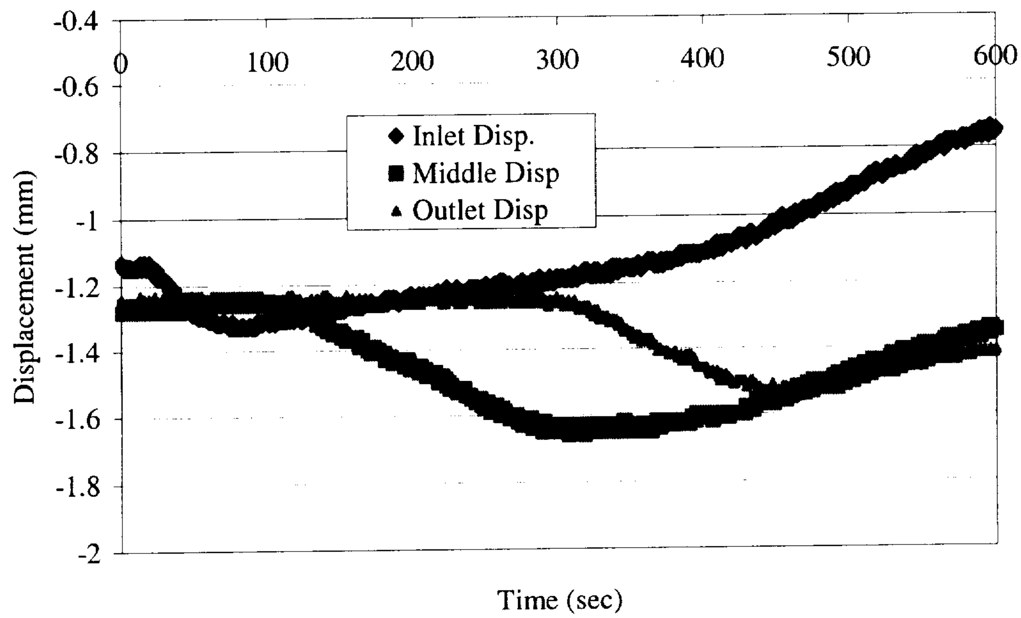

Figure 7 Measured transverse displacement of Panel 2.

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