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CARBON FIBER PLATES PRODUCTION FOR THE CMS TRACKER OUTER BARREL DETECTOR

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1. Abstract

The production methods together with the achieved flatness and thickness of the composite support structures of the CMS tracker outer barrel (TOB) detector are presented. Possible areas of improvement in the process and in the materials used are also suggested.

2. Introduction

The tracker outer barrel is built with the rod mechanics (figure 1). Each layer is made of two rods in z, each rod containing 6 detectors. The detectors are built around a carbon fiber structure (frame), which provides the silicon with the necessary stiffness (figure 2).

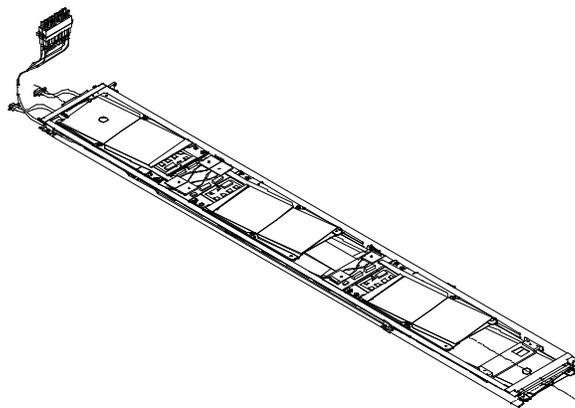


figure 1. Layout of the stereo rod with three of the six modules

The components of the frame include compensators, carrier frame rails and the hybrid mounting plate (figure 2).

Requirements for the frame components are

- a) Piece thickness between 600 and 650 μm ;
- b) Flatness within 50 μm ;
- c) Same fibers orientation on outer sides of the laminate;
- d) $0^\circ/90^\circ$ layout¹.

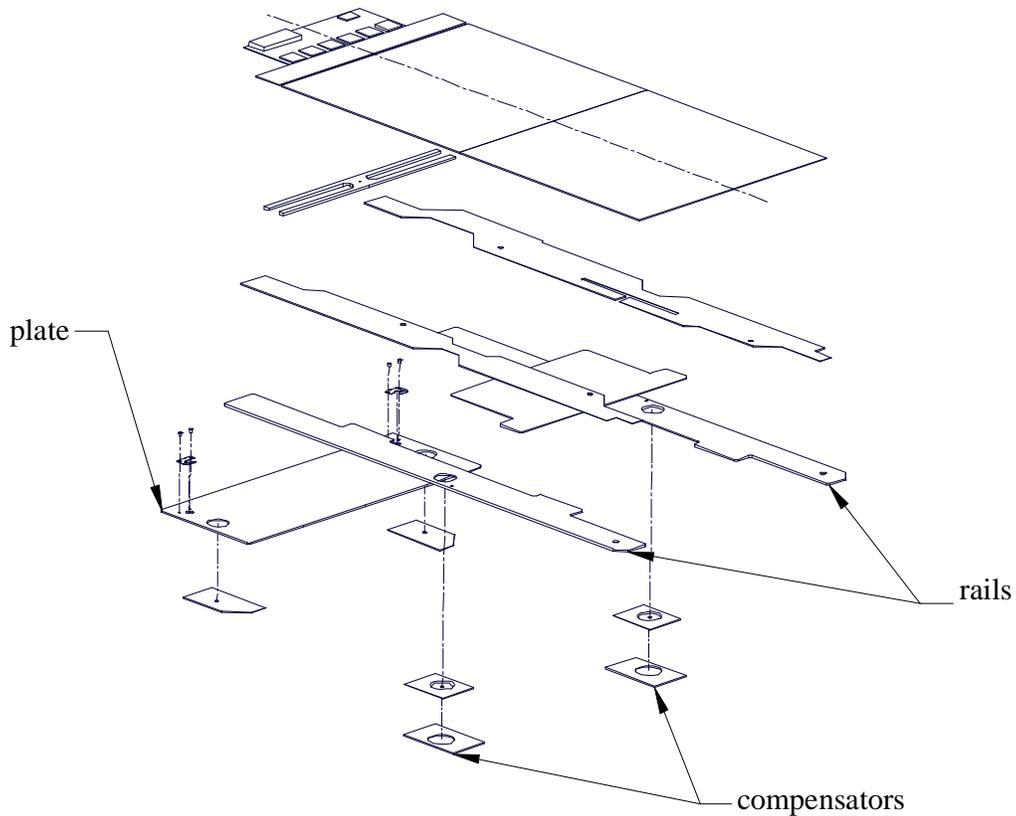


figure 2. R- Φ detector

¹ In appendix A it is showed that actually this lay-up represents the best choice in terms of achievable plate flatness.

	<i>Prototyping</i>	<i>Final</i>
<i>Fiber</i>	MR40	K800X - 2K
<i>Resin</i>	epoxy	RS-3C Toughened Polycyanate
<i>Tensile Modulus</i>	295 GPa 43 Msi	900 GPa (130.7 Msi)
<i>Longitudinal Fiber Thermal Conductivity</i>	-	800-900 W/mK
<i>Electrical resistivity</i>	-	1.36 $\mu\Omega$ m
<i>CTE at 21°C (70°F)</i>	-	-1.45 ppm/°C (-0.8 ppm/°F)
<i>Ply thickness</i>	125 μ m (5 mils)	85 μ m (3.3 mils)
<i>Cure parameters</i>	Heat to 250° F Hold at 250° F for 180 minutes (+15 min/-0 min). Cool.	Heat to 350° F (+10° F/-0° F) @ 5° F \pm 3° F/min. Hold at 350° F for 120 minutes (+15 min/-0 min). Cool. (May be postcured at 450° F for 2 hours if higher temperature service is required)

Table 1 – Prepregs properties

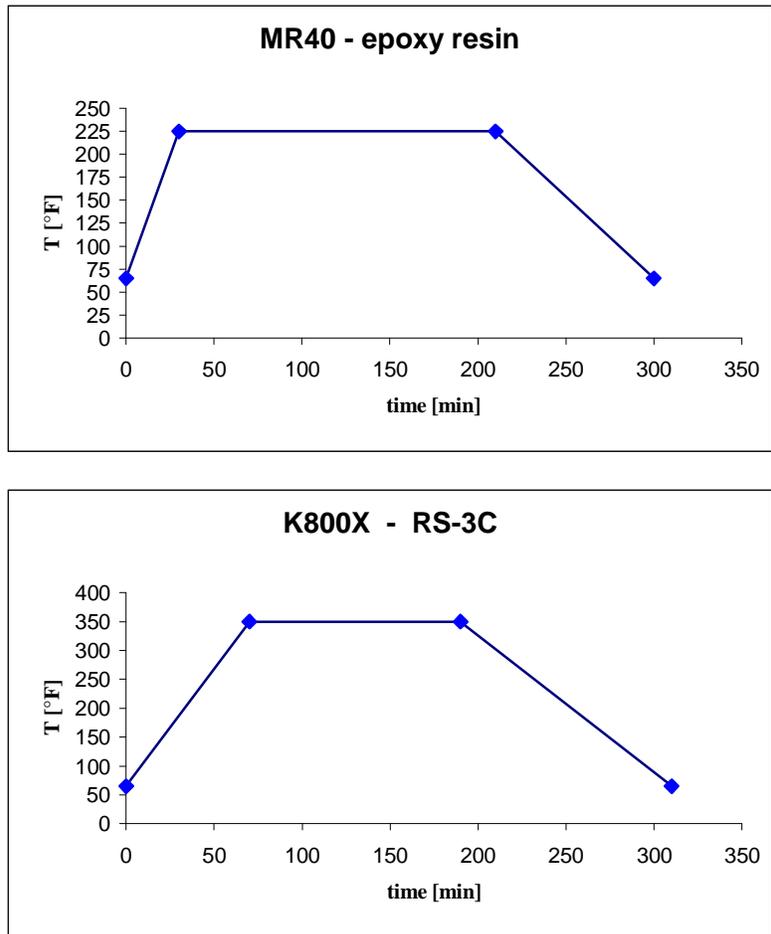


figure 3 – Curing cycles of prepregs

4. Results

The plates, once produced and tagged, have been measured using an optical inspection machine (OGP Avant 600) to check thickness and flatness. Because of the way the OGP works, it was necessary to do the measure one side of the plate at a time.

The errors affecting the measurement are mainly

- ✓ Gravity. It affects the flatness and it gives a bigger error for the material with lower Young's Modulus, MR40 in our case. Its effects are slightly different on the two sides of the plate.
- ✓ Suction effect. If the plate is not excessively warped it tends to behave as a suction cap against the glass of the OGP table thereby reducing the true curvature.

- ✓ Non optimal alignment. Since the measurement of both sides requires the plate to be flipped, inevitably the origin of the second side will not coincide with the origin of the first side. This error affects slightly the thickness.

These errors are intrinsic to the way the OGP acquires the points, that is on a horizontal plane; placing the plates vertically would drastically reduce the extent of this inaccuracies. The gravity error can be predicted through the thin plate theory calculating the sag of the laminate under its own weight.

Through a series of double-checks the error on the thickness appeared to be around 20µm.

The flatness f is defined as the distance between two parallel planes containing all the points belonging to the surface. In our case

$$f = y_{\max} - y_{\min} \tag{ 1 }$$

with y axis along the laminate thickness.

However this can lead to an extremely conservative approach. To give an indication of the points scattering, in other words to estimate how predictive equation { 1 } is, the statistical confidence interval CI is used

$$CI = z^* \frac{\sigma}{\sqrt{n}} \tag{ 2 }$$

where z^* is the area under the standard normal curve, σ is the standard deviation and n is the number of elements in the sample.

Lower values of confidence ensure that the points are less scattered, that is high values of the flatness given by equation { 1 } may not be representative⁴.

⁴ Think for example of all points lying on the same plane but just one point very off that plane.

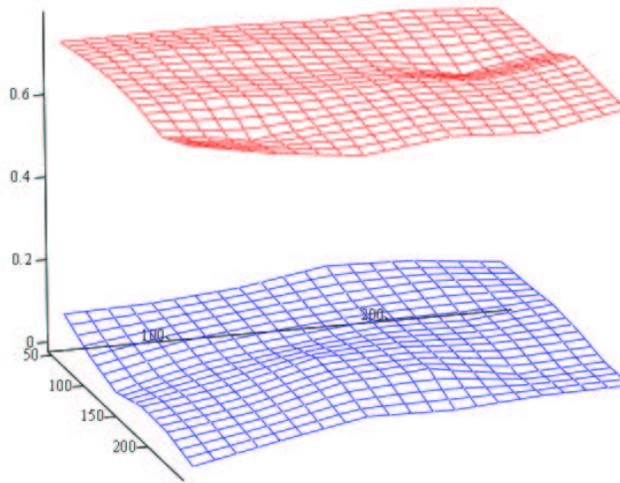


figure 4 – Typical aspect of upper and lower measured surfaces in a plate

The results are presented in figure 4 - figure 8. While the piece thickness falls consistently around $600\mu\text{m}$ for K800⁵ and $590\text{-}650\mu\text{m}$ for MR40⁶, the flatness shows an improvement due to curing refinements. The apparent worsening in flatness improvement in the plates produced on February 2nd could be explained by the fact that the MR40 used that day might have suffered from excessive frost. For double-checking the plates produced on that date, the measured cut pieces have been extracted from them.

The actual production has been further improved (with respect to the data presented) essentially in two ways: a smoother thermal ramp during curing⁷ and, to avoid any thermal shock, a longer hold period, up to 48 hrs, in the mold.

We found the K800X to be very brittle. Although thickness, flatness and cutting behavior were good, most of the cut pieces broke during extraction from the jib. By refining the gluing technique so as to have less Araldite wicking, we could solve the extraction problem. However we still have concerns about the viability of this material given its apparent brittleness.

⁵ With a peak at $680\mu\text{m}$.

⁶ With a peak at $710\mu\text{m}$

⁷ As illustrated in figure 3.

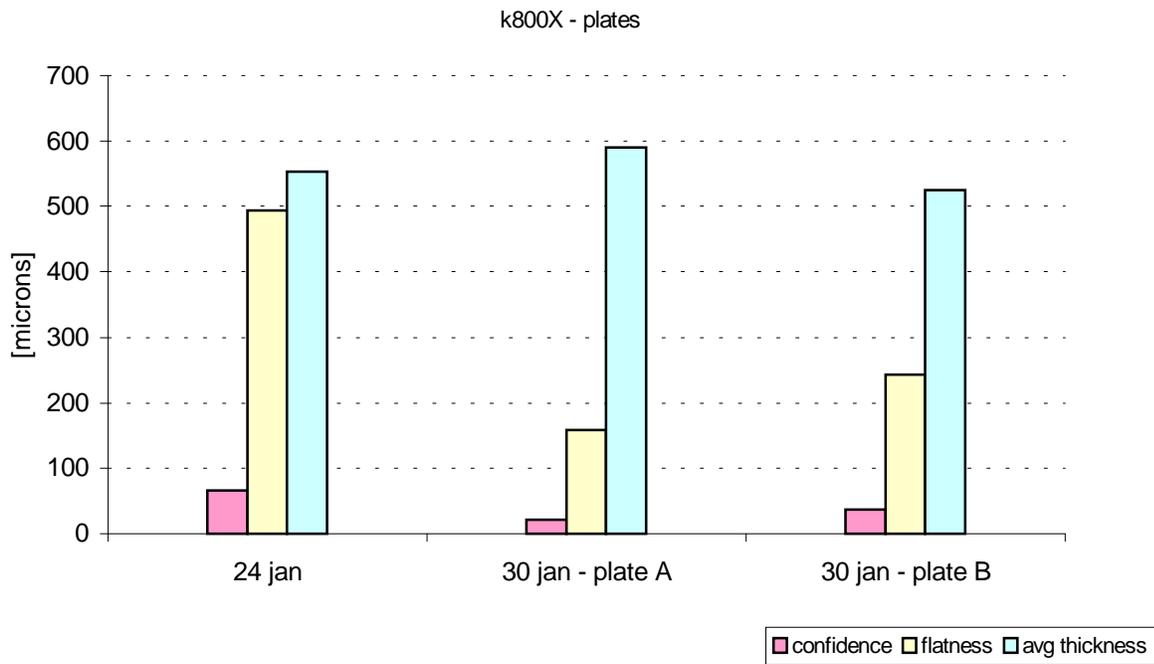


figure 5 - Flatness and thickness of the K800X plates. The date refers to the production day.

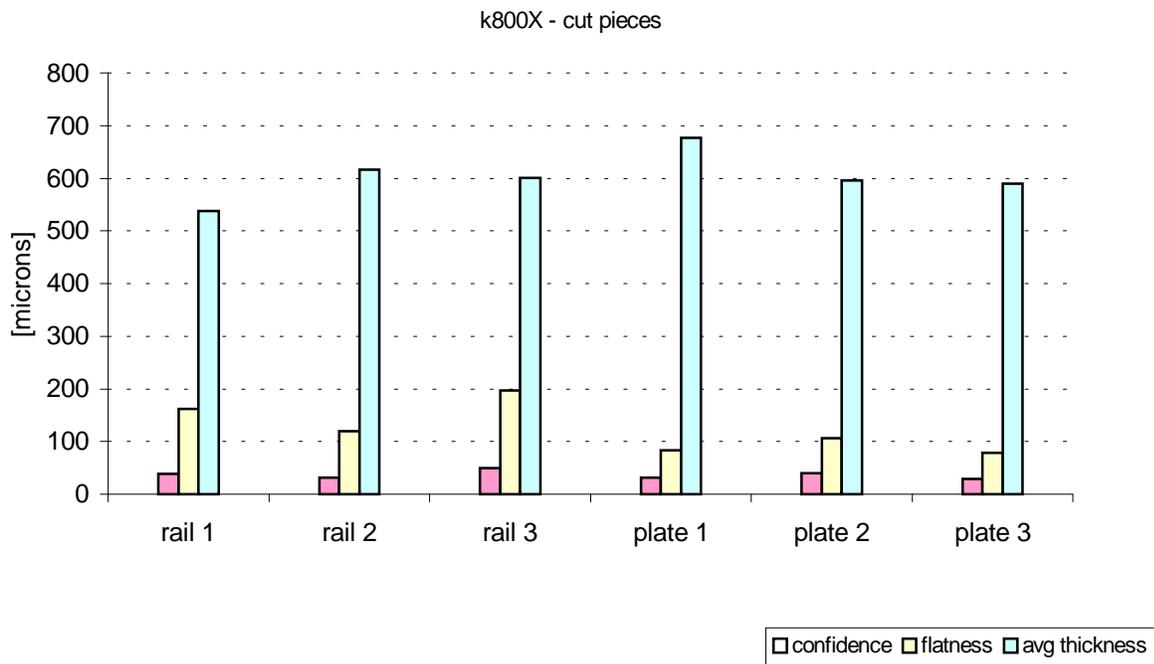


figure 6 - Flatness and thickness of the K800X cut pieces.

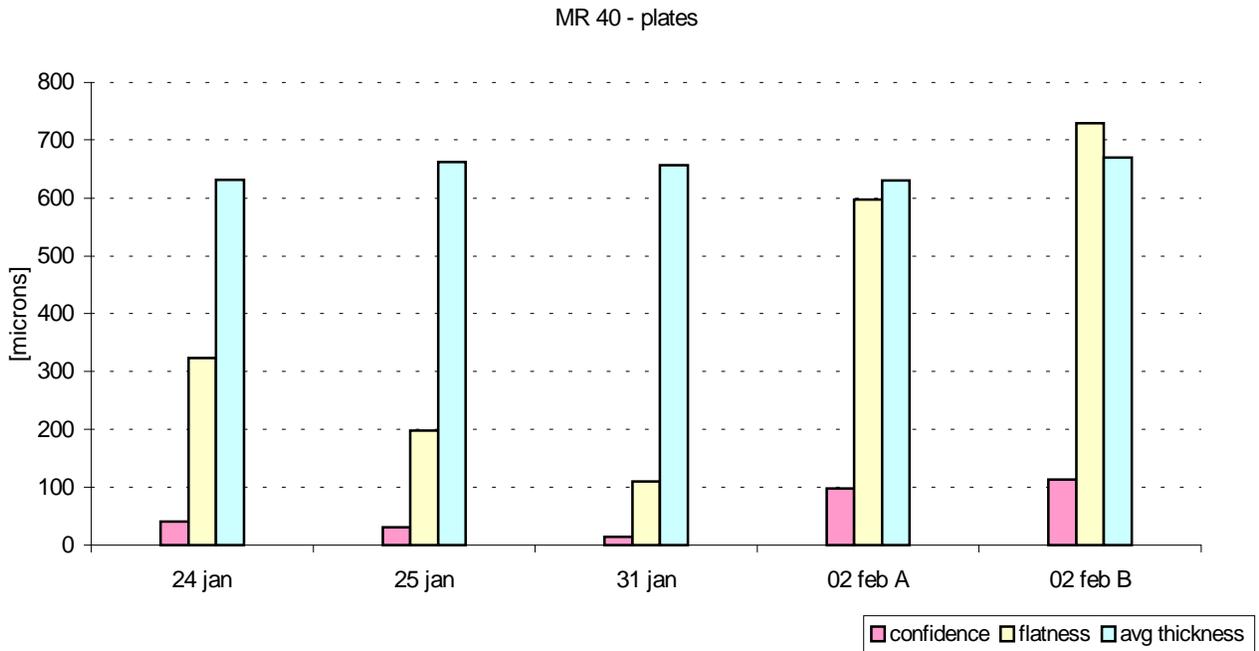


figure 7 - Flatness and thickness of the MR40 plates. The date refers to the production day.

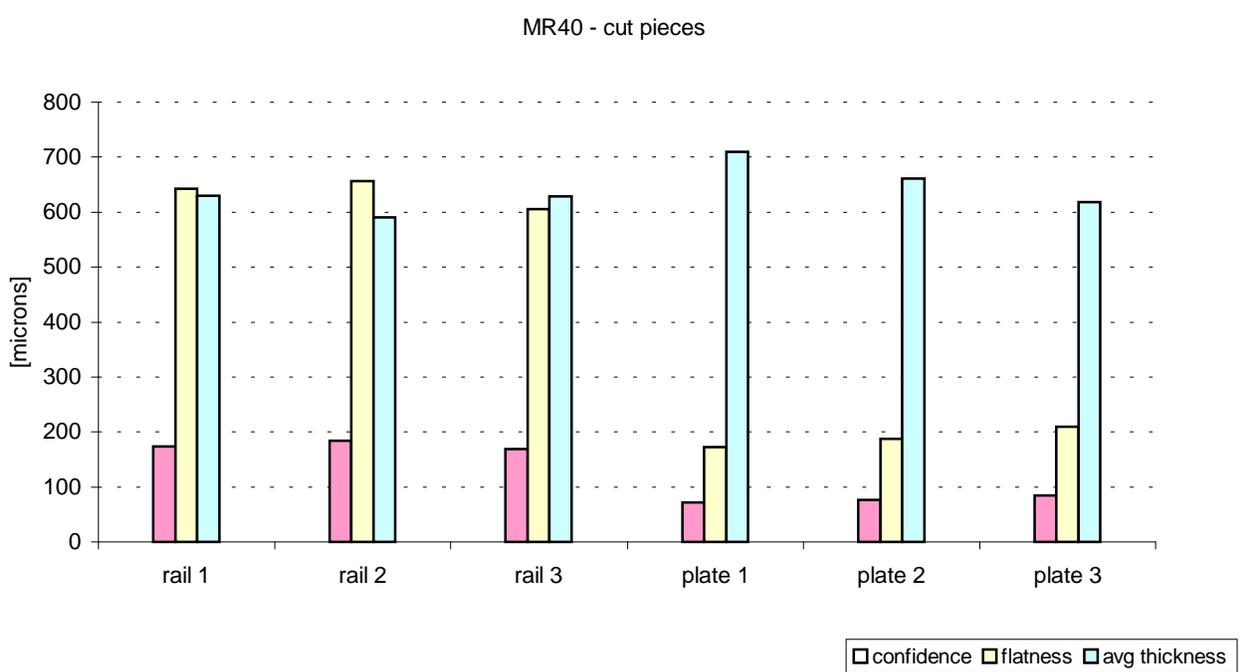


figure 8 - Flatness and thickness of the MR40 pieces cut from the plates produced on February 2nd.

5. Conclusions

The last plates produced, either in MR40 and K800X, have shown repeatability both in the flatness and the thickness.

The thickness meets with acceptable margin the requirements; a final improvement can be achieved simply adopting a ply thickness optimized to the number of wanted plies.

As far as it concerns the flatness however, unless the curing is performed in autoclave, 50µm seems hardly achievable. An improvement could come from adopting a lower temperature curing resin (for example RS-12C), even with the trade-off of a much longer curing time. With the available means, 100µm seem to be the most likely target.

Finally, K800X has showed an unacceptable brittleness that makes it necessary to investigate a different material, for example the Mitsubishi K13C2U, having a lower thermal conductivity (~650W/mK) but a more favorable Young's modulus (558 GPa ,81 Msi).

A. Understanding the laminate layout

The constitutive relationships in arbitrary coordinates for a thin orthotropic material can be expressed in terms of the transformed reduced stiffness matrix \bar{Q} as follow

$$[\sigma]_k = [\bar{Q}]_k \cdot [\epsilon]_k = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \cdot \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_{xy} \end{bmatrix}$$

{ 3 }

where the index k stands for the generic kth layer in the lay-up, $[\sigma]$ is the stress vector and $[\epsilon]$ the strain vector. Assuming

- the laminate thickness is small compared to its lateral dimensions⁸;
- the bond between the laminae is perfect⁹ and a line perpendicular to the midplane remains so after deformation;
- in-plane displacements are linear functions of the thickness¹⁰ (Kirchhoff hypothesis);

⁸ I.e. state of generalized plane stress.

⁹ I.e. continuous displacement across the bond.

we can express the strains along the laminate in terms of the midplane strains $[\varepsilon^0]$ and midplane curvatures $[k^0]$

$$[\varepsilon]_k = [\varepsilon^0] + z \cdot [k^0] \quad \{ 4 \}$$

where, given u_0, v_0, w_0 displacements in the midplane,

$$[\varepsilon^0] = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} = \begin{bmatrix} \frac{\partial u_0}{\partial x} \\ \frac{\partial v_0}{\partial y} \\ \frac{\partial u_0}{\partial x} + \frac{\partial v_0}{\partial y} \end{bmatrix}$$

$$[k^0] = \begin{bmatrix} k_x^0 \\ k_y^0 \\ k_{xy}^0 \end{bmatrix} = - \begin{bmatrix} \frac{\partial^2 w_0}{\partial x^2} \\ \frac{\partial^2 w_0}{\partial y^2} \\ 2 \frac{\partial^2 w_0}{\partial x \partial y} \end{bmatrix} \quad \{ 5 \}$$

Substituting equation { 4 } into { 3 } yields

$$[\sigma]_k = [\bar{Q}]_k \cdot [\varepsilon^0] + z \cdot [\bar{Q}]_k \cdot [k^0] \quad \{ 6 \}$$

The resultant forces and moments acting on a laminate of thickness t and N plies can be defined as

$$\begin{bmatrix} N_X \\ N_Y \\ N_{XY} \end{bmatrix} = \int_{-t/2}^{t/2} [\sigma]_k dz = \sum_{k=1}^N \int_{z_{k-1}}^{z_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}_k dz$$

and

¹⁰ $\varepsilon_{xz}, \varepsilon_{yz}$ negligible

$$\begin{bmatrix} M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \int_{-t/2}^{t/2} [\sigma]_k \cdot z dz = \sum_{k=1}^N \int_{z_{k-1}}^{z_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}_k \cdot z dz$$

{ 7 }

where the coordinate z is zero in the midplane and z_0 corresponds to the upper surface while z_N to the lower surface of the laminate. When the lamina stress-strain relations { 6 } are substituted, keeping in mind that $[\epsilon^0]$ and $[k^0]$ are not functions of z but are middle surface values as well as the stiffness matrix is constant within the lamina, it yields, with contracted notation

$$[N] = [A] \cdot [\epsilon^0] + [B] \cdot [k^0]$$

$$[M] = [B] \cdot [\epsilon^0] + [D] \cdot [k^0]$$

{ 8 }

where

$$A_{ij} = \sum_{k=1}^N (\overline{Q}_{ij})_k \cdot (z_k - z_{k-1})$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^N (\overline{Q}_{ij})_k \cdot (z_k^2 - z_{k-1}^2)$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^N (\overline{Q}_{ij})_k \cdot (z_k^3 - z_{k-1}^3)$$

{ 9 }

A_{ij} are called *extensional stiffnesses*, B_{ij} are called *coupling stiffnesses* and D_{ij} are called *bending stiffnesses*. The presence of the B_{ij} implies coupling between bending and extension of a laminate¹¹. In other words, an extensional force results not only in extensional deformations but also twisting and/or bending of the laminate; moreover, such a laminate cannot be subjected to a moment without at the same time suffering extension of the middle surface. Therefore if $[B]$ is identically zero the laminate does not have a tendency to twist because of the inevitable thermally induced contractions that occur during cooling following the curing process.

¹¹ In particular terms B_{16} and B_{26} represent tension-twisting coupling while the other terms represent the tension-bending coupling.

Besides, it can be easily seen from { 8 } that the terms A_{16} and A_{26} bring in the tension-shear coupling, while terms D_{16} and D_{26} represent flexure-twisting coupling.

From the aforementioned point, summarized in Table 2, we can conclude that a laminate with a symmetric lay-up and with a 0° - 90° fiber orientation provides the best response to a loading condition as well as a thermal cycling in terms of flatness.

Laminate	A_{16}, A_{26}	[B]	D_{16}, D_{26}
<i>Symmetric</i>	$\neq 0$	0^{12}	$\neq 0$
<i>Balanced</i>	0	$\neq 0$	$\neq 0$
<i>Antisymmetric</i>	0	$\neq 0$	0^{13}
0° - 90°	$A_{16}, A_{26}, B_{16}, B_{26}, D_{16}, D_{26} \equiv 0^{14}$		

Table 2

References

- Mechanics of Composite Materials, 1st Edition, by Robert M. Jones, Taylor & Francis
- Composite Materials : Science and Engineering”, 2nd Edition, October 1998, by Krishan Kumar Chawla, Springer Verlag
- Engineered Materials Handbook Volume 1: Composites, August 1989, by Cyril A. Dostal, Theodore J. Reinhart, ASM
- Mechanics of Fibrous Composites, November 1997, by Carl T. Herakovich, John Wiley & Sons

¹² The [B] matrix is actually related to the non symmetric stack sequence of the laminate rather than to the orthotropy.

¹³ For laminates that are not antisymmetric, $D_{16}, D_{26} \rightarrow 0$ when the number of stacked plies is large enough.

¹⁴ From the way the matrix $[\bar{Q}]$ is defined, it follows that \bar{Q}_{16} and \bar{Q}_{26} are identically zero.