Warpage of Large Curved Composite Panels due to Manufacturing Anomalies

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ABSTRACT

This paper discusses the influences of a misaligned layer, a resin-rich slightly thicker layer, and a small thermal gradient on the thermally-induced deformations of large curved composite panels during cooldown from their cure temperature. The deformations represent warpage of the panels due to anomalies that occur during layup, consolidation, and cure. Two-dimensional finite element analyses are used. The deformations are categorized as to their impact on circumferential and twist warpage metrics. The results are intended to highlight the sensitivity of manufactured panel shape to the various unwanted effects that can occur during manufacturing.

INTRODUCTION

When manufacturing flat and curved composite panels, the intention is to produce panels with specific geometric properties, i.e., length, width, radius of curvature, etc. Often, upon completion of the various stages of the manufacturing, and after the panel has cooled to room temperature and has been removed from the tool, hot press, or autoclave, the dimensions of the panel are generally not as intended. Focusing on curved panels, the lack of the proper radius of curvature and the presence of twist in the panel are among some of the problems. This lack of dimensional fidelity can be thought of, and is often spoken of, as a manufacturing distortion, or warpage. Distortion can be a serious problem because it means that panels must be forced to fit onto existing frames or stiffeners arrangements, or forced to fit with other panels to make up a complete structure. This forcing to achieve a fit can lead to unwanted stresses that result in fatigue or other stress-related problems and, in the case of production-level quantities, a lack of quality control.

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The paper will lead the reader through the mechanisms and considerations that account for some of the manufacturing distortions of curved composite panels. A very specific panel shown in Fig. 1 will be considered, namely, a 16-layer graphite-epoxy panel with a radius R of 60 in., an opening angle of 60°, and a length L_x of 80 in. This geometry translates into an arclength L_s of approximately 60 in. Note in Fig. 1 that the length coordinate is denoted by x and arclength coordinate by s. Manufacturing distortions are predicted using two-dimensional ABAQUS[1] models of the panel constructed of 392 S8R5 8-noded shell elements.

It is assumed the manufacturing process can be divided into three stages. Stage one is the room-temperature lay-up stage. In this stage the prepreg material is applied to a tool, either by hand or by an automated process. At this stage there can be variations in layer thickness, both within a layer and from layer to layer, layer waviness, gaps in the prepreg, uneven resin distribution, and broken fibers. In addition, a given layer alignment may be slightly different than the intended alignment. All of these effects, particularly the latter, can lead to unwanted changes in the geometry of the panel relative to the intended geometry. Stage two consists of consolidation and curing of the laminate at elevated temperatures and pressures. During this time a number of influences are possible. Temperature gradients along the length or circumference can lead to different curing conditions in different regions of the panel. These different curing conditions can result in spatially nonuniform mechanical and thermal expansion properties. As resin bleed, and therefore layer thickness and fiber volume fraction, depend on compaction pressure, variations in pressure from location to location can lead to spatially nonuniform layer properties in the lengthwise, circumferential, and thickness directions. It is also possible that during this second stage layer movements can cause additional fiber misalignments. If a panel is consolidated and cured in multiple steps, such as with a sandwich panel, for example, other problems can occur during this stage. The third stage in the process is cooling and removal from the tool. Though most of the factors which cause distortions occur before this stage, it is during this third stage that the factors become evident. There can be actual failures of the material during cooling, and closed sections can become bound on the tools, thereby requiring force to remove them.

Of all these influences, three will be considered here. The first will be that of layer misalignment. The second will be that of a slightly thicker layer. The final influence to be considered is that of non-uniform cooling due to thermal gradients in the autoclave.

EFFECTS OF LAYER MISALIGNMENTS

The manufacturing of composite shells requires the layup of individual layers to form the composite laminate. The shell wall may be a laminate made up of a number of layers, or it may be of sandwich construction with laminates making up the face sheets. In either case, the layers may be positioned by hand, by a tow placement device, or other process. There is generally a tolerance associated with placement of the direction of the fibers. Though it is not known for certain, and it may well change from location to location and from layer to layer, it can be assumed there may be a few degrees of misalignment of the fiber direction. With misaligned fibers, the laminate construction becomes unsymmetric. The combination of the unsymmetric construction and a temperature change, corresponding to the cooling of a laminate from the stress-free curing temperature, can result in deformations. To the study the role of layer misalignments, three lamination sequences will be considered; quasi-isotropic, axially-stiff, and circumferentially-stiff. Table 1 describes the layer orientations of these laminates, where 0° is the axial direction.

In order to investigate the role of geometric nonlinearities, which might be important due to the large deformations usually associated with unsymmetric laminates and a temperature change, two finite-element models, geometrically linear and geometrically nonlinear, are used. These two models were initially used to investigate the effects of a 5° layer misalignment in the first layer of a quasi-isotropic curved panel. The models were driven by a spatially uniform temperature change of negative 280° F, which represents the change in temperature from cure to room conditions. The nominal material properties assumed for a layer are given in Table 2. Figure 2 shows the normalized radial displacements predicted by the geometrically linear and geometrically nonlinear finite-element models. The circumferential and axial coordinate are normalized to unity and the radial displacement is normalized by the panel thickness. Note that the linear model predicts the radial displacements to be over three laminate thicknesses, while the nonlinear model predicts considerably less deformation. Additionally, with the nonlinear model the deflections are confined, to some degree, to be along the edges. It is obvious that geometric nonlinearities are important. The remainder of this paper will focus on results predicted by the geometrically nonlinear two-dimensional finite-element models.

Results

Results presented here will be in terms of warpage metrics defined in terms of curvatures as follows:

$$
\begin{aligned}
\bar{\kappa}_s &= \sqrt{\frac{1}{L_x L_s}\int_{-\frac{L_x}{2}}^{\frac{L_x}{2}}\int_{-\frac{L_s}{2}}^{\frac{L_s}{2}}\left(\frac{\kappa_s(x,s)}{1/R}\right)^2 dx\,ds} \\
\bar{\kappa}_{xs} &= \sqrt{\frac{1}{L_x L_s}\int_{-\frac{L_x}{2}}^{\frac{L_x}{2}}\int_{-\frac{L_s}{2}}^{\frac{L_s}{2}}\left(\frac{\kappa_{xs}(x,s)}{1/R}\right)^2 dx\,ds}
\end{aligned}
\qquad (1)
$$

These metrics will be referred to as normalized average circumferential and twist warpages, respectively. The curvatures $\kappa_s(x,s)$ and $\kappa_{xs}(x,s)$ are the thermally-induced changes in curvatures of the panel as computed by the finite-element model. As can be seen, the metrics are the root mean squared normalized curvatures for the panel. The normalizing factor is the curvature of the uncured panel, $1/R$. This method is advantageous due to the reduction of curvature data to a single non-dimensional number, and it simplifies the discussion of warpage. Since the finite element model is discrete, the integrals are actually sums.

Figures 3 and 4 show the normalized circumferential and twist warpages due to a 5° layer misalignment in one layer of 16-layer curved panels. The three lamination sequences are considered, and which layer is misaligned is indicated along the bottom axis, it being implied that the other plies are oriented as intended. The 'perfect' case has all plies oriented as intended. As can be seen, the warpage resulting from a layer misalignment has common features for all three laminates. In all cases the magnitude of warpage depends on three factors: the intended orientation of the misaligned layer, the through-thickness position of the misaligned layer, and the lamination sequence. It can be seen that the circumferential warpage due to misaligned layers in the axially-stiff laminate is an order of magnitude larger than for the circumferentially-stiff laminate and four times that of the quasi-isotropic laminate. This is due to the absence of fibers in the circumferential direction of the axially-stiff laminate. Overall, the quasi-isotropic laminate and the circumferentially-stiff laminate are least susceptible to warpage caused by a misaligned layer. The quasi-isotropic laminate has sufficient stiffness in the circumferential directions to resist warpage, while the circumferentially-stiff laminate has considerable stiffness circumferentially. Considering the circumferential warpage of the axially-stiff laminate as an example, it is seen that misalignment of the inner and outer ±45° layers (layers 1, 2, 15, 16) has more influence on the warpage than misalignment of the central ±45° layers (layers 5, 6, 11, 12). Therefore, the through-thickness position of the misaligned layer within the laminate is a factor. Considering further the circumferential warpage of the axially-stiff case, it is seen that the inner and outer 0° layers (layers 3, 4, 13, 14) have less influence that the central ±45° layers. This indicates that the intended orientation of the layer is also an important factor, the ±45° layers being misaligned by 5° having more of an effect than the 0° layers being misaligned by 5°. The same statement can be made regarding the twist warpage, though the influence of the specific layers and layer locations is not the same as for the circumferential warpage.

LAYER THICKNESS VARIATIONS

When a symmetric laminate is constructed, symmetry is preserved if the thicknesses of the plies are spatially uniform, and identical, and that remains to be the case throughout the curing process. However, prepreg layers can vary in thickness within a layer and from one layer to another either initially, or as a result of cure. Consequently, due to the variations in fiber volume fraction that accompany the thickness variations, the effective mechanical properties of all the layers will not be the same. This leads to an unsymmetric laminate, which can have an effect on the cured shape of the composite. While there can be variations in layer thickness from one location to the next within a layer, that will not be considered here. Rather, it will be assumed that each layer is of uniform thickness, but the thickness varies from layer to layer. To be studied are the influences of having one layer 10% thicker than the remaining layers. It will be assumed that the increased thickness is due to increase in resin content, the fiber content being the same in each layer. Table 2 lists the material properties assumed for a 10% thicker layer. These values were computed by averaging the properties predicted by various models, including rule of mixtures and finite-element results.[2]

Results

Figures 5 and 6 show the normalized circumferential and twist warpages induced by the presence of one thicker layer. In general, regarding maximum values, the effect of a thicker layer is about 25% as influential as layer misalignment, though there are exceptions. The results suggest that the curved panel is sensitive to the through-thickness location of the thicker layer. Generally, if the thicker layer is towards the inside or outside of the laminate, its influence is greater. To be noted is the sensitivity of the axially-stiff case to the inner +45° layer being thicker. The bar representing that layer in the twist warpage plot is the highest of all.

THERMAL GRADIENTS

This section investigates the thermally-induced deformations in the presence of a thermal gradient in the autoclave during cure. Of particular interest are thermal gradients in the x and s directions. Large composite panels cured in an autoclave are vulnerable to these kinds of thermal gradients due to the realities of autoclave curing of large parts. Non-uniform positioning of heating elements and the uneven proximity of the laminate to the heating elements can lead to thermal gradients in large parts. The resulting temperature distribution leads to uneven curing and a spatially nonuniform temperature change from the cure condition to room temperature. Six types of temperature distributions are considered in this section. Each of these cases will be composed of a 0.1° F/in. inplane thermal gradient. The first temperature distribution to be considered, labeled distribution 1 in Fig. 7(a), is a linear distribution in the axial direction. This distribution leads to a temperature decrease from cure conditions of 280° F at one end of the panel and 272° F at the other end. The second temperature distribution to be considered, labeled distribution 2 in Fig. 7(b), is a linear distribution in the circumferential direction. This leads to a temperature decrease from cure conditions of 280° F at one side and 274° F at the other side. The third temperature distribution to be considered, labeled distribution 3 in Fig. 7(c), is a linear distribution along the diagonal direction. This leads to a temperature decrease of 280° F at one corner and 266° F at the other corner. The fourth temperature distribution to be considered, labeled distribution 4 in Fig. 7(d), is a bi-linear distribution along the axial direction. This leads to a decrease temperature decrease of 280° F at both ends and a temperature decrease of 276° F along the s-axis. The fifth temperature distribution to be considered, labeled distribution 5 in Fig. 7(e), is a bi-linear distribution along the circumferential direction. This leads to a decrease temperature decrease of 280° F at both sides and a temperature decrease of 277° F along the x-axis. The final temperature distribution to be considered, labeled distribution 6 in Fig. 7(f), is a four quadrant bi-linear distribution. This leads to a temperature decrease of 280° F at the four corners and a temperature decrease of 273° F at the center of the panel.

Results

Figures 8 and 9 depict the normalized circumferential and twist warpages, respectively, for the three laminates if it is assumed they are exposed to the temperature distributions of Fig. 7. A quick glance shows that, overall, compared to a layer misalignment, the circumferential and twist warpages induced by the various temperature distributions are small. However, in some cases the twist warpages are similar in magnitude to those induced by a thicker layer. In other cases the magnitudes of warpages induced by the distributions are no different than the deformations induced by spatially uniform cooling of a perfect panel. The circumferentially-stiff panel is the most sensitive to thermal gradients. Figures 8 and 9 shows that for this panel the warpage induced by a thermal gradient, irrespective of the temperature distribution, is much larger than those induced by perfect uniform cooling and much larger than for the other two laminates. The result shows that for the axially-stiff and circumferentially-stiff laminates, the magnitudes of normalized warpages are basically insensitive to the temperature distribution. Warpage is primarily a function of the fact that there is a thermal gradient, independent of the distribution. Though small, the circumferential warpage of the quasi-isotropic laminate seems to be aggravated by the distributions 5 and 6.

CONCLUSIONS

It has been shown that of the three anomalies considered, manufacturing distortions of curved composite panels are most sensitive to layer misalignments. Layer thickness variations are the next most important imperfection. The effect of these imperfections on the warpage of a panel is dependent on the through-thickness location, and is dependent on the orientation of the layer containing the imperfection. It was also found that the lamination sequence can either mitigate or aggravate the resulting deformations. The thermal gradient considered did not seem to be as serious a problem. The results presented provides some insight into the magnitude and cause of the warpage of curved composite panels. A surprising result of the study was that geometric nonlinearities are important.

ACKNOWLEDGMENTS

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REFERENCES

1 - ABAQUS/STANDARD. *Theory Manual.* Hibbitt, Karlsson, & Sorensen, Inc., Pawtucket, Rhode Island, 1998.

2 - Hyer, M.W., Stress Analysis of Fiber-Reinforced Composite Materials, WCB/ McGraw-Hill, 1998, New York

Table 1 Laminate construction

Laminate	**Layup**
Quasi-Isotropic	$[\pm 45°/0°/90°]_{2S}$
Axially-Stiff	$[\pm 45°/0°_2]_{2S}$
Circumferentially-Stiff	$[\pm 45°/90°_2]_{2S}$

Table 2 Graphite/epoxy material properties

Layer	**E_1**	**E_2**	**G_{12}**	**ν_{12}**	**α_1**	**α_2**	**h**
Nominal	22.48 Msi	1.755 Msi	0.638 Msi	0.248	-1.0 e-8°F	13.5 e-6/°F	0.0059 in.
Thicker	20.40 Msi	1.516 Msi	0.546 Msi	0.258	0.0 /°F	15.7 e-6/°F	0.0065 in.

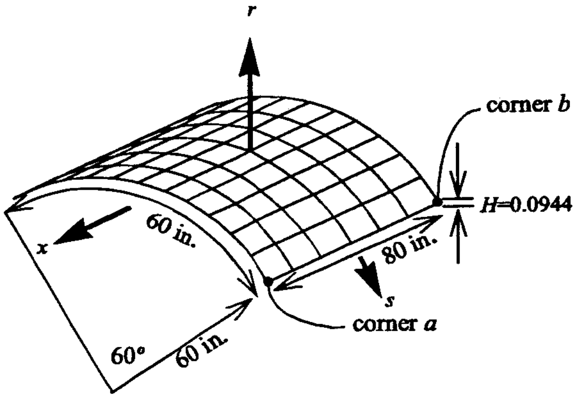


Fig. 1 Model geometry

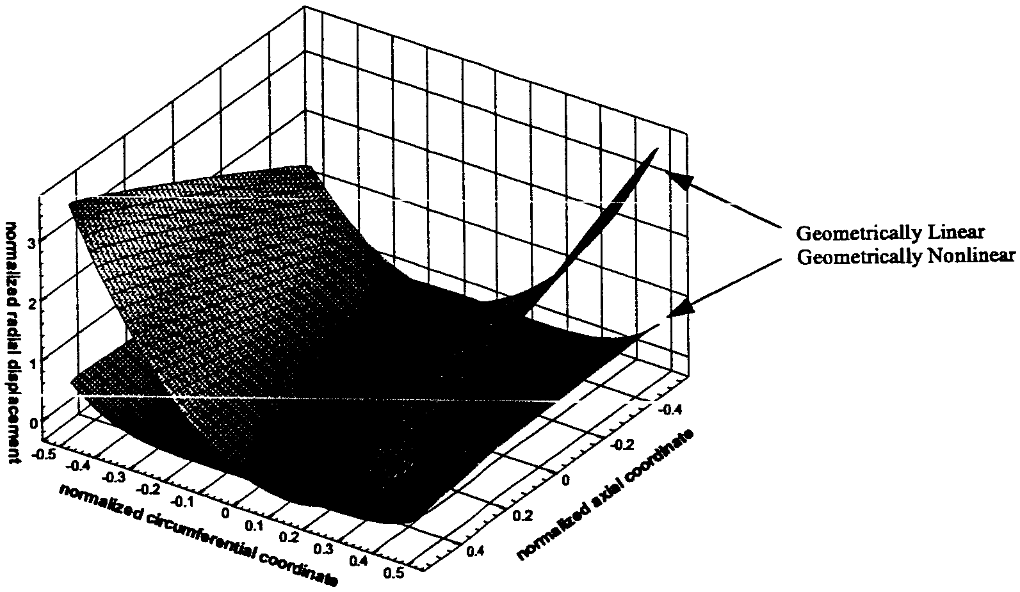


Fig. 2 Normalized radial displacement predictions

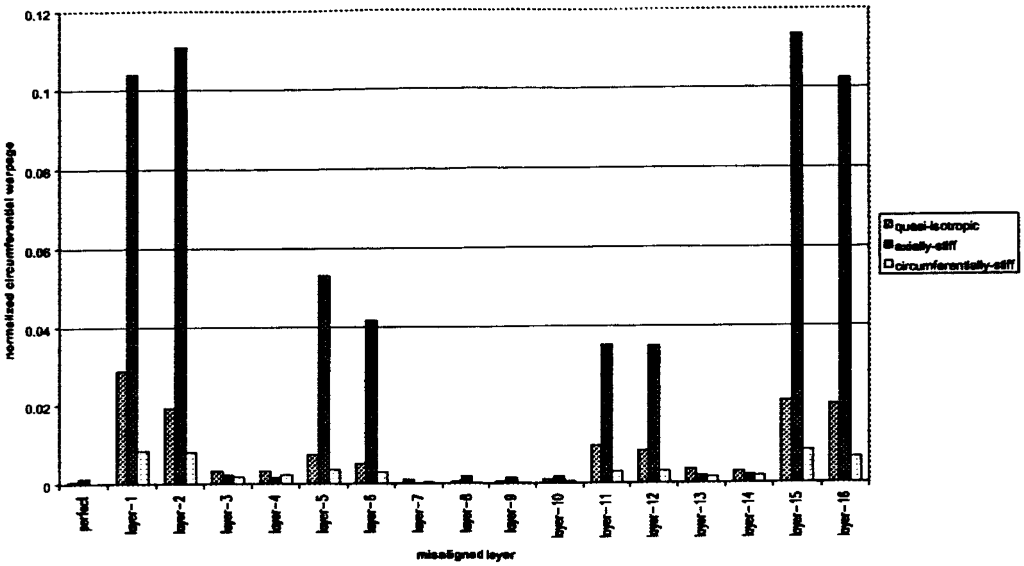


Fig. 3 Normalized circumferential warpage due to one misaligned layer

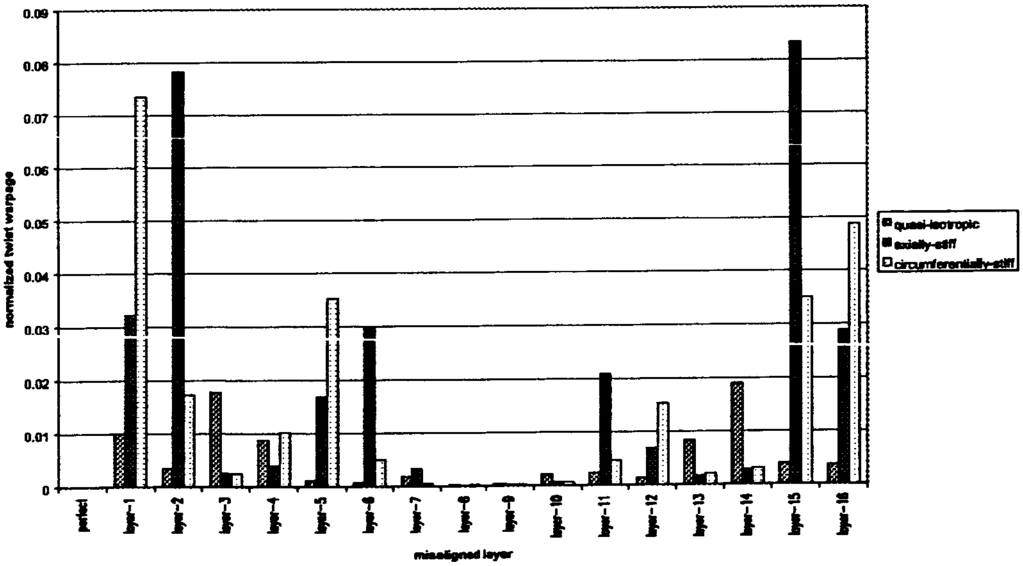


Fig. 4 Normalized twist warpage due to one misaligned layer

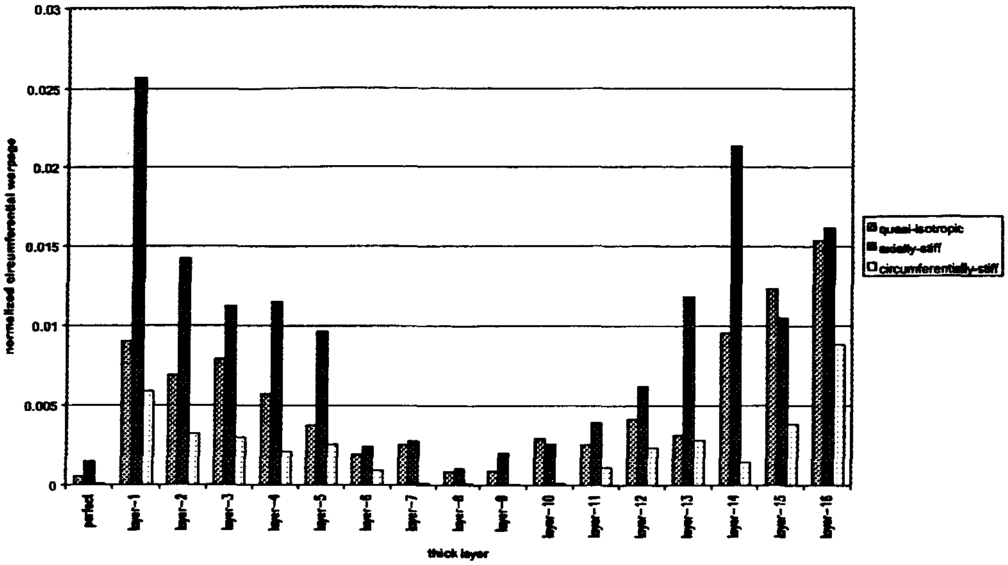


Fig. 5 Normalized circumferential warpage due to one thicker layer

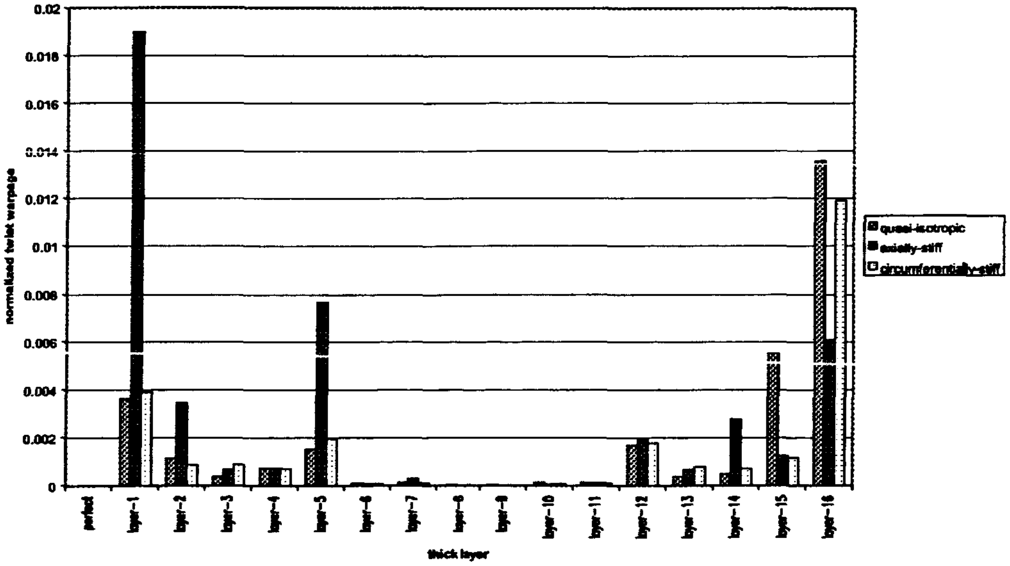
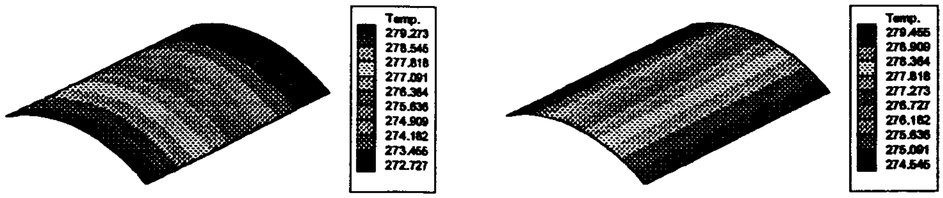
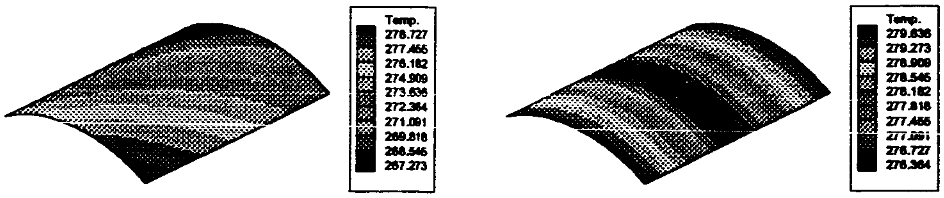


Fig. 6 Normalized twist warpage due to one thicker layer



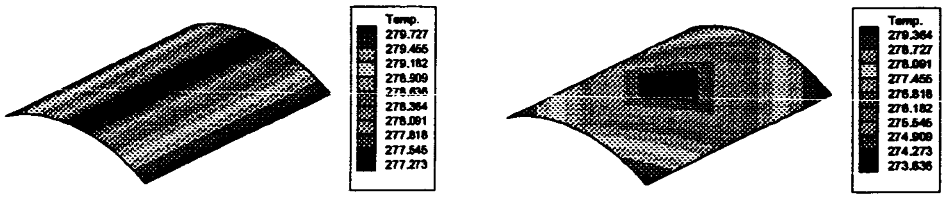
(a) Distribution 1

(b) Distribution 2



(c) Distribution 3

(d) Distribution 4



(e) Distribution 5

(f) Distribution 6

Fig. 7 Temperature distributions

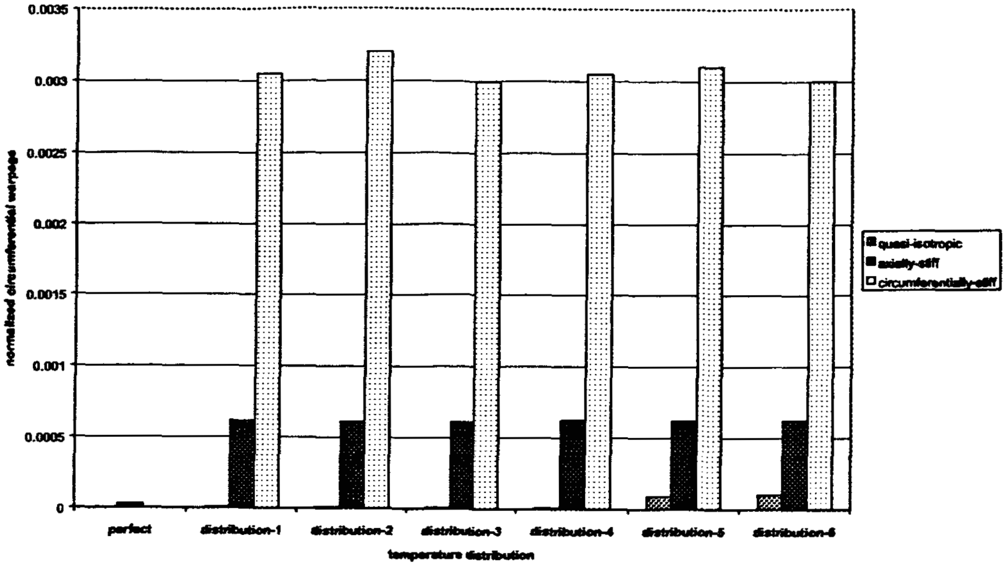


Fig. 8 Normalized circumferential warpage due to a thermal gradient

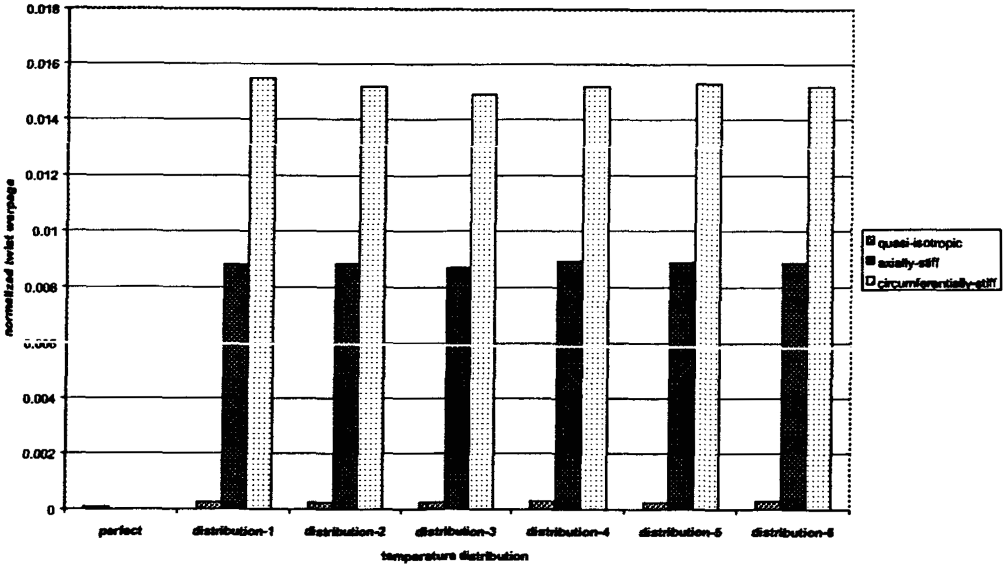


Fig. 9 Normalized twist warpage due to a thermal gradient