Hy-Bor® for Advanced Hat-stiffened Aircraft Structures

A design and verification study was undertaken by the Boeing Phantom Works, St. Louis, MO to evaluate the potential structural benefits and cost impact of the selective use of Hy-Bor® hybrid boron-graphite prepreg tape in an advanced aircraft design.

Emerging composite hat stiffened skin designs for combat aircraft are using a design approach where the inner moldline skin, web, and cap plies are continuous. This design approach has shown a performance benefit over discrete flange concepts, especially in high compression load applications. The objective of this study was to determine the structural efficiency benefits of Hy-Bor® in composite material design and to perform a manufacturing cost analysis. Using loads typical of a highly-loaded compression region of an advanced aircraft wing skin, this analysis task used Boeing software tools to optimize a composite baseline hat section design.

Typical geometric parameters considered for optimization are shown in the Figure 1. The baseline design consisted of Cytec’s T40-800/5215 tape and T300 5HS/5215 fabric. Starting with the optimized baseline design, Hy-Bor® was integrated into the cap and base regions to develop an optimized Hy-Bor® reinforced hat design. It was expected that the Hy-Bor® reinforced hat design would allow for an increase in hat spacing (Figure 2), a reduction in skin thickness, or reduction in hat size leading to significant weight savings. In addition to determining potential weight savings, a manufacturing cost comparison between the baseline and Hy-Bor® reinforced concepts was conducted.
Based on initial design requirements, the baseline skin thickness was set at 0.13-inch thickness (min.) with a mandrel height of 2" and mandrel cap width of 1.5". Based on these requirements and design loads, a baseline concept was determined.

Using this baseline concept, Hy-Bor® plies were then added to both the hat cap and the skin area under the hat. Five variations in skin laminates ranging from 0.1302" - 0.141" in thickness were considered. The addition of Hy-Bor® plies in into the skin had no effect on weight, mostly due to the closeness of the skin panel to the structure’s neutral axis. A weight savings of only 1% (0.2 lbs for the 17.5 lb study panel section) was realized.

Thinner skin laminates, ranging from 0.1192 to 0.1248-inch, were then evaluated. With Hy-Bor® plies only in the cap regions of the hats, the weight savings were still in the 1% range. The hat height was then varied between 1 and 2-inches at 0.25-inch increments. The hat cap width was varied in the same manner. The hat web angle remained the same since this angle was found to be optimum based on studies conducted on previous Boeing programs. Three skin laminates at two thicknesses (0.1194 and 0.1302-inch) were considered. As before, Hy-Bor® plies were placed in the cap of the hat. At this point a weight savings of 0.8 lbs or nearly 5% on a panel basis was realized. Final panel geometries for the Baseline and Hy-Bor® designs are shown in Figure 3.

Considering an advanced aircraft platform with approximately 3000 lbs integrated hat-stiffened composite structure, this translates into an appreciable 150 lbs of weight savings. A potential secondary benefit would be the 28% smaller hat height that was obtained. In a wing portion of such a design the smaller hat sections could allow increased fuel capacity.
A cost comparison was completed for the baseline hat stiffened panel design and the Hy-Bor® hat stiffened panel design. Design and manufacturing information for each design was loaded into Boeing’s DFM software and labor outputs were compared. Inputs
consisted of the number of skin plies and skin lay-up information, and the number of hats and hat ply lay-up information.

It was assumed that the same outer mold line (OML) tool would be used for both designs and would not impact the cost comparison; therefore, only mandrel tooling was estimated. Estimates for the mandrel tooling were made by tool engineering rather than using the DFM software.

A summary of the cost comparison breakdown between the baseline and Hy-Bor® designs is presented in Figure 4. Assumptions used in the cost estimating process are listed below:

1. The part lay-up was broken down as follows to get the most accurate estimate:
   - Skin -- Two plies of cloth and 11 plies of tape
   - Hat web -- Two plies of cloth wrapped around the mandrel
   - Hat cap -- 5215 tape or Hy-Bor® tape depending on which design
   - Over lay plies -- 2 Cloth plies laid over the skin and hats

2. Cytec material cost per pound for small quantities supplied by Cytec:
   - T40-800/5215 tape -- $81.63/lb
   - T300 5HS/5215 cloth – $49.08/lb

3. Calculations were made to determine a cost in $/lb for Hy-Bor® prepreg with a 5215 resin as follows:
   A. Cost of T40-800/5215 tape was converted from $81.63/lb to $1.73/LF
      \[ \frac{81.63}{0.055} \times \frac{1}{0.0054} \times \frac{144}{0.5} = 1.73 \text{$/LF} \]
   B. SMI cost of $17.75/LF and added to cost of 5215 tape of $1.73/LF
      \[ 5215 \text{ Hy-Bor} = 19.48 \text{$/LF} \]
   C. Cost of 5215 Hy-Bor® was converted from $19.48/LF to $693/lb
      \[ \frac{19.48}{1/0.4392 \times 0.064} = 693 \text{$/lb} \]

4. There were no manufacturing differences between the two designs; the only differences were the hat cap material and hat sizes. The DFM results show a slight cost savings for the Hy-Bor® design because of less 5215 material cost and slightly
less labor (due to smaller hat size) but a significant cost increase in the hat cap material as compared to the baseline hat cap material cost.

<table>
<thead>
<tr>
<th></th>
<th>Baseline Design</th>
<th>Hy-Bor Design</th>
<th>Hy-Bor Cost Increase</th>
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<tbody>
<tr>
<td><strong>SKIN</strong></td>
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<td><strong>HATS</strong></td>
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*Added cost of web plies and cap plies and multiplied by 6 hats

** These are the 2 cloth plies that go over the hats and continue over the skin. They were not accounted for in the skin or hats.

**Figure 4 - Cost Comparison Summary**
The structure used as the basis of this trade study represented an advanced airframe concept containing approximately 3,000 lbs. of hat-stiffened skin composite structure. Application of Hy-Bor® to the skins of the structure did not result in a significant weight savings; however, a weight saving of 5% (150 lbs. total) was achieved with the inclusion of Hy-Bor® in the hat components and appropriate resizing. The reduction in hat depth resulting from increased compression properties in the cap region provides an opportunity for significant increase in fuel capacity in the wing portions of the structure. On a total baseline structural weight of 3,000 lbs., the projected materials and manufacturing cost to save 150 lbs. would be $127,575, or $850.50/lb of weight saved. The value of increased internal wing volume for fuel was not estimated.

In the verification portion of this study a Hy-Bor reinforced, hat stiffened panel (Figure 5) was fabricated and machined to produce three hat stiffened panel subcomponents for structural testing in combined compression-pressure.

![Figure 5 - Subcomponent Plan for Hat-Stiffened Panel](image-url)
The panel fabrication consisted of a series of debulking operations to remove entrapped air and aid in compaction. Figure 6 shows one such operation that occurred after the majority of the skin, hat mandrels, inner wrap hat plies, and first three Hy-Bor cap plies were located.

Figure 6 - Hat-Stiffened Panel During Typical Debulking Operation
(Skin, Hat Mandrels, Inner Wrap Hat Plies and First Three Hy-Bor Cap Plies in Place)

After curing, the panel underwent a post cure at 350°F for four hours. The hat ends were trimmed and the panel has been sent to NDI prior to subcomponent extraction. The completed stiffened panel is show from the inner mold line and outer mold line in Figures 7 and 8, respectively.
Ultrasonic nondestructive inspection revealed that no significant indications were present and the panel was of production quality. The test subcomponents were then machined from the panel (Figure 9) and configured with load adapters in preparation for instrumentation and test (Figure 10).
Figure 9 - Machined Subcomponents
The compression test set-up is shown in Figure 11 with a close up of the subcomponent from the inner moldline (IML), stiffener side, shown in Figure 12. The simulated air pressure of 5 psi was applied to the tension pads, Figure 13, through a dead-weight setup which simply utilized a mobile hydraulic lift which held the dead weight in place and slowing released the weight to apply load to the tension pads (Figure 14).
Figure 12 - Close-up of Subcomponent 1 during Test IML (Stiffener Side)
Figure 13 - Tension Pads on OML Surface of Subcomponent 1
Design ultimate compression load (DUL) for the subcomponent was 16,500 lbs. Subcomponent 1 achieved that level with no audible indications of failure events. Continuation of the test resulted in failure at 22,555 lbs of compression load with no audible indications of failure until the failure load was reached; audible cracking and associated response in strain data indicated failure had occurred. Failure occurred in the hat run-out region at the top of the subcomponent, Figure 15. This failure is typical of this advanced hat design concept which precludes failure from occurring at the hat flange/skin location at lower loads since there is no discrete hat flange/skin interface.
The compression with pressure load testing was subsequently conducted on subcomponents 2 and 3. The failing loads for all three subcomponents were:

- Subcomponent 1 22,560 pounds
- Subcomponent 2 16,180 pounds
- Subcomponent 3 32,080 pounds

While this is a considerable spread in the test results, the failure mode, delamination in the hat taper run-outs, was similar for all subcomponents. Failure locations for each of the subcomponents relative to key strain gage locations are shown in Figure 16. Axial strain gage response on each side of the hat run-out at each end of the subcomponents is shown in Figures 17 through 19 for Subcomponents 1, 2, and 3, respectively. The deviation in strain at loading onset is due to the applied 5 psi pressure load.
**Figure 17 - Axial Strain Gage Results – Subcomponent 1**

**Figure 18 - Axial Strain Gage Results – Subcomponent 2**
Figure 19 - Axial Strain Gage Results – Subcomponent 3

The strain response indicates the presence of beam-column action which is expected for combined compression-pressure loading. The results indicate that the degree of bending strain caused by beam-column action has a profound effect on failure load. It should also be noted that the strain results indicate that subcomponents’ stiffness were similar.

Prior to this project Boeing conducted an in-house program to develop an advanced all carbon/epoxy concept that was designed to similar loading and tested in compression with 5 psi simulated pressure. Although all the details of this design cannot be disclosed in this paper, enough detail can be shown to make a strength vs. unit volume weight comparison, Figure 20. It should be noted that the highest (32,080 lb.) Hy-Bor test result was used in the comparison. Also, the advanced hat concept value is based on one test.

Key information that can be observed from this comparison is:

- Strengths per Unit Volume Weight are very similar ~ 500 Kips/lb.
- Hy-Bor design is over 8% lighter.
- Reduced hat height will result in increased fuel or payload capacity.
Figure 20 - Strength per Unit Volume Comparison

Conclusion

This design and verification study was conducted to demonstrate the structural and cost effectiveness of hybrid boron/graphite composite tape (Hy-Bor®) in an advanced composite hat stiffened skin aircraft structure. The design study revealed that, for the specific structure in the study, Hy-Bor could be used in the cap portion of the integral hat stiffeners to reduce weight by 5%, at an additional cost of $851 per pound of weight saved. An additional benefit to the study design was a 28% reduction in hat height that might translate into a usable volume increase. The verification portion of the study confirmed the ability to meet and exceed the DUL. Comparison to a baseline design with equal strength per unit volume capability reveals an 8% weight savings.