# MEASUREMENT OF MANUFACTURING DISTORTION IN FLAT COMPOSITE LAMINATES

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**SUMMARY:** Distortion in composites during manufacture has been noted by many authors and has been attributed to numerous sources. Past efforts have shown manufacturing distortion in complex shaped components to be related to the anisotropy introduced by differences in the in-plane and through-thickness properties. However, this explanation does not account for all distortions observed, and in particular, does not explain distortion in flat laminates. To further understand the sources of manufacturing distortion in flat laminates experiments measuring the distorted shape, at both room temperature and elevated temperatures, have been performed. The factors evaluated include the tooling material, the interaction between the tool and the composite, and the degree of resin bleed during processing. It is observed that varying the interaction between the tool and composite significantly effects the degree of distortion, as does the amount of resin bled. Further, results indicate that the major portion of the distortion in these flat laminates is not affected by changing measurement temperature.

**KEYWORDS**: Distortion, Warpage, Composites Manufacture, Part/tool interaction, Volume Fraction Gradient, Quantitative Optical Microscopy

## INTRODUCTION

Autoclave processing is a proven source of high performance, reproducible composite parts; yet, with many years of process development, difficulties continue to arise during the creation of complex composite parts requiring a precise, specified shape. In curved composite "angle brackets", manufacturing distortion results in a change in included angle that is often referred to as "spring-in". Such manufacturing distortion results from the internal balancing of process-induced residual stresses [1] and can be severe, leading to out-of-tolerance dimensions and rejected parts or even difficulty extracting the part from the tooling [2]. Spring-in results in closure of a curved composite included angle, as predicted by a number of authors during the last decade. This distortion has been suggested to be primarily related to differences in the composite material properties, and responses, in the in-plane and through-thickness directions to the change in temperature from the process conditions to room temperature. This is probably the most commonly described source of distortion [3,4,5]. Examples of components where "spring-in" has been measured include wing leading edges [6], U-channel cross-sections [7], and waveguides [3]. In addition, this same anisotropy mechanism of distortion has been shown to result in permanent warpage related to cure shrinkages in thermoset matrix composites. Thus, distortion can be categorized as either thermoelastic (reversible), relating to coefficient of thermal expansion (CTE) contributions, or as non-thermoelastic (irreversible), relating to isothermal cure shrinkage and other manufacturing induced contributions [8].

Unfortunately, in many cases, the measured distortion exceeds that predicted based solely on the anisotropy of the composite. This leads to the continued discussion of other possible mechanisms of distortion, including mechanisms which predict process related warpage, even in nominally flat laminates [9,10,11]. Two such mechanisms are related to through-thickness gradients in laminated composites. The gradients can be either material property variations or changing residual stresses. Material property gradients, in the form of through-thickness volume fraction ($V_f$) variation, have been measured and related to the top bleed process often used in laminate consolidation [11,12,13]. Further, residual stress gradients have been suggested to result from interactions of the laminate and tool surface during cure [10,14].

These two mechanisms, not related to anisotropy, have inherent differences related to the interaction with temperature. Volume fraction gradients lead to changing shape with both temperature and isothermal cure shrinkage, while residual stress gradients are not expected to respond to temperature. Therefore, it is predicted that material property gradients will result in both thermoelastic and non-thermoelastic contributions to distortion, while part-tool interaction will generate only non-thermoelastic warpage. Thus, for geometries such as flat laminates, no distortion due to anisotropy should be expected and the relative contributions of the volume fraction gradient and part-tool interaction should be able to be separated, based on the differing response to temperature of these two mechanisms.

This research investigates the distortion observed in flat laminates with the goal of separating the distortion related to temperature change from the warpage that is independent of temperature. Since $V_f$ gradients are expected to respond to both the thermoelastic and non-thermoelastic components, while part-tool interaction is expected to show only a non-thermoelastic contribution, the separation of components will also result in information on the relative magnitude of these two mechanisms of distortion.

## EXPERIMENTAL MEASUREMENT OF DISTORTION

Thin, symmetric, carbon fiber/epoxy laminates were autoclave-processed using a variety of subtle process variations which were planned to effect not only the total distortion, but also the relative thermoelastic and non-thermoelastic contributions. Variations included the amount of bleeder material, the type of mold release, and the tooling material. A coordinate measurement apparatus was developed which enables three-dimensional surface mapping at temperatures up to 200°C. This allows measurement of both thermoelastic and non-thermoelastic components of distortion through contour mapping over a range of temperatures. The data was evaluated by comparing the curvatures and curvature changes measured for each laminate. In conjunction with these distortion maps, continuous $V_f$ gradients were measured using a new quantitative optical microscopy technique that is based on the location of each fiber center in a series of through-thickness laminate slices.

## Experimental Apparatus

*Panel Contour Mapping System*

To perform measurements of composite laminate distortion over a range of temperatures a custom panel contour mapping apparatus was developed and is shown in figure 1. The apparatus utilizes an oven, containing the specimens, that moves in the X-Y plane under an insulated glass plate allowing the operator to observe and control the motion (figure 2). A Linear Voltage Displacement Transducer (LVDT) generating a voltage proportional to the out-of-plane displacement is in contact with the specimen and the probe is counterbalanced to minimize the contact force. All data is automatically collected using computerized data acquisition. The oven size can accommodate 30.5 cm x 30.5 cm square specimens with out-of-plane distortions up to 7.6 cm as shown in figure 3. A temperature controller regulates power to a heating element and maintains the specimen at desired temperatures. A small electrical fan is installed to ensure a uniform thermal environment.

This apparatus developed allows the contour of a panel to be measured at temperatures ranging from room temperature to 200°C. The data to generate the surface map is obtained isothermally, in multiple passes over the specimen surface, creating a set of Z-data corresponding to positions on an X-Y grid over the specimen surface. Data is post processed and contour maps representing the data, and thus the shape at each temperature, can be plotted as shown in figure 4. This information can be further manipulated to determine information such as the curvature and the change in curvature, which are used in this research.

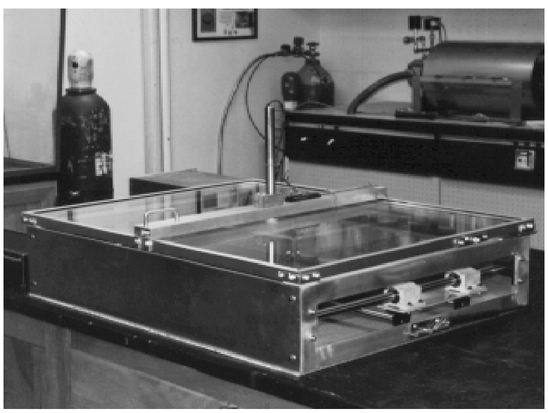

*Figure 1 Panel Distortion Test Apparatus*

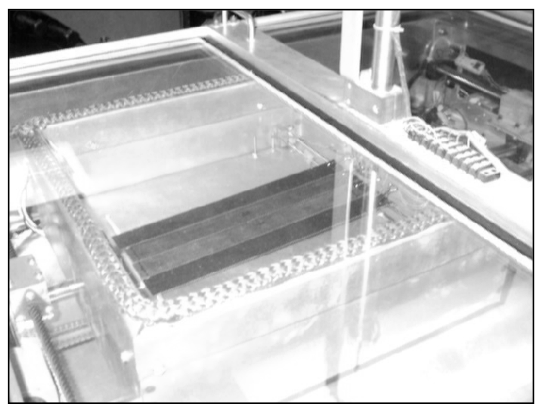

*Figure 2 Specimens measured under glass*

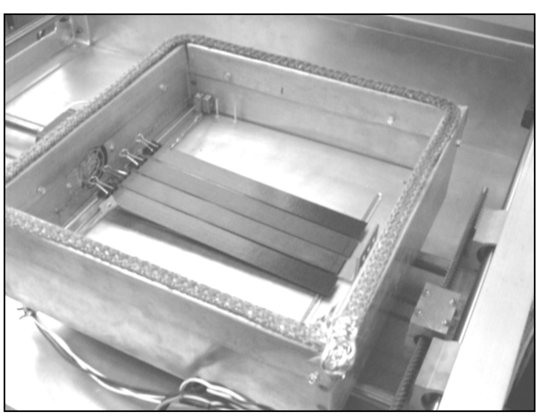

*Figure 3 Oven detail exposed*

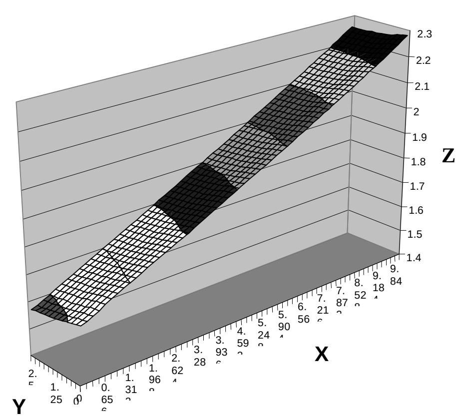


*Figure 4 Typical Contour Map Generated*

*Quantitative Measurement of Volume Fraction Gradient*

To investigate distortion due to gradient microstructures generated by changes in processing conditions it was necessary to measure the relative amounts of resin and fiber through the laminate thickness. The measurement of the continuous variation in volume fraction through the specimen thickness was accomplished by using a quatitative optical microscopy system and Optimas software. Macros and an operational technique were developed which enable the determination of the coordinates of the center of each fiber in the field of view. This mapping of the fiber center coordinates can then be used to determine changing volume fraction with through-thickness position. The approach allows a much better approximation of changes in volume fraction than previous methods which were based on the measurement of volume fractions in discrete steps through the laminate [11,12].

## Experimental Approach and Materials Used

Carbon fiber/epoxy specimens were produced from 121°C cure, unidirectional prepreg tape. These specimens were 4 plies, with a stacking sequence of $[0/90]_S$, and were cut to nominal dimensions of 25 mm x 250 mm. The specimens were produced using several manufacturing variations that were chosen to test the effect of "part-tool" interaction and "gradient material properties". To further investigate "part-tool" interaction tooling plates of steel, aluminum and ceramic were used. Dilatometer testing was used to determine the coefficient of thermal expansion (CTE) of each of the tool materials over the temperature range of interest. It was found that the CTE for the ceramic was the lowest, at 5.82μm/m/°C, followed by steel at 12.0μm/m/°C and then aluminum at 22.7μm/m/°C. The different tool materials were tested to evaluate different levels of thermal strain introduced into the laminate by the tool.

Two different mold releases were included in an attempt to evaluate the role of stress transfer from the tool to the part during processing. These mold releases were 1) spray-on PTFE and 2) non-porous PTFE release film. To evaluate effects related to the amount of resin bled during cure, three cases were tested, which were 1) no bleeder, 2) one bleeder ply and 3) two bleeder plies. In the specimens with no bleeder, the same non-porous film described above was placed on top of the laminate. For the specimens that utilized the Whatman 2 filter paper bleeder, a porous PTFE release ply was included directly in contact with the top surface of the laminate, beneath the bleeder.

Tables 1 and 2 summarize the tests performed. Ten specimen variations were produced, and each case included three repetitions. A single complete set of specimens was produced in an individual autoclave run, with the three repetitions requiring three separate autoclave cures.

*Table 1 - Part-Tool Interaction Test Matrix*

| **NO BLEED** | Spray | Film |
|---|---|---|
| Aluminum | X | X |
| Ceramic | X | X |
| Steel | X | X |

*Table 2 - $V_f$ Gradient Test Matrix*

| **ALUMINUM** | Spray | Film |
|---|---|---|
| No Bleeder | X | X |
| 1 Bleeder ply | X | X |
| 2 Bleeder plies | X | X |

Groups of specimens were placed in the panel mapping apparatus and measured at room temperature (27°C) and then at 20°C increments to a maximum temperature of 127°C. The contour data was used to determine specimen curvatures, with changes in curvature with temperature indicating a thermoelastic contribution, while the distortion measured independent of temperature is the non-thermoelastic contribution. Specimens representative of the three different bleeder cases and the two release types were sectioned, polished and measured using quantitative microscopy to evaluate volume fraction gradients.

## RESULTS AND DISCUSSION

The data collected was separated into two sets as shown in figures 5 and 6, matching the previously described test matrices of Tables 1 and 2, to more readily evaluate the results.

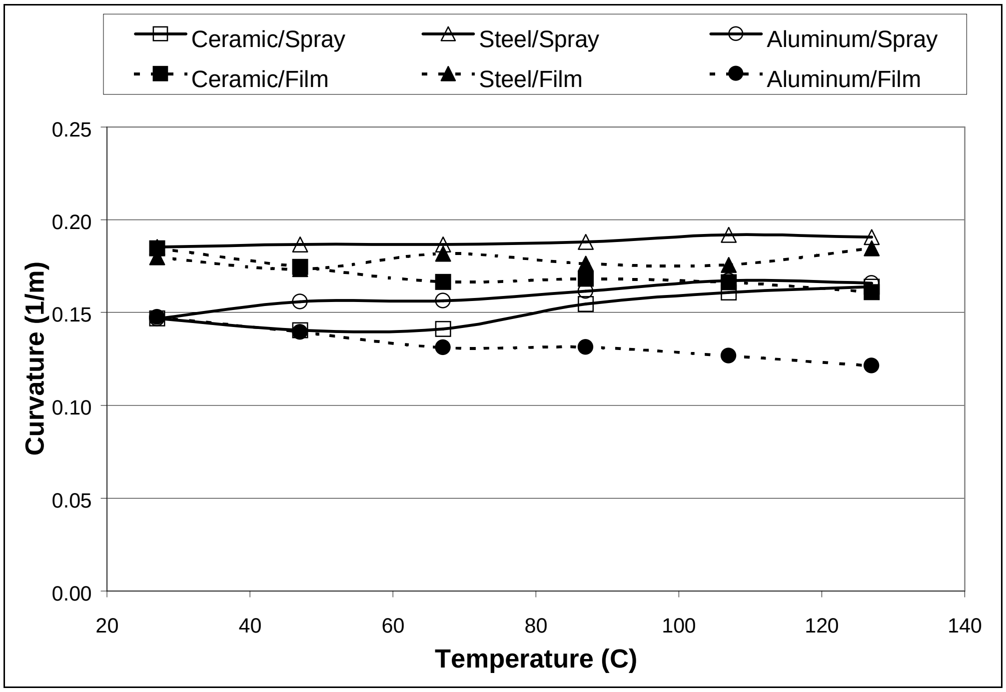


*Figure 5 Effects of Tool Material and Release Method*

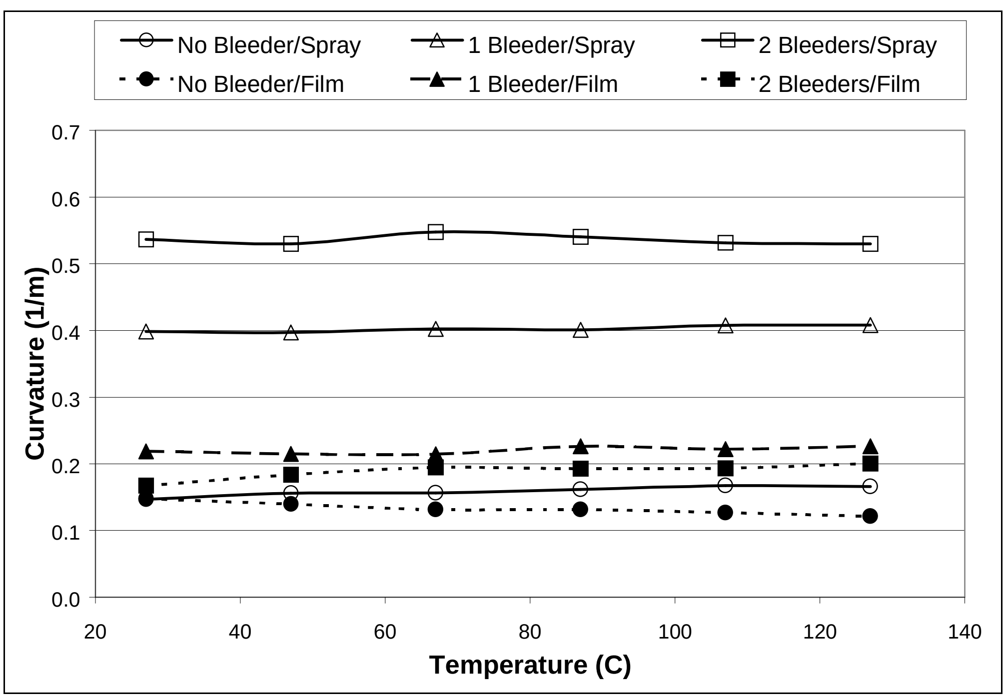


*Figure 6 Effects of Bleeder and Release Method*

The first set of results, presented in figure 5, shows the effects of tooling material variation and of the two mold release methods tested. The chart relates the measured curvature to temperature for the cases described in Table 1. The data represents the average values of the results from the second two sets of specimens produced. The first set of specimens were poorly consolidated due to a loss of pressure during the autoclave run and were therefore not included in the graphs nor the data. The second set of results, corresponding to the test matrix of Table 2, is presented in figure 6 and displays the effects of variations in bleeder and part-tool interaction while standardizing on aluminum tooling. The difference in scale of the curvature data between figures 5 and 6 must be noted. It was necessary to plot the data on different scales because of the small range of curvature data found for all specimens that were not bled during cure. For reference the cross-over data for the case of aluminum tooling and no bleeder can be compared on the two plots.

**Thermoelastic Contribution**

The data for curvature versus temperature, as seen in figures 5 and 6, show only weak trends as indicated by slight differences in the slope of the curves, and therefore little thermoelastic contribution to distortion can be determined solely from the plotted data. Based on the assumption that the thermal expansion coefficients remain relatively constant over the temperature range of interest, a linear regression was applied to the data to determine slopes which should be indicative of the thermoelastic contributions. These results are presented, numerically, in Tables 3 and 4. In addition, the room temperature curvature, predicted from the linear regression, is also shown in Tables 3 and 4. For the "no bleed" cases in Table 3 the thermoelastic slope seems to be consistently more positive for the PTFE sprayed tools then for the parts and tools separated by the layer of non-porous film. Further, the steel tooled specimens seem to show notably smaller thermoelastic effects.

*Table 3 - Part-Tool Interaction Test Results*

| **NO BLEED** [Slope ($m^{-1}$/C)] [Curvature ($m^{-1}$)] | Spray | Film |
|---|---|---|
| Aluminum | $+1.93\text{x}10^{-4}$ | $-2.32\text{ x}10^{-4}$ |
| | 0.144 | 0.152 |
| Ceramic | $+2.28\text{ x}10^{-4}$ | $-2.02\text{ x}10^{-4}$ |
| | 0.134 | 0.186 |
| Steel | $+0.61\text{ x}10^{-4}$ | $+0.37\text{ x}10^{-4}$ |
| | 0.183 | 0.176 |

*Table 4 - $V_f$ Gradient Test Results*

| **ALUMINUM** [Slope ($m^{-1}$/C)] [Curvature ($m^{-1}$)] | Spray | Film |
|---|---|---|
| No Bleeder | $+1.93\text{x}10^{-4}$ | $-2.32\text{ x}10^{-4}$ |
| | 0.144 | 0.152 |
| 1 Bleeder ply | $+1.12\text{ x}10^{-4}$ | $-1.02\text{ x}10^{-4}$ |
| | 0.394 | 0.213 |
| 2 Bleeder plies | $-0.55\text{ x}10^{-4}$ | $+2.76\text{ x}10^{-4}$ |
| | 0.540 | 0.167 |

For the tests which involved the variation in the amount of bleeder there is a clear trend toward decreasing thermoelastic slope with increased bleeder for the spray release specimens. For the specimens manufactured with the PTFE film between the specimen and the tool the trend is the opposite and this total variation in slope is actually the greatest noted in any of the columns of Tables 3 and 4. Figure 7 compares the measured fiber distributions through the thickness of the two most extreme cases in Table 4, the "no-bleed/film" and the "2-bleeder/film" specimens. While differences are apparent between the volume fraction profiles for each bleed condition, and it seems clear that the volume fraction is weighted to opposite surfaces of the two cases, more development of this technique needs to be undertaken before a high level of confidence can be expected. Based on the argument that the only thermoelastic mechanism operating in these flat specimens is the volume fraction gradient, these results indicate that only a small change in fiber fraction is occurring. However, it does seem that there is a response of the thermoelastic slope, and therefore the volume fraction gradient, to the changing tool surface conditions which may be an important concept in ultimately overcoming distortion. Thus, the indication is that the volume fraction gradient contribution is small in these specimens and that the overwhelming majority of the non-thermoelastic contribution measured must be related to other mechanisms, such as part-tool interactions.

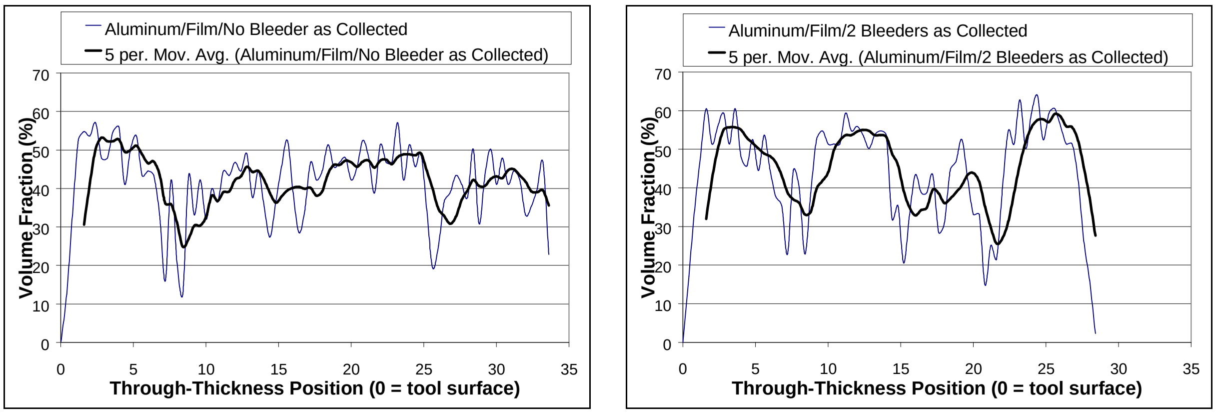


*Figure 7 Effect of Bleeder on Volume Fraction as Measured based on Fiber Centers*

**Non-thermoelastic Contribution**

While the trends for the thermoelastic contribution are not extremely strong, figures 5 and 6 and Tables 3 and 4 indicate significant non-thermoelastic distortions. The curvature varies measureably depending on the method of part-tool separation. For the specimens using the non-porous film to separate the part and the tool, the curvatures seem to be little affected by tool material choices or by the amount of bleeder. For all specimens except those processed with bleeder and spray release, on aluminum tooling, the curvature only ranges from 0.134 $m^{-1}$ to 0.213 $m^{-1}$. However, the curvature is strongly affected by the amount of bleeder, for the spray release on the aluminum tooling, as seen in Table 4.

Variations which were expected to be related to tooling material were not apparent and the small differences which were measured are not consistent with the relative values of the tooling material coefficients of thermal expansion. It does seem that the non-porous teflon film effectively isolates the curing laminate from the tool, minimizing the distortion generated, independent of the amount of resin bled during processing. However, for the spray release specimens the measured curvature varies from 0.144 $m^{-1}$ to 0.540 $m^{-1}$ as the amount of resin bled during cure is increased. While it is possible that this effect is the result of enhanced part-tool interaction with increased consolidation, such a result was expected to be principally tied to a volume fraction gradient mechanism. Yet, the existence of a strong volume fraction gradient component of distortion is not supported based on thermoelastic slope measurements discussed in the previous section. Thus, this strong correlation between amount of resin bled and curvature for the spray release cases, must be related to enhanced thermally induced strain transfer into the laminate from the tool. This enhanced strain transfer is suggested to be due to the more intimate fiber contact in the laminates with increasingly greater amounts of resin bled.

### Determining the Role of the Different Mechanisms of Distortion

As described in the introductory section, the most commonly suggested mechanism of distortion in curing composites, anisotropy, is not expected to play a role in distortion occurring in flat laminates. This leaves two principal mechanisms, material property gradients and stress gradients, to consider. Since the material property gradient mechanism, or more specifically for this effort the volume fraction gradient, is predicted to result in proportional thermoelastic and non-thermoelastic distortions, the lack of a large thermoelastic contribution indicates that the stress gradient mechanism is the controlling factor.

The part-tool interactions suggested previously have only non-thermoelastic character, and thus seem to control the distortion measured in these experiments. The indication is that the more strongly coupled the curing part is to the tool, the more of the strain induced from the differential thermal expansion will be transferred to the laminate. This increasing level of strain is expected to result in larger cured-in stress gradients and correspondingly greater non-thermoelastic curvatures. The trend is seen in the experimental results as the non-porous film seems to isolate the part from the tool, significantly reducing the distortion. The strong relationship between the degree of consolidation and the distortion is a further indication of the need to account for this mechanism of distortion during processing.

## FUTURE WORK

This experimental direction in the development of an enhanced understanding of distortion mechanisms holds much promise, both as an aid to determining the total distortion in more complex components and in predicting approaches to overcome manufacturing distortion. Future efforts will continue to enhance the abilities of the fiber volume fraction gradient technique. Further, it is of specific interest to perform a similar set of tests on non-aluminum tooling, with varying bleeder content, to determine if effects related to the different tool material thermal expansion coefficents can be measured.

## CONCLUSIONS

Both thermoelastic and non-thermoelastic distortion have been measured in flat, symmetric, carbon fiber reinforced epoxy composite laminates. Thermoelastic variations related to $V_f$ gradients through the laminate thickness were only a small contributor to the total curvature measured. The trends noted were quite weak and more detailed experiments will need to be performed to determine if the responses to temperature that were noted are reproducible. Since the thermoelastic contribution is expected to come totally from material property gradients, the relatively small changes in curvature with temperature indicate that the non-thermoelastic contribution of this mechanism will also be a relatively small amount. However, the fact that significant distortion does occur in these flat laminates supports the presence of distortion mechanisms other than anisotropy, and the ability to measure responses to changing $V_f$ gradients and to changes in part-tool interaction enables further separation of these other mechanisms.

Non-thermoelastic curvature, not related to material property gradients, was measured to be much more highly dependent upon the degree of interaction between the composite laminate and the tool surface than on the material of the tool. Greater consolidation, as induced by enhanced resin bleeding, had a large effect on the distorted shape, increasing the room temperature curvature from $0.144 m^{-1}$ to $0.540 m^{-1}$ as the number of bleeder plies was increased. It is suggested that as the consolidation is increased the thermal expansion induced strain transfer from the tool to the part increases due to lesser amounts of resin at the interface and tighter fiber-to-fiber packing. Decoupling the laminate from the tool, through the use of non-porous release film, resulted in a decrease in room temperature curvature from $0.540m^{-1}$ to $0.167m^{-1}$ for the most highly consolidated specimens. The use of the film essentially defeated the action of the increased consolidation. Thus, by separating thermoelastic and non-thermoelastic effects in flat laminates a greater understanding of the processing factors responsible for distortion may be determined which may ultimately lead to solutions to the manufacturing distortion problem.

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