DESIGN AND MANUFACTURE OF A VARIABLE-STIFFNESS CYLINDRICAL SHELL

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SUMMARY

Advanced fiber placement technology enables the placement of curved fibers on a surface, which makes it possible to continuously vary the stiffness within a composite laminate. A cylindrical shell with circumferentially varying stiffness optimized for maximum bending load carrying capability was built at the Boeing Company using an Ingersoll fiber-placement machine. A detailed description of the design for manufacturing is given for the laminate configuration that was built and the design is compared to the actual product. Issues encountered during the design and manufacturing are discussed and recommendations for the future are made.

1. INTRODUCTION

Composite aerospace structures typically consists of 0°, 90° and ±45° plies in different compositions, while stacking sequence is used to change the laminate properties. In the past, the amount of different fiber angles was limited by manufacturability, but nowadays manufacturing methods such as advanced fiber placement make it possible to produce a wide variety of fiber angles at no additional cost. Advanced fiber placement even allows fiber steering, which enables the fiber orientation to change within a ply, resulting in a variable-stiffness laminate. As a consequence, the design space is increased, which naturally results in a better optimum, either in structural performance or weight.

Research on steered laminates manufactured by advanced fiber placement was performed by Schueler and Hale [1], while Tatting, Gürdal, and Jegley both designed, built, and subsequently tested flat panels with varying stiffness [2-4]. They showed that considerable structural improvements could be obtained by spatially varying the stiffness through the use of curved fiber paths. A follow-up on this research was done by Blom et al [5], who presented a method for designing fiber paths on conical shells based on fiber placement technology, and optimized a cylindrical shell for maximum buckling load under bending by varying the stiffness in circumferential direction [6,7].

Based on the optimization described in reference [6,7], Blom built a variable-stiffness cylinder using an Ingersoll fiber placement machine located at Boeing in Seattle, WA. In this paper, a detailed description of the design for manufacturing is given for the laminate configuration that was built and the design is compared to the actual product. Problems encountered during the manufacturing process are shown and explained and possible solutions to these problems are provided. Finally, general considerations are given on advanced fiber placement technology and variable-stiffness composites, and a preview of future work is stated.

2. FIBER PLACEMENT TECHNOLOGY

Advanced fiber placement machines typically have a multi-degree-of-freedom machine head that places up to 32 individual tows of fiber on a surface [8]. Each prepregged tow is 1/8 inch wide (3.175 mm) and is laid down at differentially different speeds from the other tows. Additionally, every tow can be cut and restarted independently, so that the amount of waste material can be minimized and overlaps can be prevented. When the tows are being placed on the mandrel, they are being heated by a torch to increase tackiness and at the same time a compaction roller is applied in order to suppress any local tow wrinkling that might occur and to pull the tows forward once they reach the surface. In combination with the differential pay-out of the tows, this system allows for in-plane steering of fibers.

A complete ply is constructed by placing multiple courses on the surface. Blom [5-7] uses the so-called shifting method: a fiber path is constructed based on the desired fiber angle variation, which is then shifted perpendicular to the direction of variation in order to fill the complete surface. The value of the shift is determined by the maximum number of tows used and the fiber angle variation. If the course width is kept constant and no gaps are allowed, this method results in overlaps, unless the fiber paths are straight. If desired, these overlaps can be eliminated by using the cutting and restarting capabilities of the fiber placement machine.

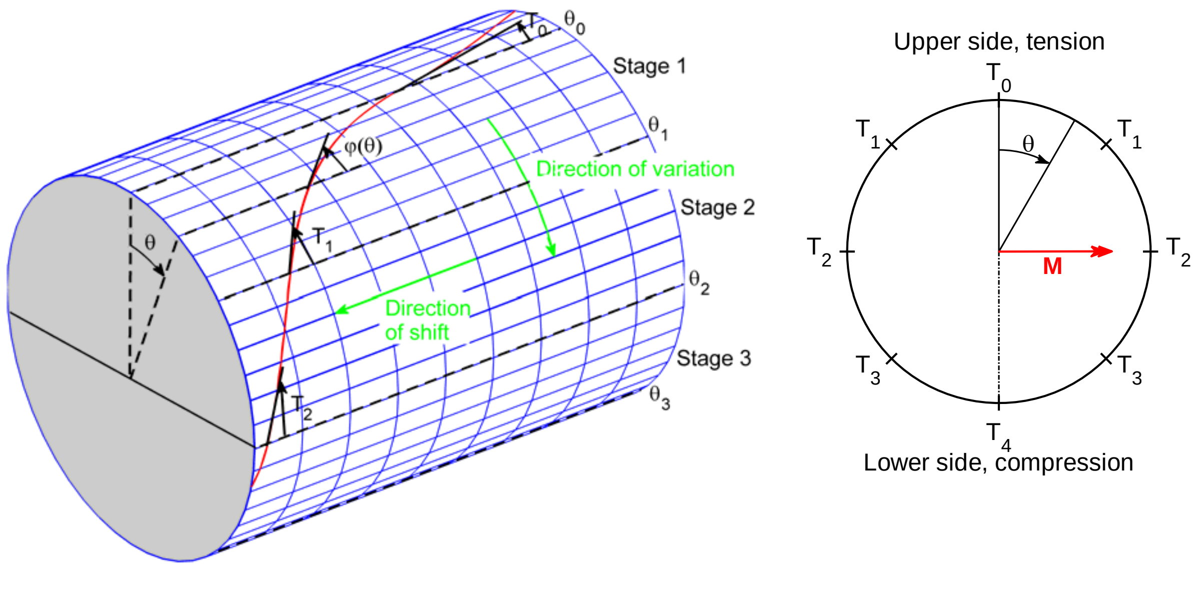


Figure 1: Definition of design variables and fiber paths

3. CYLINDER DESIGN STUDY

The cylinder that was built at Boeing is made of a different material system than the cylinder described by Blom [6,7], and thus the optimization results are slightly different. A comparison between the optimized traditional laminate and the optimized variable-stiffness laminate is given in Table 1. Both cylinders have the same structural mass.

Table 1: Comparison between a traditional and a variable-stiffness shell

Configuration	M_{cr} (in-kips)	M_f (in-kips)	EI (lbs-in^2)	Improvement in buckling load
Constant stiffness	6,000	6,001	$7.55 \cdot 10^9$	-
Variable stiffness	7,120	7,124	$10.17 \cdot 10^9$	18.6 %

The variable-stiffness layup contains pre-selected 0, ±45 and 90 plies and is assumed to be in the following form $[\pm 45, \pm\varphi_1, 0, 90, \pm\varphi_2, 0, 90, \pm\varphi_3]_S$. Each steered ply is indicated by the symbol φ and is a function of the circumferential coordinate θ. The fiber angle variation within the steered plies is defined by the design variables T_0 until T_4, representing the fiber orientation angles at 45 degree increments around the circumference as indicated in Figure 1. In between these locations the fiber angle varies with a constant in-plane curvature [6,7]. The optimum values determined for these design variables are given in Table 2. When two adjacent design variables have the same value, the fiber angle in between these locations is constant [e.g. T_0 and T_1 in $\varphi_1(\theta)$].

Table 2: Design variables for each steered ply definition

Ply definition	T_0 (deg)	T_1 (deg)	T_2 (deg)	T_3 (deg)	T_4 (deg)
$\varphi_1(\theta)$	10.0	10.0	10.0	10.0	24.7
$\varphi_2(\theta)$	10.0	10.0	10.6	56.9	61.7
$\varphi_3(\theta)$	10.0	12.0	10.0	34.2	68.9

4. DESIGN FOR MANUFACTURING

4.1 Curvature constraint

Only one manufacturing constraint was taken into account during the optimization [6, 7]. This is the so-called *curvature constraint* and it requires the in-plane radius of curvature of the central path to be larger than 20 inches. In conventional design this value is set to be 25 inches, but due to the small dimensions of the test specimen, the minimum turning radius was set to 20 inches. This constraint should prevent severe local wrinkling of the tows on the inside of the turn (called puckering). Some puckering still occurs, but intermediate debulking of the laminate takes care of this problem and results in a smooth end product. An example of puckers can be seen in Figure 2(a), while a picture of the finished product can be seen in Figure 2(b).

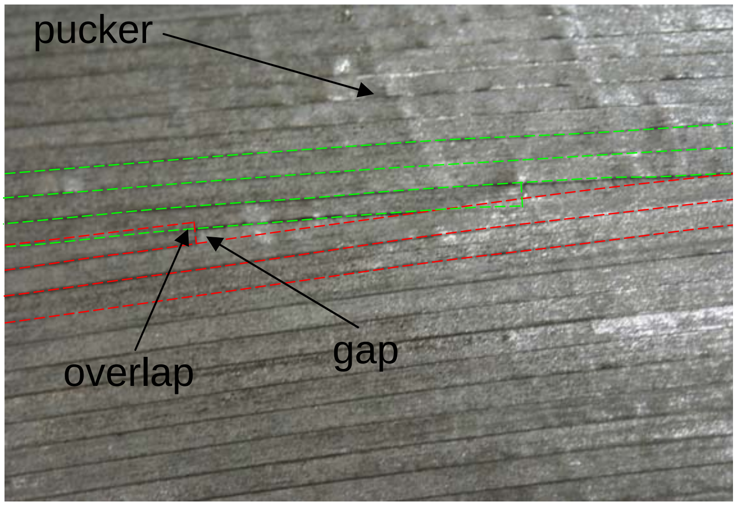
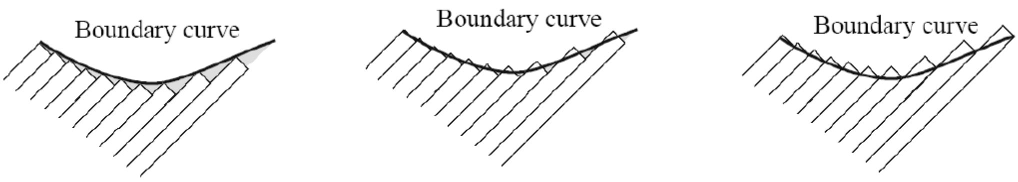


Figure 2(a): Close-up of tow-drop areas and puckers

Figure 2b: finished product



(a) 0% coverage (b) 50% coverage (c) 100% coverage

Figure 3: Coverage parameter [2]

4.2 Coverage Parameter and Parallel Courses

The so-called *coverage parameter* [2] determines where tows are being terminated and restarted, thereby creating either small triangular gaps or small overlaps or a combination of gaps and overlaps. A coverage of 0 percent indicates that a tow is cut as soon as one edge reaches the boundary of the adjacent course. This results in a small triangular area without fibers. At 100 percent coverage the tow is cut only when the second tow edge crosses the boundary, hence creating a small triangular overlap area. Coverage values between 0 and 100 percent

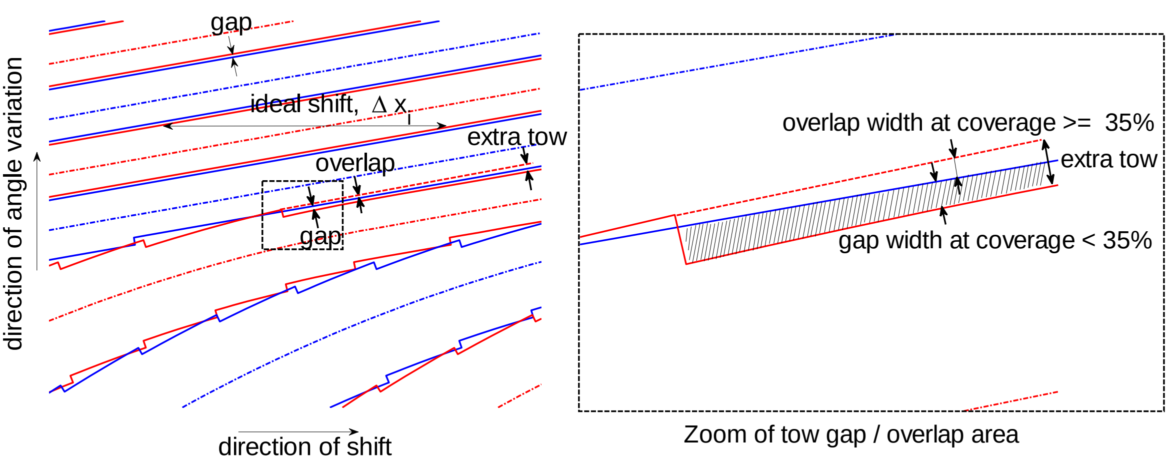


Figure 4: Gaps and overlaps in parallel course areas

represent the intermediate cases. Three examples are given in Figure 3.

A coverage parameter of 0 was demonstrated to be undesirable by Blom [8], while 100 percent coverage might result in an uneven surface. Therefore, a coverage parameter close to 50 percent is preferred [7]. The result can be seen in Figure 2(a), where the red tows belong to one course and partially overlap the green tows belonging to the other course.

Figure 5: Tow-cut and parallel course details

In some cases adjustment of the coverage parameter alone will not be sufficient to eliminate large gaps or overlaps [7]. The first steered ply of the optimum laminate for example has a large area where the fiber orientation angle is constant, which results in long stretches of parallel courses. In general these parallel courses do not exactly line up, causing either a long slit or a long line with overlapping tows. A schematic view of this is shown in Figure 4. By the proper amount of shift between courses the parallel parts of the laminate can be designed such that the courses exactly line up and a good laminate quality is obtained. The result of this design adjustment is shown in Figure 5.

The location of the tow cuts can be seen in the NDI scan of the cylinder in Figure 6. On one side of the cylinder the courses are steered more, requiring more tow drops in order to maintain a constant thickness (the areas on the left and the right in the figure). The other side of the cylinder contains mainly parallel courses, showing less irregularities (middle of the figure). The circumferential irregularities in the middle of the figure (dark horizontal lines) are suspected to be due to a thermal mismatch between the part and the tool.

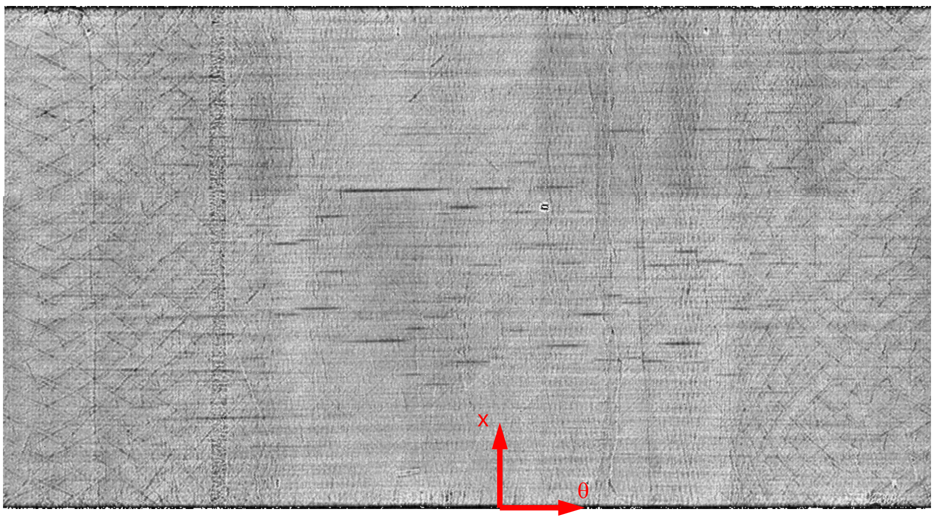


Figure 6: NDI scan of the variable-stiffness cylinder

4.3 Minimum Cut Length and Tow Straightening

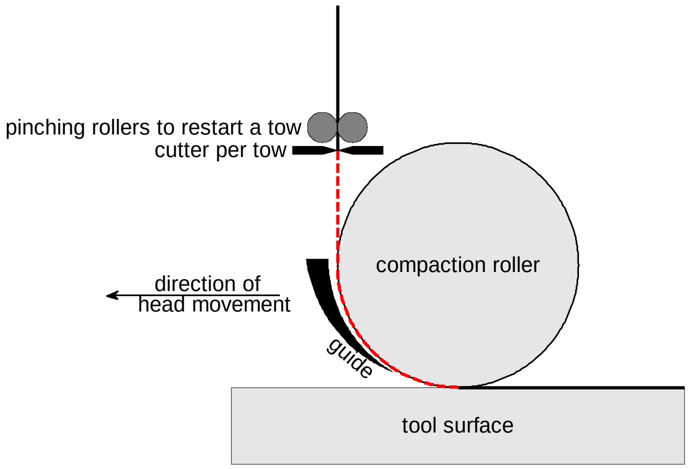


Figure 7: Schematic view of fiber placement

When a tow is restarted it is moved forward by pinching rollers until the tow reaches the surfaces and is being pulled forward by the friction between the compression roller and the tool surface. If the desired length to be put down is smaller than the distance between the cutter and the contact point, there is no control over the tow and thus the software prevents the placement of the tow. The minimum required length is called the *minimum cut length* and is indicated by the red dotted line in Figure 7. For the Ingersoll machine used, the minimum cut length is 4.2 inches. In case of minimum cut length violations small adjustments of the coverage parameter were made in order to meet the required minimum length of 4.2 inches. At the part edges the minimum cut length requirement could not always be met, and were therefore filled in by hand. Most of these areas will be trimmed from the final part.

The minimum cut length also plays a role when a steered fiber path is being placed on the surface and tows are cut on the outside of the turn. Once the tow is cut, there is very little control over the direction by the guiding rollers anymore and the tow follows the geodesic path instead of the curved path, so-called *fiber straightening*. This is not the case when the tow is cut on the inside of the turn, because then the neighboring tow forces it to follow the curve. Since the fiber straightening was not anticipated, no design adjustments were made to prevent it. The length over which the tow path deviates from the designed path was measured on the manufactured variable-stiffness cylinder and is equal to the minimum cut length. The fiber straightening is shown in Figure 8. For the current test specimen the straight tows were realigned with the curved tows by hand in order to obtain the intended configuration. In future designs fiber straightening can be avoided by designing the steered courses such that no tows are cut on the outside of a turn. Also the deviation from the intended path will be smaller when a larger turning radius is used.

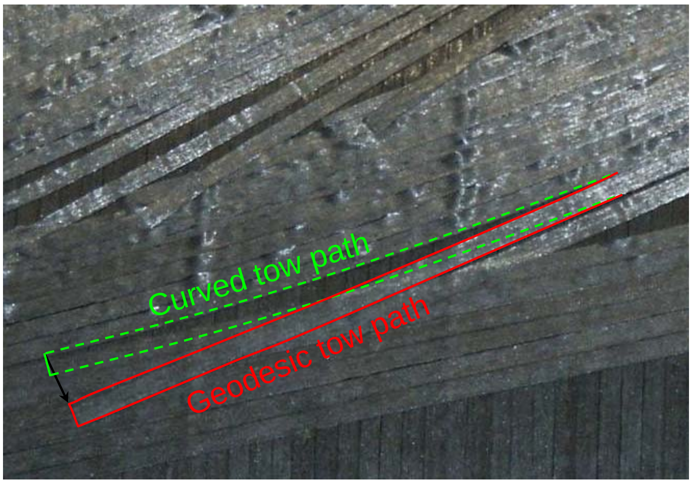


Figure 8: Fiber straightening at the outside of a steered course

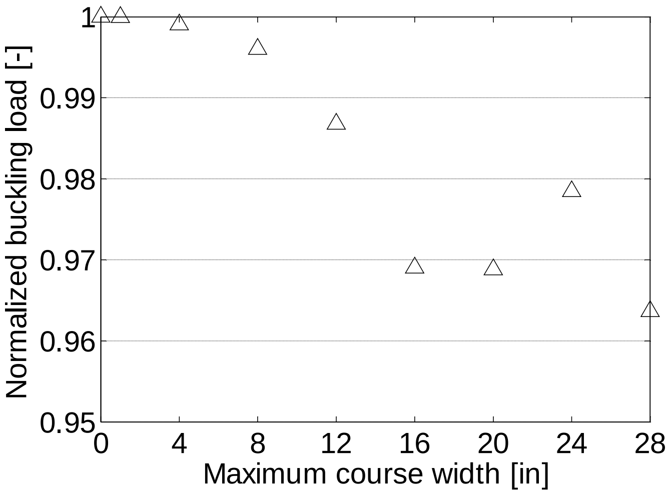


Figure 9: Buckling load vs maximum course width

Furthermore, the number of tow cuts and adds could be reduced by placing a number of courses parallel, as if a wider course was placed on the surface. This causes a larger deviation from the intended fiber angle distribution, as described in reference [6], but as this deviation can be taken into account in the finite element analysis the influence on structural performance can be evaluated. For example, the variation of the buckling moment as a function of the maximum course width is shown in Figure 9 normalized with the buckling moment of a cylinder with a perfect circumferential variation. The built cylinder which has a maximum course width of 4 inches shows less than 0.1 percent reduction in buckling load compared to the ideal layup. A maximum course width of 12 inches would result in less than 2 percent reduction in buckling load, while the number of tow drop boundaries would be three times less than in the current design.

5. CONCLUSIONS AND FUTURE WORK

A cylindrical shell with varying fiber orientations was manufactured using advanced fiber placement technology. The small dimensions of the shell required a small turning radius, causing puckers to form during lay-down which were not visible in the end product. On a product with larger dimensions a larger turning radius can be used to obtain the same stiffness variation, resulting in less puckering. The amount of small triangular gaps and overlaps was minimized by using a 50 percent coverage parameter, while long gaps between parallel courses were avoided by adjusting the shift between courses. The minimum cut length requirement was taken into account during design, preventing any deficiencies. Cutting tows on the outside of a steered course caused problems, because the outer tows were not restrained and thus followed a geodesic path. In future designs this can be avoided by not allowing tows to be cut on the outside of a turn. Furthermore increasing the maximum course width will result in less tow drop areas.

Currently a modal test is being carried out on both the variable-stiffness shell and the traditional shell, after which they will be prepared to be structurally tested in pure bending. Comparisons between analytical and experimental results will be published for both tests.

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