# NASA Ares V Heavy Lift Vehicle Structural Analysis and Composite Material Weight Savings

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**For the NASA Heavy Launch Vehicle (HLV), substantial weight reduction is possible by designing the Payload Shroud, Interstage, and the Core Intertank structures with composite material. Previous trade studies reported included honeycomb and reinforced core sandwich panels and Hat, I, Tee, Blade, and PRSEUS stiffened panel concepts. The composite hat stiffened panel was reported as the lightest concept for each HLV structure. The honeycomb sandwich and hat stiffened concepts were down selected. This paper provides an update to the 2010 paper and focuses on the panel acreage, ring frames, and joints of the Interstage; a cylindrical barrel axially compressed that must withstand crushing and internal pressure causing compressive and tension hoop panel loads. For the Interstage, a composite honeycomb sandwich design is 33 percent heavier than a composite hat stiffened panel design. Likewise, the lightest metallic design is 54 percent heavier than the composite hat stiffened panel design. HyperSizer® commercial software is being used to further mature the hat design's composite laminates of hybrid fabric and tape and panel cross-sectional dimensions to achieve minimum weight, damage tolerance, producibility, and affordability.**



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# Contents

# 1 Introduction

NASA's Constellation Program for human spaceflight was officially cancelled in October 2010. The Ares V launch vehicle was a key component in NASA's Constellation Program. The Advanced Composite Technology Project was evaluating the performance of three primary composite "dry" structures: Shroud, Interstage, and Core Intertank. HyperSizer® commercial software was used by a nationwide NASA team for the analysis, design sizing, and weight reduction of all three structures as reported in Reference 1 and Reference 2.

Collier Research Corporation is continuing technology development for large axially loaded cylindrical structures for the next generation heavy lift vehicles (HLV). This paper reports on the current assessment of progress that is directed to composite structures weight savings, producibility, affordability, and damage tolerance.

Previous trade studies reported included honeycomb and reinforced core sandwich panels and Hat, I, Tee, Blade, and PRSEUS stiffened panel concepts. Though several different panel designs were considered, the hat stiffened panel was determined to be optimum for each composite HLV structure. The honeycomb sandwich and hat stiffened concepts were down selected. This paper provides an update to the 2010 paper [1] and focuses on the panel acreage, ring frames, and joints of the Interstage. Hat weight along with associated ring frame weight, joints, and fasteners, in total, is lighter than the honeycomb sandwich panel concept.

### 2010 Hat Design

For the Ares V composite Interstage, the optimum composite honeycomb sandwich design is 33 percent heavier than the 2010 optimum designed composite hat stiffened panel. Likewise, the lightest metallic design is 54 percent heavier than the composite hat stiffened panel design. HyperSizer® commercial software is being used to further mature the hat's 2011 design of hybrid fabric and tape composite laminates and panel cross-sectional dimensions to achieve minimum weight, damage tolerance, producibility, and affordability.

### 2011 Hat Design

The 2011 hat designed for producibility and affordability is 640 pounds heavier than the 2010 hat design [1]. This causes a 10 percent weight growth, and the 2010 design of 33 percent weight savings to now be 23 percent. The redesign is very recent and was not considered in reference 2 and is intended to address the cost concern listed in the figure-of-merit of reference 2. Affordability is the driving factor for 2011 plus, the new hat design is more manufacturable and the recurring and non-recurring cost reported in [2] should be substantially less. Cost estimates should also consider benefits of a relatively simple and easily fabricated and assembled internal ring frame attachment joint design that stiffened panels offer that other concepts do not.

In this paper, Section 2 summarizes previous work and ongoing research. Section 3 shows cross-sectional dimensions and laminates of improved hat designs. Other sections address ring frame integration and joint impacts on weights. The final section combines all data in summarized tables for the latest and most current weights for all panel concepts for HLV/Ares V structures. Lastly, weights for metallic sandwich and metallic stiffened panel designs are included for trade study completeness. Though they are substantially heavier, with friction stir welding automation of the stiffener to skin, they appear to be the most inexpensive barrel structures to fabricate.

### 1.1 The NASA Heavy Lift Vehicle (Ares V)

The Ares V was intended as a cargo launch vehicle. It was designed as a two-stage rocket that consisted of a Core Stage and an Earth Departure Stage (EDS). Dimensions are reported in Reference 1. Notably, the Interstage is a 33-foot diameter, 48-foot tall cylindrical (barrel) that connects the EDS to the lower stage in the vertical stack, Fig. 1. The cylindrical structure is axially compressed but must also withstand crushing and internal pressure causing compressive and tension hoop loads.

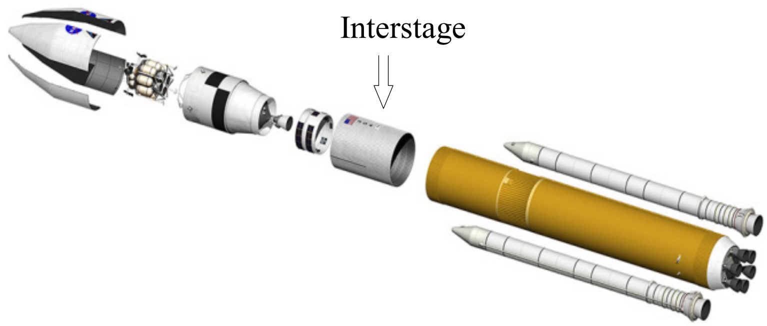



*Fig. 1- NASA teams used HyperSizer for Ares V heavy lift composite structures for weight trade studies and automated analysis.*

The length of each composite Ares V structure requires ring frames to provide buckling stability.. Stiffened panels require more ring frames than sandwich panels. Ring frame weight is an important contributor to the acreage design and was quantified for each concept in trade studies [1].

### 1.2 NASA-HyperSizer National Team

In 2009, NASA formed the Advanced Composites Technology (ACT) program with the objective to study and develop technology to build a lightweight, cost-effective space structure from composite materials. The Advanced Composites Team was composed of research engineers from nearly all of NASA's research centers (Langley, Glenn, Marshall, Ames, and Goddard) who were using HyperSizer to perform weight trade studies. A major accomplishment of ACT was the complete design, analysis, and documentation of the Ares V composite Shroud, Interstage, and Intertank structures. By using HyperSizer, the ACT team members have produced high fidelity panel designs and detailed weight reports for many concepts in a relatively short period of time. During this process, two new panel concepts were introduced (Reinforced Core Sandwich and Poltruded Rod Stiffened PRSEUS) and seamlessly incorporated into the trade space without effecting the schedule.

The results reported in this paper are those from Collier Research Corporation, the developers of HyperSizer software. They are similar in trend and magnitude as those produced by the NASA team using HyperSizer. The differences between results reported here and those of NASA [2], are due to Collier Research's experience optimizing with HyperSizer and having more current sizing results that include producibility cost reduction efforts with fabricating demonstration articles. This evaluation is the basis of the scoring presented in the Weight Maturity Level (WML) tables, Section 8.3.

## 1.3 Panel Concepts

Many panel concepts are considered for each Ares V structure, Fig. 2, and each concept is optimized to find the lightest weight combination of cross-sectional dimensions, materials, and layups based on ring frame spacing.

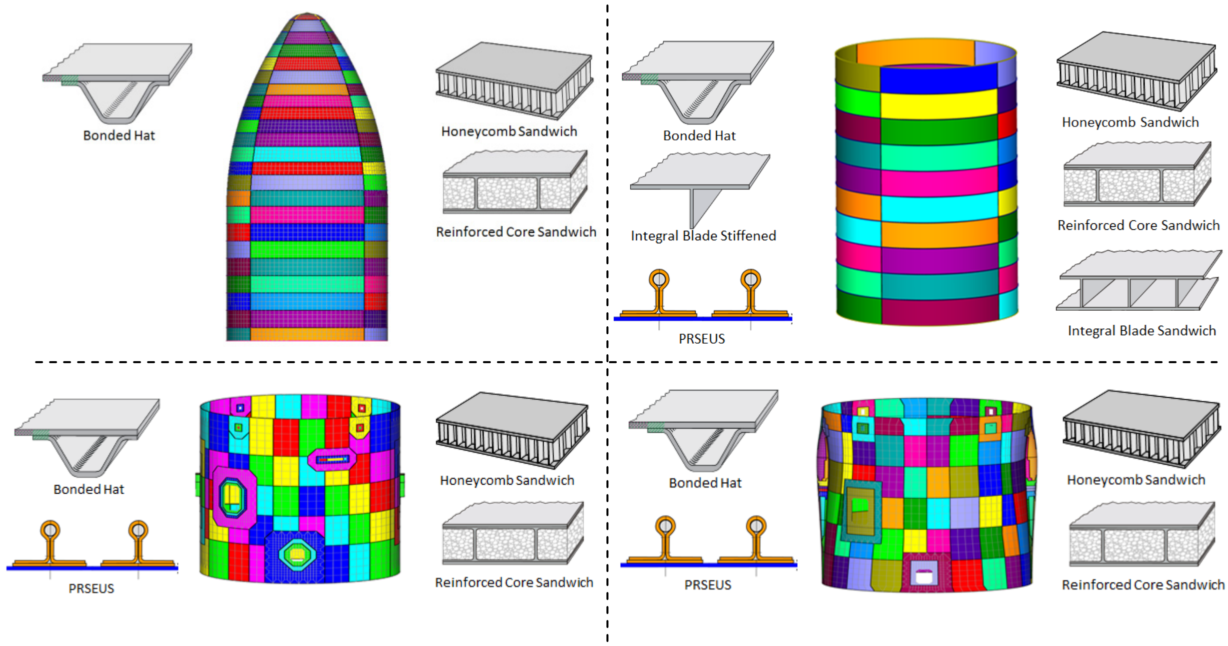



*Fig. 2 - Primary panel concepts considered for each structure: left Shroud, right Intertank, and bottom Core Intertank. Both variations of Core Intertank are depicted above, (bottom right) beamed Core Intertank, (bottom right) beamless Core Intertank. Color regions on the FEM represent component sizing zones.*

## 2 Analysis and Design Technology Status

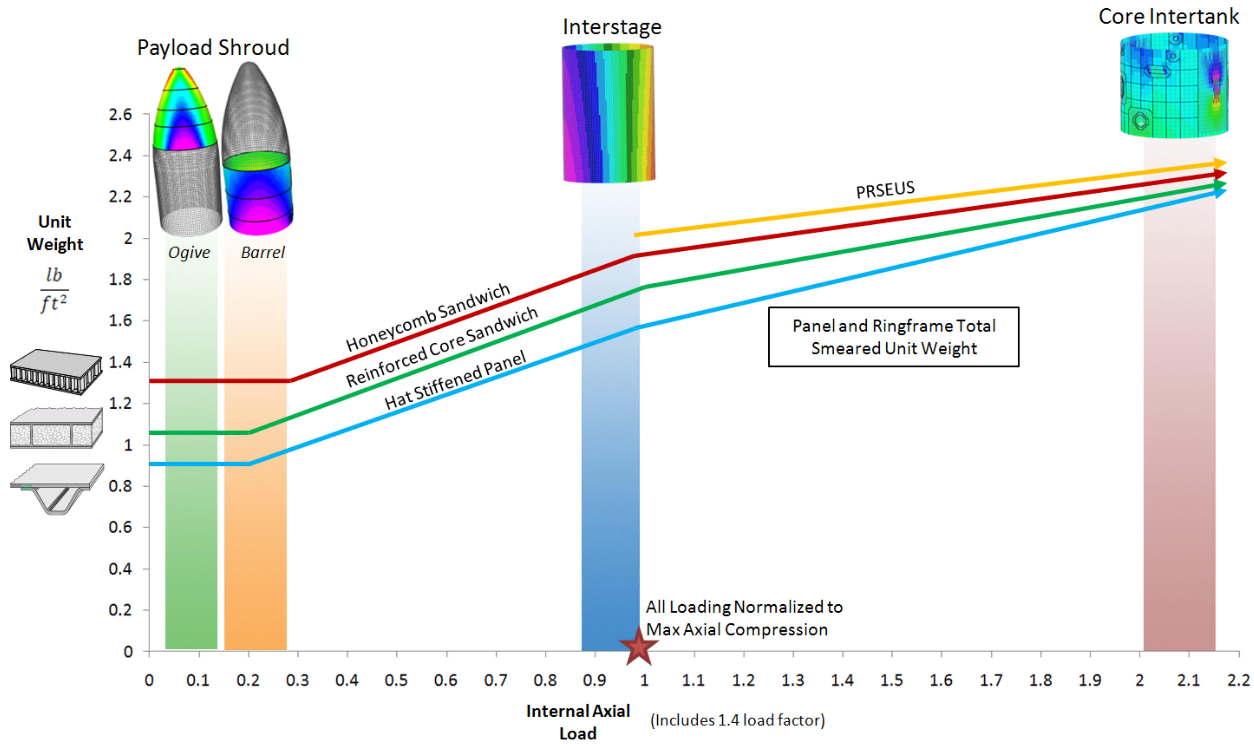



*Fig. 3 - Total weight trends for panel concepts of composite structures.*

The three weight competitive panel concepts for the Shroud, the Interstage, and beam Core Intertank are hat stiffened panel, reinforced core sandwich, and honeycomb sandwich, see Fig. 3. Hat stiffened is the lightest overall panel concept for all three Ares V structures, followed by reinforced core sandwich and honeycomb sandwich. The PRSEUS (Pultruded Rod Stitched Efficient Unitized Structure) concept is added to the design space for the Interstage and Core Intertank. Due to its ability to carry high biaxial loads, the PRSEUS concept proves to be a weight-competitive option for the Interstage and Core Intertank.

The Ares V Payload Shroud is lightly loaded which causes most panel concepts to optimize to minimum gage, Fig. 3. The zero slope section of the curve represents minimum gage. Hat stiffened panels are lighter for this application mainly because they have no parasitic weight as sandwich panels with core and adhesive do. The Interstage is moderately loaded in axial compression. Hat stiffened panels are lighter in this scenario because they are more efficient at providing the material strength and stability required to carry the axial compression. When higher loadings are present in the Core Intertank, the panel weights begin to converge. The most current weights are presented in Section 8.

## 2.1 Previous Research

Many weight trends as a function of ring frame spacing for each panel concept are presented in Reference 1. By plotting the trend lines that include panel acreage weights and associated ring frame weights, the optimal solution for each panel concept is determined. All trades include accurate failure analyses performed by HyperSizer. All panel concepts reported achieved positive margins of safety for all relevant failure modes and for all load cases.

Once a general trend line is determined, per panel concept, its unique optimum ring frame spacing is evaluated in more detail and matured by iterating HyperSizer with FEA static and buckling solutions, using full-scale finite element modelswith HyperFEA®. This insured that all of the FEA-computed internal loads were converged between load sharing ring frames and panels.

FEA was used for another purpose. For the most promising panel designs, detailed and discretely meshed models were made using HyperFEMgen™ and used for advanced FEA verifications. Multiple independent verifications of HyperSizer's failure predictions were performed with FEA. These included linear static stress analysis, buckling eigenvalue solutions for full barrel cylindrical buckling, panel buckling, local buckling, and cross-section crippling [1]. The buckling FEA was performed with NEi/Nastran, Nx/Nastran, and Abaqus. Geometric nonlinear Abaqus analyses were performed to quantify imperfection sensitivity and post buckling strength until the laminate strain reached the damaged tolerance allowable, or until ultimate collapse, whichever occurred first.

Reference 1 also describes why hat stiffened panels are the lightest panel concept. Hat stiffened panels have more design variables than sandwich panels. The additional design variables of a stiffened panel provide more opportunity for weight savings and if fully explored, as is done with HyperSizer, a stiffened panel with a proper combination of cross-sectional dimensions and laminates can be lighter than a honeycomb sandwich. Also, the core of a sandwich panel doesn't carry membrane loads such as the axial compression. For this reason, its weight and its adhesive are considered parasitic.

A weight saving recommendation was made to not use the NASA SP8007 cylindrical buckling knockdown factor for stiffened panels that have a relatively short span distance between ring frames in relation to the barrel diameter [1]. The panel aspect ratio creates a direct load path which puts the stiffeners into column compression. The observed controlling buckling modes are not cylindrically influenced and as such, are not benefiting from curved buckling methods. A case in point, the difference between flat and curved panel buckling predicted loads for stiffened panels are less than the 0.65 knockdown factor used for trade studies. However, the sandwich panel benefits from being curved and a knockdown is appropriate for them as well as orthogrid panels. All of the total results reported, including this paper, have applied the 0.65 buckling knockdown factor to all panel concepts regardless of their applicability. The use of a 0.65 knockdown together with a 1.4 ultimate load required the overall barrel to be buckling stable up to 2.15 limit loads (1.4/.65).

The stiffened panels were allowed to have skin buckling at limit loads. Stiffened panels were optimized to carry additional ultimate load in a post buckled state. [Collier, post buckling]

### Increasing the Crown Width

In attempts to reduce the count of 0° plies in the bottom crown, a hat design with a wider crown was studied. A wider crown allows less 0° plies to achieve the same $D_{11}$ ($EI_1$), panel bending stiffness. However, this allows the crown to local buckle sooner. HyperSizer reoptimized the crown width to achieve close to a zero margin at limit load. As predicted by HyperSizer, and verified with

Abaqus nonlinear FEA, the post buckling collapse strength of the hat panel was significantly reduced. The local buckling of the crown and web lead to a significant reduction in bending stiffness which cause crippling and panel buckling. Unsuccessful attempts were made in 2010 to design a more producible hat cross section. Success was achieved in 2011 as reported later.

**90 Degree Plies on the OML/IML to Prevent Transverse Buckling**

The Interstage design criteria is a 2.5 psi crush pressure which produces transverse (Ny) compression in the panels that is superimposed with the flight axial compression Nx loads. Biaxial compression loading causes transverse "scissor" stiffener buckling observed in hat stiffened panels. This mode is greatly influenced by the transverse bending stiffness (D22) of the skin [1]. The transverse bending stiffness in the skin prevents the compressive hoop load from causing transverse buckling waves.

Transverse bending stiffness is gained in the skin by placing 90 degree fibers close to the outside of the laminate. This design objective must be compromised with the damage tolerant guideline of placing a 45 ply on the outer laminate surface. Many trade studies were performed to understand the weight impact of moving the 90 degree fibers off the IML and OML of the facesheet and replacing them with 45 degree fibers. It was determined that by forcing a 45 ply or plies on the outer fibers, the open span width has to decrease to minimize the transverse buckling. The 2010 design uses a $[+45/90/-45]_{GSS}$ global stack sublaminate for the laminate outer surfaces.

The crush pressure loading that produces transverse (Ny) compression also causes additional weight growth in stiffened panels to avoid skin buckling. Again, this buckling mode is best avoided by placing 90 degree fibers close to the laminate outer fibers. As a side note, in-plane shear load magnitudes experienced by these structures do not significantly increase weights of the stiffened panels.

The ratio of axial compression to transverse compression design criteria was set at 10.8 percent (Ny/Nx). If this ratio was relaxed, uniaxial stiffened panels (including the hat) would have optimized to be lighter than reported in this paper by not having to resolve the transverse "scissor", stiffener buckling mode and transverse loaded skin local buckling.

## *2.2 Current Research*

Stiffened panels by definition of their many cross-sectional sizing variables, provide a wider spectrum of coupled weight-cost metrics. Sandwich panels provide few sizing variables and as a result, have a more narrow spectrum of coupled weight-cost metrics. Composite materials with layup tailoring provide a wider spectrum of coupled weight-cost metrics than metallics. So on the far spectrum, composite stiffened panels, particularly closed-section hat shaped, provide the widest range of coupled weight-cost performance metrics. Based on the flexibility of the hat composite stiffened panel, it can be optimized to better meet a target weight-cost metric.

Current research is directed to exploring designs that are more manufacturable. Many optimization trials were performed using a combination of hybrid fabric and tape laminates together with hat shapes that made tooling more assessable. Section 3.2 provides the leading candidate's design dimensions and layups. This section summarizes design features that make the hat composite stiffened panel more producible and quantifies measures of improvement.

1. The number of hat stiffeners have been reduced by 23 percent. The stiffener spacing was increased from 4.575 inches to 5.65 inches. Based on the circumference of 1,244 inches (33'*12*π), the quantity of stiffeners was reduced from 272 to 220.

2. The number of ply stack (charges) formed individually over the mandrel and then placed into the female tool was reduced by 67 percent. The number of charges decreased from five to three inches. See Section 3 for details.

3. Several cross-sectional changes were made to allow easier placement of material on the tooling, insertion of charges, and better and easier compaction:

    - Crown width was made twice as wide, from 0.835" to 1.65"
    - Angle of the web was made more shallow, from 82° to 75°
    - 45° fabric replaces tape for the OML/IML of the skin
    - 45° fabric replaces tape for the OML/IML of the stiffener
    - Ply drops are removed from the stiffener web to the flange that bonds to the skin
    - The ply count ratio of crown to web remains ≤ 4
    - Laminate thickness ratio of the crown to web is reduced from 4 to 3
    - The layup for the web is now symmetric and balanced (use of fabrics)

4. Hat longitudinal construction joints are relatively inexpensive to make, with little weight penalty; see Section 6.2. This allows fabrication of the full barrel in smaller width pieces. In turn, this allows the use of shorter arc length tooling, which eases handling and permits more parallel work flow stations.

As reported in Section 3.2, a 2011 design that includes all of these producibility attributes is 640 pounds heavier. This makes optimum sandwich panel design 23 percent heavier than the hat panel's design.

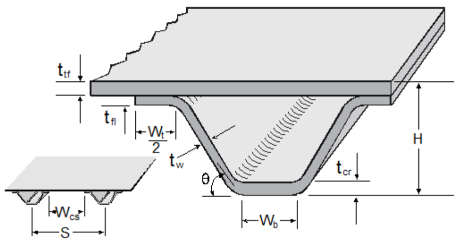
## 2.3 CAI Considerations

A hat panel exhibits fairly good compression after impact (CAI) performance. A 45° ply on the laminate outside provides damage tolerance. It keeps the 0° fiber from microbuckling, sort of like an overwrap to secure the second ply down. In a sense, it's like a sacrificial ply. If the panel is hit hard enough to completely damage a hat stiffener, the load would redistribute to the other hat stiffeners. The load capability may drop a little but is able to restore the initial value. The hat stiffener acts as a damage arrestor. Therefore, it is fail-safe.

In contrast – in compression, if the sandwich panel is impacted, a crease forms in the skin of the barrel with no damage arrestment design feature, potentially allowing the buckling crease to zip around the barrel in complete catastrophic failure.

# 3 Composite Hat Stiffened Panel Design Update

## 3.1 2010 Hat Stiffened Panel Design




| Object | Thickness (in) | Layup |
|---|---|---|
| Top Facesheet | 0.0969 | [+45/+90/-45/+90/0/90/$0_2$/_0]s |
| Bonded Flange | 0.0228 | [+45/-45]s |
| Stiffener Web | 0.0342 | [+45/-45/+45/-45/-45/+45] |
| Crown | 0.1368 | [+45/$0_3$/-45/$0_4$/+45/$0_4$/-45/$0_4$/-45/$0_3$/+45] |

**57" RF Spacing Hat Stiffened Panel Component Dimensions**

| Component | Panel Height H | Stiffener Spacing S | Crown Width wb | Web Angle θ | Flange Width wt | Unit Weight Panel Only | Area | Total Weight Panel Only |
|---|---|---|---|---|---|---|---|---|
| Type | (in) | (in) | (in) | (°) | (in) | (lb / ft$^2$) | (ft$^2$) | (lb) |
| Hat Stiffened | 2.73 | 4.575 | 0.835 | 82 | 1.5 | 1.378 | 4926 | 6798 |

*Fig. 4 - Optimum Hat Stiffened Panel Dimensions and layups*

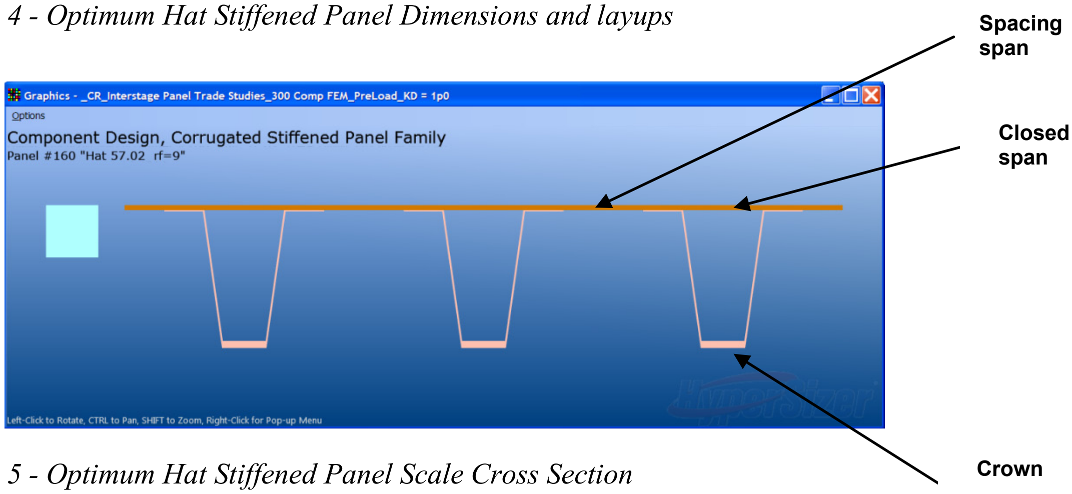
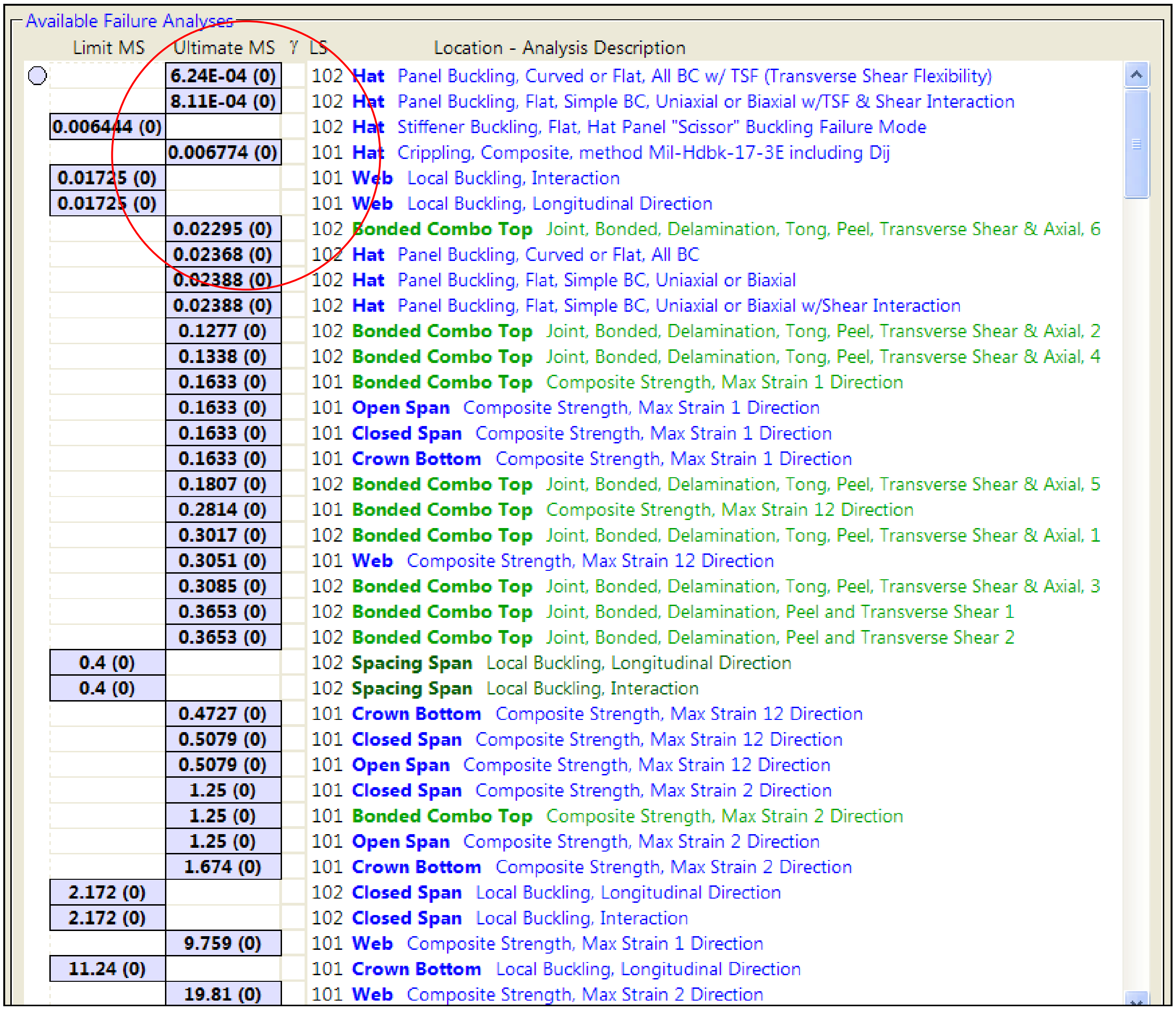



*Fig. 5 - Optimum Hat Stiffened Panel Scale Cross Section*

Biaxial compression loads present in the Ares V Interstage influence the layups of the hat stiffened panels differently than the sandwich panels. The extra 90 degree fibers are more effective at carrying the compressive hoop load created by the crush pressure and ring frame pinching effect. The stiffened panel has to carry the entire hoop load in the facesheet while providing enough strength to carry, along with the stiffener, the axial compression load.

The hat achieves panel buckling stability primarily by adding 0° plies in the crown and increasing hat height to obtain a high EI. The hat skin has a higher percentage of 45° and 90° plies to provide material strength for hoop loads and skin local buckling stability. The web is all 45° plies for laminate buckling stability. In fact, adding 0° plies to the web is detrimental in that it will cause the web to pick up more axial load and buckle sooner.



Available Failure Analyses

| Limit MS | Ultimate MS | γ | LS | Location - Analysis Description |
|---|---|---|---|---|
| | 6.24E-04 (0) | | 102 | **Hat** Panel Buckling, Curved or Flat, All BC w/ TSF (Transverse Shear Flexibility) |
| | 8.11E-04 (0) | | 102 | **Hat** Panel Buckling, Flat, Simple BC, Uniaxial or Biaxial w/TSF & Shear Interaction |
| 0.006444 (0) | | | 102 | **Hat** Stiffener Buckling, Flat, Hat Panel "Scissor" Buckling Failure Mode |
| | 0.006774 (0) | | 101 | **Hat** Crippling, Composite, method Mil-Hdbk-17-3E including Dij |
| 0.01725 (0) | | | 101 | **Web** Local Buckling, Interaction |
| 0.01725 (0) | | | 101 | **Web** Local Buckling, Longitudinal Direction |
| | 0.02295 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Tong, Peel, Transverse Shear & Axial, 6 |
| | 0.02368 (0) | | 102 | **Hat** Panel Buckling, Curved or Flat, All BC |
| | 0.02388 (0) | | 102 | **Hat** Panel Buckling, Flat, Simple BC, Uniaxial or Biaxial |
| | 0.02388 (0) | | 102 | **Hat** Panel Buckling, Flat, Simple BC, Uniaxial or Biaxial w/Shear Interaction |
| | 0.1277 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Tong, Peel, Transverse Shear & Axial, 2 |
| | 0.1338 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Tong, Peel, Transverse Shear & Axial, 4 |
| | 0.1633 (0) | | 101 | **Bonded Combo Top** Composite Strength, Max Strain 1 Direction |
| | 0.1633 (0) | | 101 | **Open Span** Composite Strength, Max Strain 1 Direction |
| | 0.1633 (0) | | 101 | **Closed Span** Composite Strength, Max Strain 1 Direction |
| | 0.1633 (0) | | 101 | **Crown Bottom** Composite Strength, Max Strain 1 Direction |
| | 0.1807 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Tong, Peel, Transverse Shear & Axial, 5 |
| | 0.2814 (0) | | 101 | **Bonded Combo Top** Composite Strength, Max Strain 12 Direction |
| | 0.3017 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Tong, Peel, Transverse Shear & Axial, 1 |
| | 0.3051 (0) | | 101 | **Web** Composite Strength, Max Strain 12 Direction |
| | 0.3085 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Tong, Peel, Transverse Shear & Axial, 3 |
| | 0.3653 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Peel and Transverse Shear 1 |
| | 0.3653 (0) | | 102 | **Bonded Combo Top** Joint, Bonded, Delamination, Peel and Transverse Shear 2 |
| 0.4 (0) | | | 102 | **Spacing Span** Local Buckling, Longitudinal Direction |
| 0.4 (0) | | | 102 | **Spacing Span** Local Buckling, Interaction |
| | 0.4727 (0) | | 101 | **Crown Bottom** Composite Strength, Max Strain 12 Direction |
| | 0.5079 (0) | | 101 | **Closed Span** Composite Strength, Max Strain 12 Direction |
| | 0.5079 (0) | | 101 | **Open Span** Composite Strength, Max Strain 12 Direction |
| | 1.25 (0) | | 101 | **Closed Span** Composite Strength, Max Strain 2 Direction |
| | 1.25 (0) | | 101 | **Bonded Combo Top** Composite Strength, Max Strain 2 Direction |
| | 1.25 (0) | | 101 | **Open Span** Composite Strength, Max Strain 2 Direction |
| | 1.674 (0) | | 101 | **Crown Bottom** Composite Strength, Max Strain 2 Direction |
| 2.172 (0) | | | 102 | **Closed Span** Local Buckling, Longitudinal Direction |
| 2.172 (0) | | | 102 | **Closed Span** Local Buckling, Interaction |
| | 9.759 (0) | | 101 | **Web** Composite Strength, Max Strain 1 Direction |
| 11.24 (0) | | | 101 | **Crown Bottom** Local Buckling, Longitudinal Direction |
| | 19.81 (0) | | 101 | **Web** Composite Strength, Max Strain 2 Direction |

*Fig. 6 - HyperSizer Hat Stiffened Panel Margins of Safety*

For the hat stiffened panel concept, both load cases effect the layups and panel geometry. Ten different potential failures have a MS from 0.0 to 0.02 with both load cases controlling, see Fig. 6. Load case 101 (compression Nx, tension Ny) is driving the material strength and crippling analysis and load case 102 (compression Nx, compression Ny) is driving local buckling, panel buckling, and stiffener "scissor" buckling.

*Fig. 7 - Fabricated hat panels; 2010 design*

| Ply | Angle | L2 | L3 | L4 | Thickness |
|---|---|---|---|---|---|
| 24 T | +45° | ■ | ■ | ■ | 0.0057 |
| 23 | 0° | □ | □ | ■ | 0.0057 |
| 22 | 0° | □ | □ | ■ | 0.0057 |
| 21 | 0° | □ | □ | ■ | 0.0057 |
| 20 | -45° | ■ | ■ | ■ | 0.0057 |
| 19 | 0° | □ | □ | ■ | 0.0057 |
| 18 | 0° | □ | □ | ■ | 0.0057 |
| 17 | 0° | □ | □ | ■ | 0.0057 |
| 16 | 0° | □ | □ | ■ | 0.0057 |
| 15 | -45° | □ | ■ | ■ | 0.0057 |
| 14 | 0° | □ | □ | ■ | 0.0057 |
| 13 | 0° | □ | □ | ■ | 0.0057 |
| 12 | 0° | □ | □ | ■ | 0.0057 |
| 11 | 0° | □ | □ | ■ | 0.0057 |
| 10 | +45° | □ | ■ | ■ | 0.0057 |
| 9 | 0° | □ | □ | ■ | 0.0057 |
| 8 | 0° | □ | □ | ■ | 0.0057 |
| 7 | 0° | □ | □ | ■ | 0.0057 |
| 6 | 0° | □ | □ | ■ | 0.0057 |
| 5 | -45° | ■ | ■ | ■ | 0.0057 |
| 4 | 0° | □ | □ | ■ | 0.0057 |
| 3 | 0° | □ | □ | ■ | 0.0057 |
| 2 | 0° | □ | □ | ■ | 0.0057 |
| 1 B | +45° | ■ | ■ | ■ | 0.0057 |

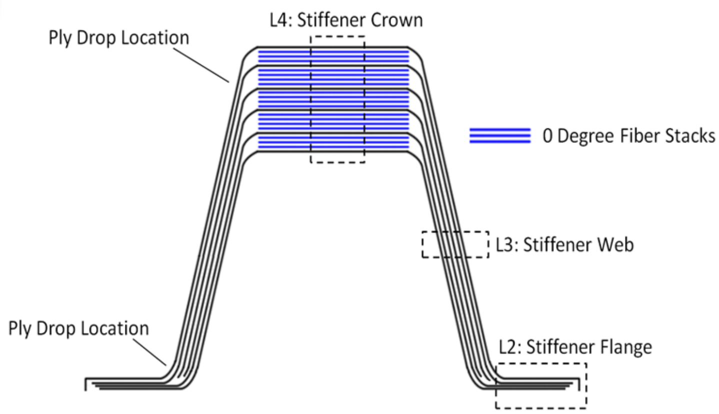
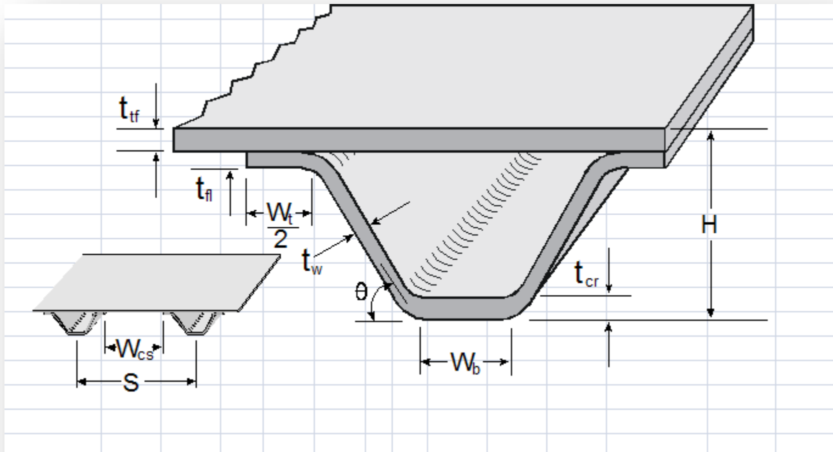



*Fig. 8 - Fabrication of stiffener crown in five charges. A charge is a stack of four 0° plies and a 45° ply.*

As seen in the photograph, Fig. 7, the crown is much thicker than the web. A unidirectionally dominate laminate in the hat crown is much like a spar cap on a wind blade. For a wind turbine blade, it is customary to have about 2 inches thick of axial laminate interleaving into a relatively thin sandwich facesheet. In these scenarios, Fig. 8, the 20 to 1 ratio ply drop off limit does not apply since the loading is also uniaxial.

The hats made were not autoclaved. Even still, the structural performance from testing proved them structurally efficient. The flange to skin cocured bond was very strong; it never pulled off even when the skin was allowed to go far into post buckling with a large amplitude mode shape.

## 3.2 2011 Hat Stiffened Panel Design




**Component Dimensions**

| Component ID | $t_{tf}$ (in) | $t_w$ (in) | H (in) | S (in) | $w_b$ (in) | θ (°) | $w_t$ (in) | $w_{cs}$ (in) | $t_{fl}$ (in) | $t_{cr}$ (in) | Unit Weight (lb / ft²) | Area (ft²) | Weight (lb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D1 1 | 0.0969 | 0.0342 | 2.74 | 4.575 | 0.85 | 80 | 1.5 | 1.321 | 0.0228 | 0.1368 | 1.385 | 0.01389 | 0.01923 |
| D2 2 | 0.1026 | 0.0342 | 2.83 | 4.9 | 1 | 78 | 1.5 | 1.274 | 0.0228 | 0.1368 | 1.439 | 0.01389 | 0.01998 |
| D3 3 | 0.1026 | 0.0399 | 2.75 | 5 | 1 | 74 | 1.5 | 1.034 | 0.0285 | 0.1539 | 1.513 | 0.01389 | 0.02102 |
| D4 4 | 0.1026 | 0.0342 | 2.65 | 5.05 | 1.4 | 75 | 1.5 | 0.8261 | 0.0342 | 0.1197 | 1.482 | 0.01389 | 0.02059 |
| D5 11 | 0.114 | 0.0342 | 2.65 | 5.6 | 1.5 | 75 | 1.5 | 1.282 | 0.0342 | 0.1197 | 1.529 | 0.01389 | 0.02124 |
| D6 12 | 0.114 | 0.0342 | 2.7 | 5.65 | 1.65 | 75 | 1.5 | 1.151 | 0.0342 | 0.1026 | 1.515 | 0.01389 | 0.02104 |
| D7 13 | 0.1083 | 0.0342 | 2.65 | 5.3 | 1.45 | 73 | 1.5 | 0.8429 | 0.0342 | 0.1197 | 1.51 | 0.01389 | 0.02097 |
| D8 14 | 0.1083 | 0.0342 | 2.85 | 5.25 | 1.075 | 75 | 1.5 | 1.242 | 0.0342 | 0.1026 | 1.438 | 0.01389 | 0.01997 |

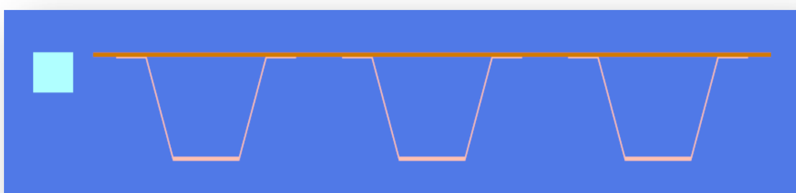


*Fig. 9 – Cross-sectional dimensions of the hat shaped stiffener. Image in blue is scaled to the one inch square to the left.*

Ply Sequence Top to Bottom

| 1 | Ply | Angle | L2 | L3 | L4 | Thickness | Density | Material |
|---|---|---|---|---|---|---|---|---|
| | 16 T | +45° | ■ | ■ | ■ | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric, |
| | 15 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 14 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 13 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 12 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 11 | -45° | ■ | ■ | ■ | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric, |
| | 10 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 9 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 8 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 7 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 6 | -45° | ■ | ■ | ■ | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric, |
| | 5 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 4 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 3 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 2 | 0° | □ | □ | ■ | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thicknes |
| | 1 B | +45° | ■ | ■ | ■ | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric, |

*Fig. 10 - Stiffener Laminate*

Ply Sequence Top to Bottom

| 1 | Ply | Angle | Thickness | Density | Material |
|---|---|---|---|---|---|
| | 18 T | +45° | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric |
| | 17 | +90° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 16 | +90° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 15 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 14 | +90° | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric |
| | 13 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 12 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 11 | -45° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 10 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 9 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 8 | -45° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 7 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 6 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 5 | +90° | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric |
| | 4 | 0° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 3 | +90° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 2 | +90° | 0.0057 | 0.057 | [O-2] Graphite/Epoxy "NASA AresV ACT IM7/8552 OHC CR", Form: Tape, Thickne |
| | 1 B | +45° | 0.00855 | 0.057 | [O-1] Graphite/Epoxy "NASA AresV ACT IM7/8552 Fabric OHC CR", Form: Fabric |

*Fig. 11 - Skin Laminate*

By comparing Fig. 9 to Fig. 5, the dramatic difference in hat designs becomes apparent. Hundreds of thousands of variations were optimized. Displayed in Fig. 9 are the eight leading candidates, D1 through D8. Highlighted in yellow is D6, the current favored design.

Due to the change in design to meet producibility, by happenstance this design is not as prone to post buckling as the previous design. No local skin post buckling occurs before ultimate loads. However, transverse, "scissor" stiffener buckling occurs right after the 1.0 limit.

# 4 Design Criteria

*Table 1 - Factors used for all Weight Trade Studies*

| Ares V Structure | Allowables Knockdown | FOS Acreage | FOS Discontinuities | Knockdown Factor | Ref: Temperature | Non-opt Factor |
|---|---|---|---|---|---|---|
| Shroud | Pristine | 1.4 | 2 | 0.65 | 72° F | 1.25 |
| Interstage | OHC | 1.4 | 2 | 0.65 | 120° F | 1.0 |
| Intertank | OHC | 1.4 (1.1 limit) | 2 | 0.65 | 72° F | 1.0 |

## *4.1 Composite Materials*

### *Payload Shroud*

An IM7/977-3 composite material system is used for the Ares V Payload Shroud design. The stiffnesses and allowables are based on F-22 and Orion data.

### *Interstage and Core Intertank*

An IM7/8552 class composite material system is used for the Ares V Interstage and Core Intertank designs. The allowables reflect knockdown open hole compression values, see Table 1. The reference temperatures defined for the trade studies are 72°F and 120°F; the material properties are evaluated at these elevated temperatures.

## 4.2 Load Factors/Knockdown factors

A 1.4 ultimate load factor is applied to the limit loads and a cylindrical knockdown factor of 0.65 is imposed for all panel concepts. Per NASA's request, a 1.1 limit factor is used for all Core Intertank panel trade studies (Table 1).

## 4.3 Failure Methods

The maximum strain failure criteria is the primary material strength requirement for all Ares V panel trade studies; cylindrical buckling with transverse shear flexibility is the panel buckling requirement.

Specifically for sandwich panels, additional failure checks include flat wise tension, facesheet wrinkling, crimping, intracell dimpling, core shear strength, etc. Stiffened panels are checked for numerous failure modes not present in honeycomb sandwich panels. These failures include initial skin buckling, post-skin buckling, local buckling of all objects such as flanges and webs, cross-section crippling, stiffener flexural torsional buckling, and hat "scissor" buckling. Bonded joint analysis is also performed for the acreage and panel stiffened flange bond to the skin using out-of-plane interlaminar shear and peel stresses. Bolted joint analysis was performed for segmented barrel construction and the end ring frame attachments.

## 4.4 Unitized Design

### *Interstage*

All weight reports presented for the Ares V Interstage assume the entire structure is designed as a single, uniform panel concept. Panel dimension changes are not permitted around the circumference of the Interstage or along the span.

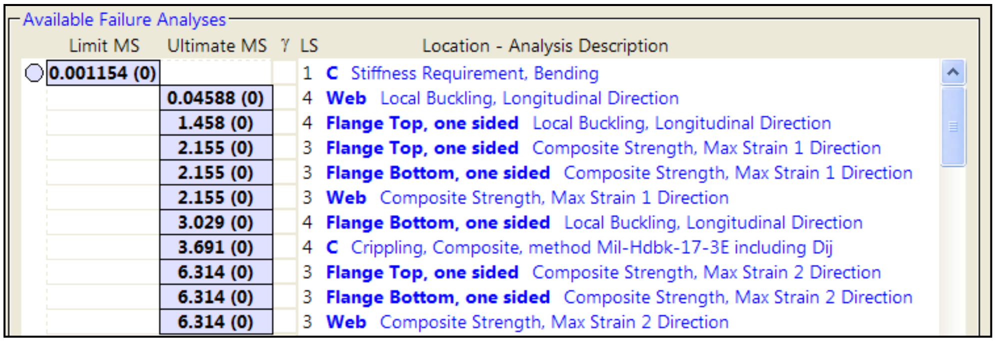
### *Payload Shroud and Core Intertank*

All weight reports presented for the Ares V Shroud and Core Intertank assume a uniform spanwise stiffener design for all stiffened panel concepts and a constant spanwise core height for all sandwich concepts.

# 5 Ring Frame Sizing and Optimum Spacing

### *Ring Frame Failure Analysis Margins of Safety (MS)*

All ring frames are sized to a required EI stiffness to prevent global buckling, material strength, local buckling of each beam object, and crippling, see Fig. 12.


Available Failure Analyses

| Limit MS | Ultimate MS | LS | Location - Analysis Description |
|---|---|---|---|
| 0.001154 (0) | | 1 | **C** Stiffness Requirement, Bending |
| | 0.04588 (0) | 4 | **Web** Local Buckling, Longitudinal Direction |
| | 1.458 (0) | 4 | **Flange Top, one sided** Local Buckling, Longitudinal Direction |
| | 2.155 (0) | 3 | **Flange Top, one sided** Composite Strength, Max Strain 1 Direction |
| | 2.155 (0) | 3 | **Flange Bottom, one sided** Composite Strength, Max Strain 1 Direction |
| | 2.155 (0) | 3 | **Web** Composite Strength, Max Strain 1 Direction |
| | 3.029 (0) | 4 | **Flange Bottom, one sided** Local Buckling, Longitudinal Direction |
| | 3.691 (0) | 4 | **C** Crippling, Composite, method Mil-Hdbk-17-3E including Dij |
| | 6.314 (0) | 3 | **Flange Top, one sided** Composite Strength, Max Strain 2 Direction |
| | 6.314 (0) | 3 | **Flange Bottom, one sided** Composite Strength, Max Strain 2 Direction |
| | 6.314 (0) | 3 | **Web** Composite Strength, Max Strain 2 Direction |

*Fig. 12 - Active Failure Analysis for Ring Frames*

By imposing the stiffness requirement, the ring frames size adjusts to tall beams with wide flanges. By virtue, this makes the web and flanges buckling critical. To meet the local buckling requirement, more 45 degree plies are added to the web. To prevent the flanges from becoming too wide, 0 degree fibers are added to the flanges to achieve the required EI. The ability to tailor the laminates to meet the design criteria allows for weight savings in composite ring frames.

### *Payload Shroud*

The ring frames for the Payload Shroud are composite and are sized to meet a required EI to prevent global buckling. Limit loads are applied to the FEM. Therefore, to achieve ultimate load with the 0.65 buckling knockdown, a 2.15 eigenvalue is required (2.15 = 1.4/.65), see Fig. 13.

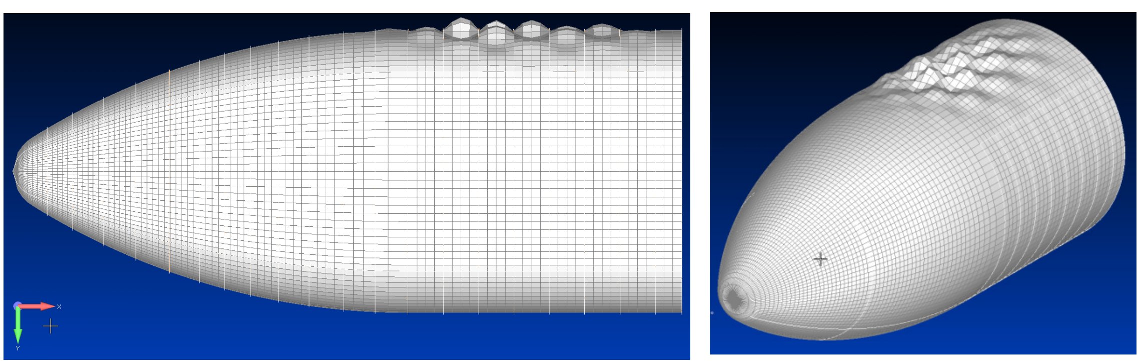


*Fig. 13 - The lowest mode shape is panel buckling between ring frames. The weight of these ring frames are included with the hat panel to get a total weight of the barrel section. HyperSizer predicts the same buckling load as the FEA eigenvalue solution (5% different).*

### *Interstage*

All Interstage ring frames are composite. For each panel concept, there are two critical ring frame stiffness values which are considered, see Table 2. The first prevents global buckling before ultimate load and the second is more conservative and prevents the buckling wave from passing through the ring frames altogether. The two FEA solutions, shown in Fig. 14 and 15, achieve the required 2.15 eigenvalue. Both solutions verify that the ring frames are stout enough to prevent global buckling from occurring before reaching the ultimate design load and that the panels themselves are stout enough to prevent buckling before reaching the ultimate design load.

*Table 2 - Required Stiffness to Prevent Global Buckling (Optimum 57" Hat Stiffened Panel)*

| EI Specified ($lb\text{-}in^2$) | Resulting EA (lb) | Beam Unit Weight (lb/ft) | Panel Buckling EigV | Buckling EigV > 2.15? | Buckling Across Ring Frame? |
|---|---|---|---|---|---|
| **1.60E+08** | 1.72E+07 | 0.73 | 2.14 | No | Yes |
| **1.70E+08** | 1.75E+07 | 0.74 | 2.148 | No | Yes |
| **1.75E+08** | 1.75E+07 | 0.75 | 2.15 | Yes | Yes |
| **1.80E+08** | 1.77E+07 | 0.76 | 2.16 | Yes | No |

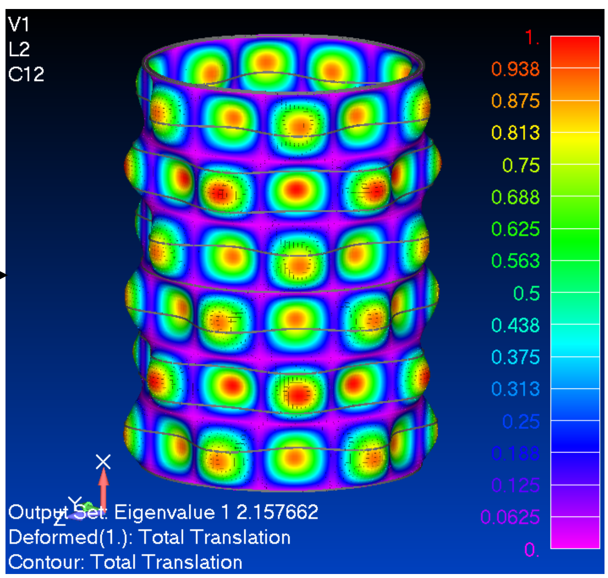



*Fig. 14 - Buckling Mode Shape for Interstage with Ring Frames Sized to Prevent Global Buckling Before Ultimate Load*

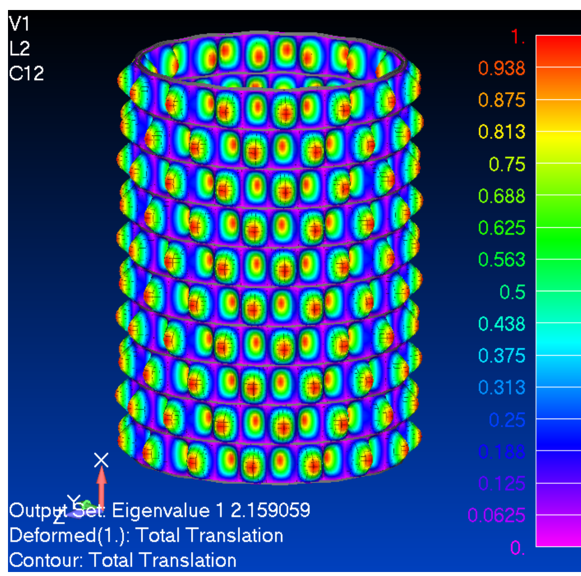



*Fig.15 - Buckling Mode Shape for Interstage with Ring Frames Sized to Prevent Global Buckling from Occurring as First Buckling Mode Shape*

### *Core Intertank*

Currently, the ring frames for the Core Intertank are metallic (Al-7075). Each ring frame is sized to minimally gage the dimensions determined to prevent global buckling using the Shanley equation. No FEA-global buckling ring frame sizing was performed to determine a required EI. There is a significant amount of weight to be removed from the ring frames once composite materials are used.

# 6 Joints

## 6.1 Ring Frame to Acreage Skin Joints

### *Honeycomb Sandwich*

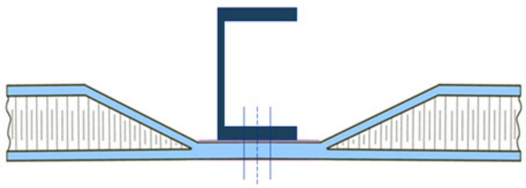


**Fig. 16 - Sandwich Ring Frame Joint Concept 1:**
Tapered Core: Weight Penalty (lb) = 140
1 Row of ¼" Fasteners: Weight Penalty (lb) = 20
Total Weight Penalty per Frame (lb) = 160

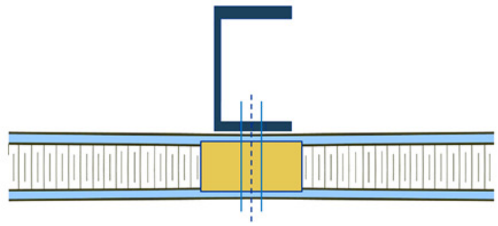


**Fig. 17 - Sandwich Ring Frame Joint Concept 2:**
Potted Core: Weight Penalty (lb) = 115
1 Row of ¼" Fasteners: Weight Penalty (lb) = 70
Total Weight Penalty per Frame (lb) = 185

Two ring frame to acreage skin joint concepts were studied for honeycomb sandwich panels, Fig. 16 and 17. The first concept is weight optimum and is listed in all honeycomb sandwich weight statements.

### *Stiffened Panel*

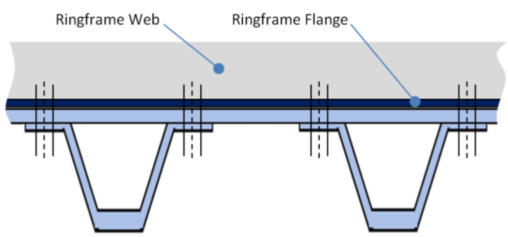



**Fig. 18 - Hat Ring Frame Joint Concept 1:**
1 Row of ¼" Fasteners: Weight Penalty (lb) = 20
Total Weight Penalty per Frame (lb) = 20

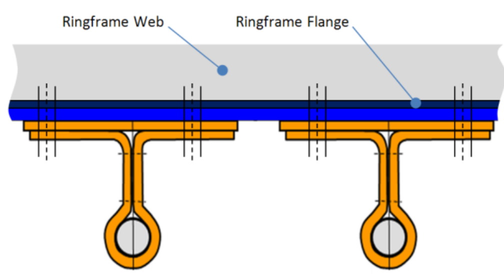



**Fig. 19 - PRSEUS Ring Frame Joint Concept <u>(Core Intertank Only)</u>:**
1 Row of ¼" Fasteners: Weight Penalty (lb) = 20
Total Weight Penalty per Frame (lb) = 20

For stiffened panels the ring frames can be attached directly to the inner mold line IML skin thus, the weight penalty is much less severe, see Fig. 18 and 19.

### *Reinforced Core Sandwich*

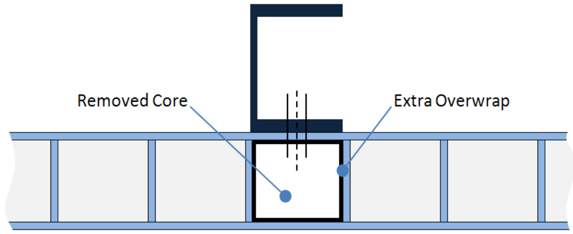



**Fig. 20 - Reinforced Core Sandwich Ring Frame Joint Concept:**
Removed Core: Weight Penalty (lb) = +7
Extra Overwraps: Weight Penalty (lb) = 42
1 Row of ¼" Fasteners: Weight Penalty (lb) = 20
Total Weight Penalty per Frame (lb) = 55

### *PRSEUS (Rod Stiffened)*

The PRSEUS concept has transverse frames that act like ring frames for cylindrical structures. In HyperSizer, the frame dimensions are sizing variables and no CBAR elements are required to represent the frames.

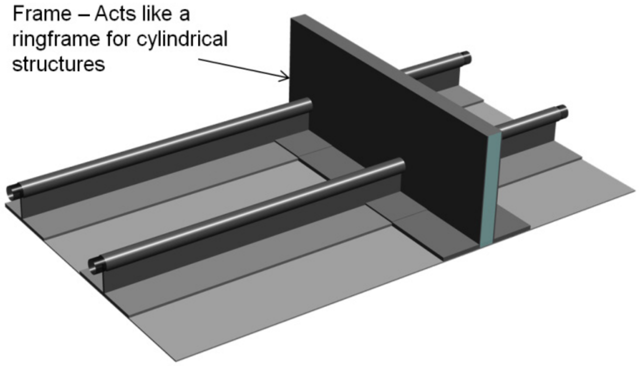



**Fig. 21 - PRSEUS Ring Frame Joint Concept (Interstage):**
Total Weight Penalty (lb) = 0

For the Interstage, the transverse frames are bonded and stitched to the skin. Since the frame weight is included in the acreage panel weight, no additional weight is required to attach the PRSEUS frames, see Fig. 21. These transverse frames are not used for the Core Intertank designs.

## 6.2 Longitudinal Construction Joints

Segmented designs are considered for use with smaller autoclaves and higher fabrication rates. The increased weight of segmenting the cylindrical structure is determined from the following sandwich and stiffened panel splice joint designs, Fig. 22 and 23.

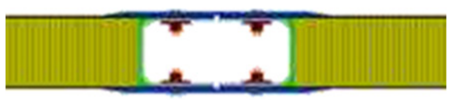


*Fig. 22 - Honeycomb Sandwich Longitudinal Construction Joint Concepts*

*Fig. 23 - Hat Stiffened Panel Longitudinal Construction Joint Concepts*

For the flight conditions it cannot be determined where the highest compressive axial load will occur, either between the splice joints or directly at the splice joints. Therefore, for the segmented barrel designs no load is removed from the panels so the panel designs remain constant [1]. Thus, the effect of segmenting the structure is simply the additional weight of each longitudinal joint, as listed in table 3.

*Table 3 – Additional Weight for Segmented Interstage Structure*

| Panel Config. (Number of Segments) | Additional Weight (lb) | |
|---|---|---|
| | Hat Concept | Honeycomb Concept |
| **1** | 30 | 55 |
| **3** | 90 | 165 |
| **4** | 120 | 220 |
| **6** | 180 | 330 |
| **8** | 240 | 440 |

Though the hat stiffened panel joints are lighter than the sandwich, both panel concepts have minimal weight growth due to longitudinal construction joints. Hence, segmented barrel designs are weight competitive with the unitized barrel designs.

## 6.3 Circumferential Assembly Joints

Circumferential end frames are required for all Ares V structures to join each adjacent component in the vertical stack. The common end frame geometry evaluated for each panel concept is illustrated in Fig. 24.


*Fig. 24 - Common end frame geometry for sandwich and stiffened panels. (Left) the web of the metallic end frame is positioned over the neutral axis of the acreage panel to avoid load eccentricity caused from applying load off the neutral axis of the acreage panels. (Right) the acreage panel is tapered to a solid laminate then inserted into the metallic clevis joint.*

The primary design considerations are to (1) maintain the load path without inducing a bending moment caused by the load eccentricity and (2) maintain the bending stiffness through the end frame joint. Doing so will prevent the first buckling mode shape from occurring in the first panel bay and allows the barrel acreage to achieve full load carrying capacity.

Extensive trade studies were performed to determine the metallic and composite thicknesses required to force the first global buckling mode into the acreage, illustrated in Fig 25.

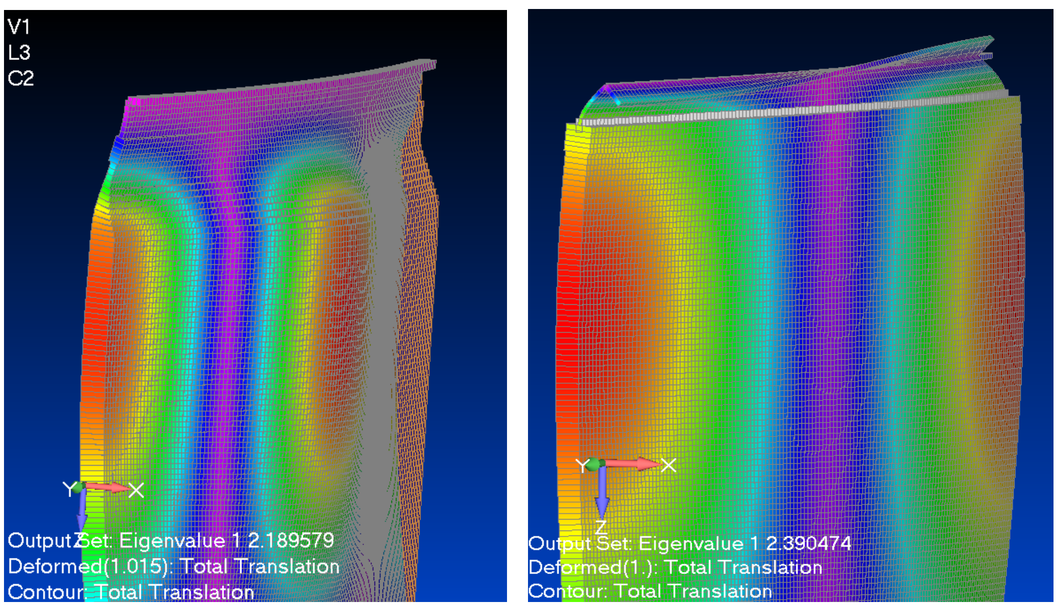



*Fig. 25 - Global Buckling Results for Optimum Hat Stiffened Panel End Frame Sizing Study. (Left) Tapered Joint Design, (Right) Neutral Axis Maintained*

No composite padup is required for the joint where the neutral axis is maintained; the weight penalty is only the added metallic weight. However, the tapered joint concepts require composite padups to increase the local joint stability. The additional composite plies are listed for both the hat and honeycomb sandwich panel concepts in figures 26 and 27.

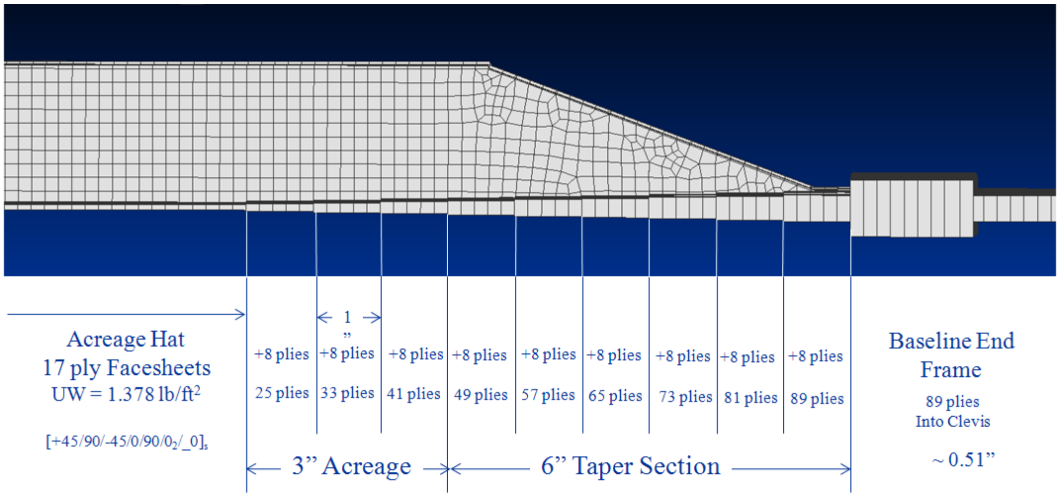



*Fig. 26 - Composite Facesheet Padup Summary for Optimum Hat Stiffened Panel, Tapered End Frame Design. 327 lb. Extra Composite Weight Required to Pass All Global/Local Buckling and Composite Strength Checks.*

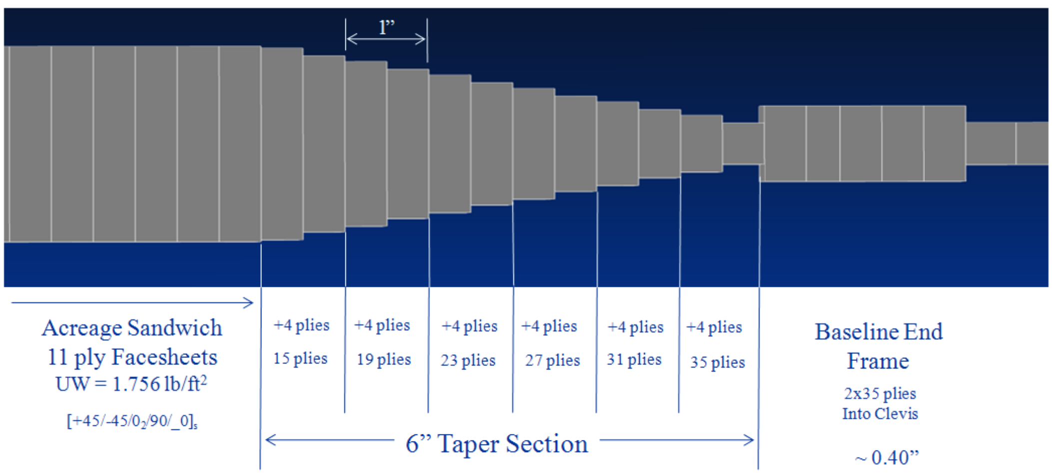



*Fig. 27 - Composite Facesheet Padup Summary for Optimum Honeycomb Sandwich Panel, Tapered End Frame Design. 317 lb. Extra Composite Weight Required to Pass All Global Buckling and Composite Strength Checks (Core Padup Weight Included).*

Additional weight is required to increase the composite strength to handle the unsymmetric axial load distribution, caused from the load eccentricity. The total added weight for each joint concept is shown in Fig. 28

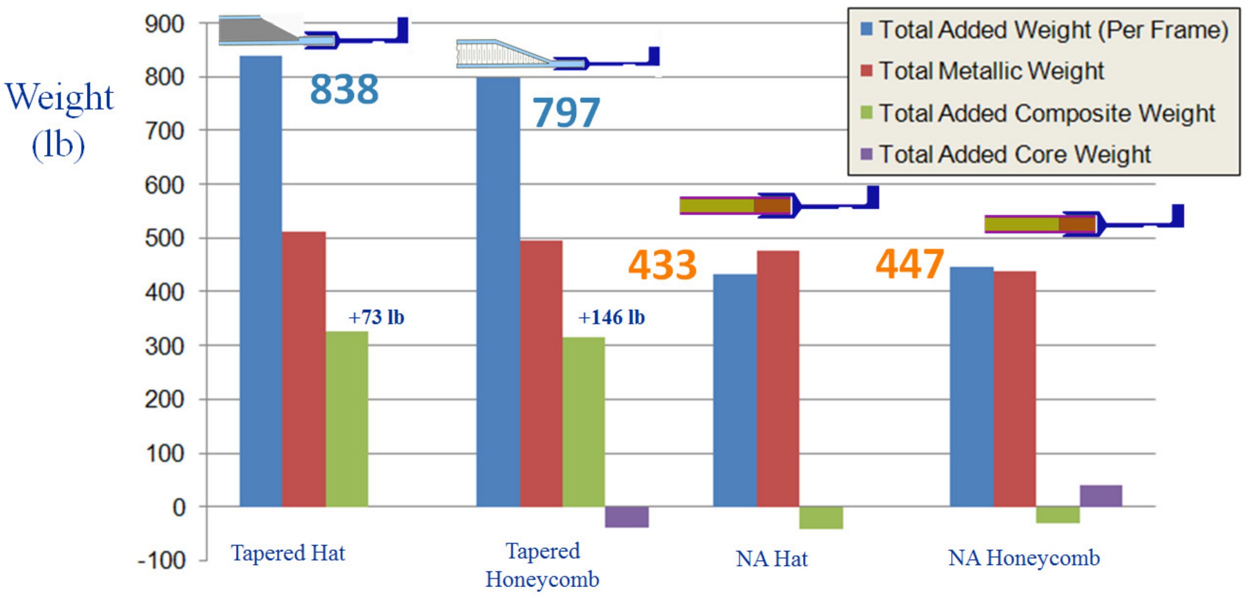



*Fig. 28 – Added weight of end frames for sandwich and stiffened panels. Weight of adhesive and fasteners required to bond/bolt panel to metallic clevis not included.*

# 7 External and Internal Element Loads

## *Payload Shroud*

The primary load supported by the Payload Shroud is the aerodynamic pressure of flight. At the base of the shroud, there are two components of load comprised of the vertical acceleration and the bending moment as illustrated in Fig. 30.

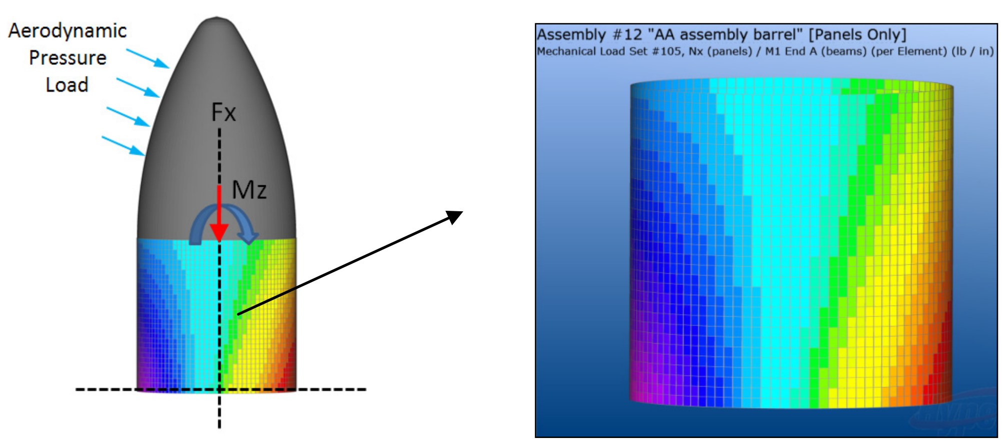



*Fig. 30 - Ares V Payload Shroud-Internal Axial (Nx) Loads due to Flight Conditions*

The compressive hoop load caused by external pressure must also be considered. This loading type is particularly challenging in the ogive section which has additional high loads due to its geometric shape, see Fig. 31. The internal loads are effected by the ring frames that present additional internal loads in hoop tension and hoop compression loads. Ring frames create a pinching effect on the panels as the shroud is loaded in axial compression. Each of these loading types are considered in this study.

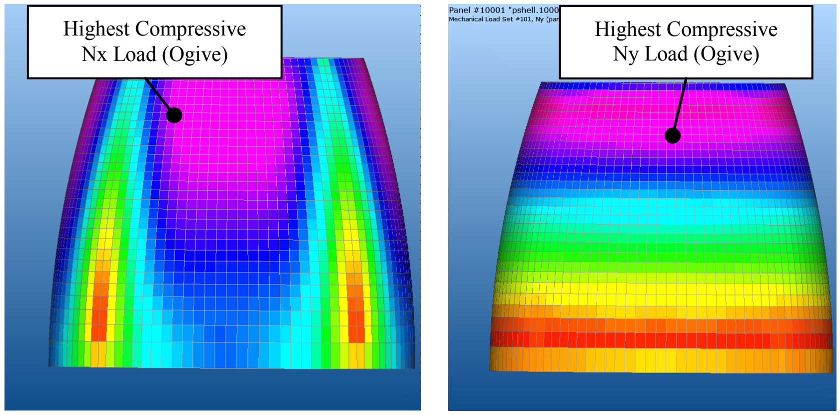



*Fig.31 – FEA-computed internal load, shown above are the challenging bi-axial compression loads in the ogive section of the shroud.*

## Interstage

The primary load supported on the Interstage is axial compression from a combination of vertical acceleration and the bending moment, see Fig. 32. However, two other loadings must be considered: (1) hoop tension caused by the internal pressurization, (2) compressive hoop load caused by crushing pressure, see Fig. 33.

To determine static loads, the external axial, moment, and shear loads are applied to the top of the cylindrical Interstage. The reaction loads are derived at the bottom of the Interstage. Fig. 32 shows how the flight loads are applied to derive the internal loads.

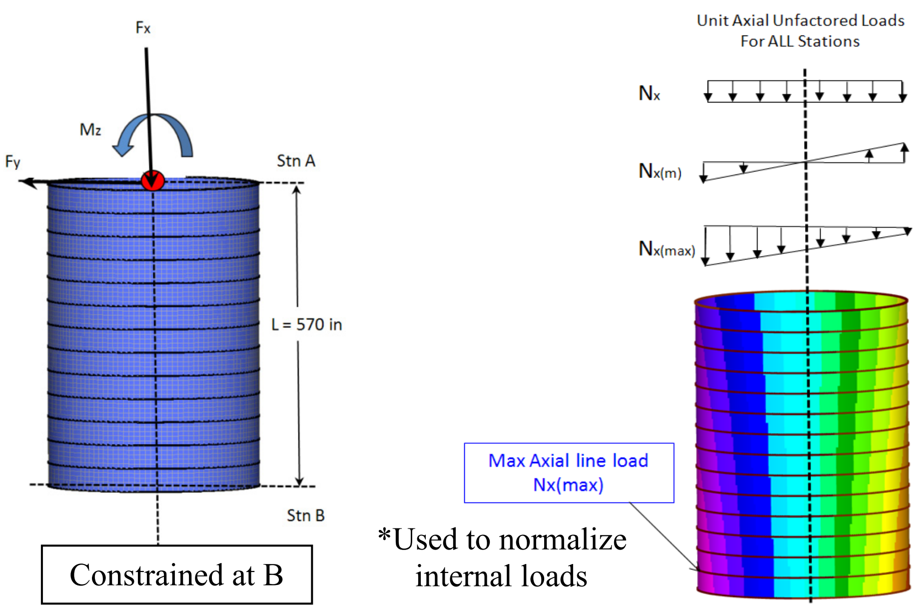
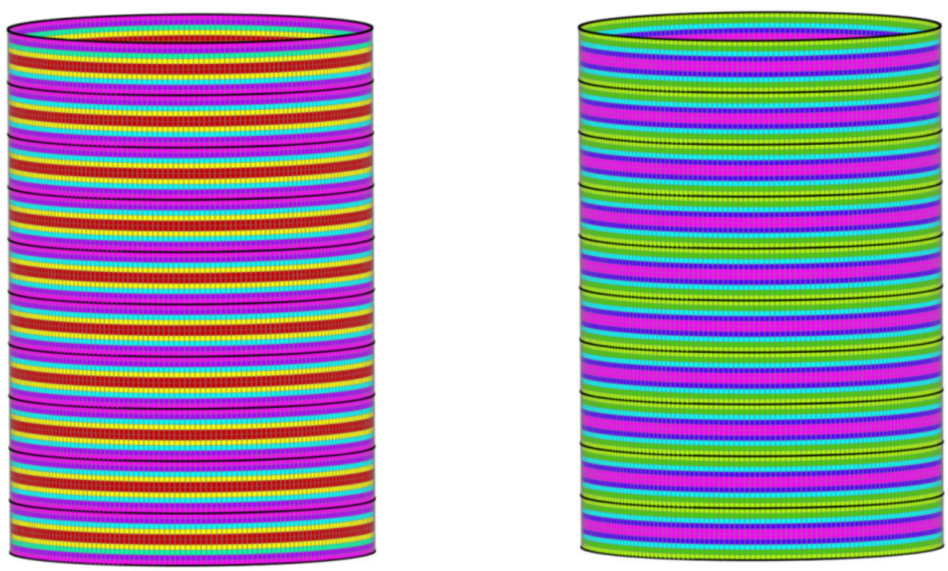



*Fig. 32 - Ares V Interstage internal axial (Nx) loads due to flight conditions.*

The maximum line load at the base of the Interstage results from the combination of axial and moment load. The assumption that angle of attack is applicable in all directions, forces any clocked position of the barrel to be capable of carrying the peak load. Currently, NASA requires the entire barrel to be the same design so the barrel from bottom to top is sized to the maximum line load experienced at Station B. Therefore, the barrel is not allowed to get thinner at the upper part where the load is less severe. The maximum line load is a significant design criterion.

*Note: Per NASA's request, all internal loads reported in this document for the Ares V composite structures have been normalized to the ultimate maximum compressive line load present at the base of the Interstage.*

In a unitized, cylindrical structure the compressive hoop loads are straightforward and can be calculated from the external pressure and the surface area. However, for a structure with ring frames, the ring frames do present additional internal loads which must be considered. The load sharing between the ring frames and acreage panels causes variance in the hoop load. Additionally, the ring frames will create a pinching effect on the panels as the Interstage is loaded in axial compression, see Fig. 33. The uniform Ny hoop loading at the barrel ends is accomplished by setting the end ring frames to half the stiffness of the internal, mid-bay ring frames. This is the proper Ny value for both static internal loads and overall barrel buckling. If possible, the mechanical, frangible end ring frame joint should be designed to these stiffnesses.



**Load Case 1: Max. Axial Load, Internal Pressure**
Hat Stiffened Concept
Ave Hoop Tension = 13% of Max. Axial Load
Std Dev = 20 lb/in
Honeycomb Sandwich Concept
Ave Hoop Tension = 13% of Max. Axial Load
Std Dev = 94 lb/in

**Load Case 2: Max. Axial Load, Crush Pressure**
Hat Stiffened Concept
Ave Hoop Compression = 10% of Max. Axial Load
Std Dev = 5 lb/in
Honeycomb Sandwich Concept
Ave Hoop Compression = 13% of Max. Axial Load
Std Dev = 11 lb/in

*Fig. 33 - Internal Hoop Load Gradient of the Interstage Due to Ring Frame "Pinch".*

A high level summary of both driving load cases is provided in Table 4. Remember that all internal loads reported in this document have been normalized to the ultimate maximum compressive line load present at the base of the Interstage.

*Table 4 - Summary of Primary Load Cases used for all Pure Interstage Panel Sizing Studies*

| | **Cylinder FEM Internal Loads** | |
|---|---|---|
| **Load Case** | **Panel Axial Load Nx** | **Panel Hoop Load Ny % of Maximum Axial Load** |
| **Load Case 1 (101)** | Max Axial Compression | 21.7% Tension (FEA = 13%) |
| **Load Case 2 (102)** | Max Axial Compression | 10.8% Compression (FEA = 10% to 13%) |

Stiffened panel weight savings could be significantly more if sized to pure axial compression load. In plane-shear loads, magnitudes of these structures do not significantly increase weights of the stiffened panels. However, the criteria of designing to a crush pressure case does. Stiffened panels are subject to skin buckling between stiffeners from transverse (Ny) compression. The ratio of axial compression to transverse compression design criteria was set at 10.8 percent (Ny/Nx). If this ratio was set lower, uniaxial stiffened panels (including the hat panel), would have optimized to be lighter than reported in this paper.

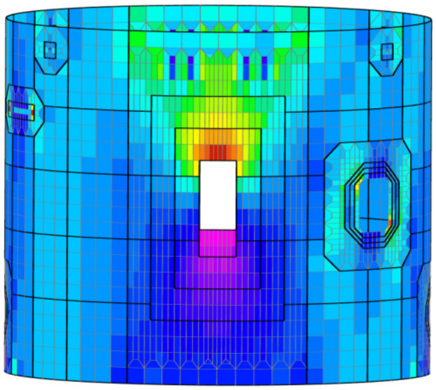
## *Core Intertank*

The Core Intertank is sized to three primary load cases. A high level summary of each load case is provided in Table 5. Remember that all internal loads reported in this document have been normalized to the ultimate maximum compressive line load present at the base of the Interstage.

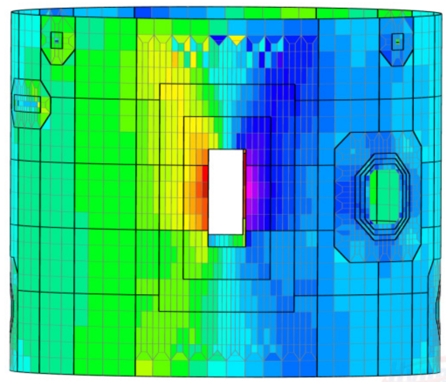
*Table 5 - Summary of Load Cases used for Intertank Trade Studies*

| Load Case | Description | Max Panel Compression Nx Load | Max Panel Compression Ny Load | Max Panel Nxy Load | Comments |
|---|---|---|---|---|---|
| **101** | AFT END PINNED - MAX Q-A | 460% | 40% | 170% | Max Acceleration at angle of attack |
| **102** | AFT END PINNED - MAX G | 260% | 40% | 60% | Max Acceleration |
| **103** | SRB PINNED - ON-PAD: PRE-LAUNCH | 500% | 40% | 220% | On Pad Load Case, Full |

The maximum axial load is caused by the full on pad load case (LC 103) where the entire weight of the Ares V launch vehicle is transferred through the solid rocket booster SRB attachment points on the Core Intertank, Fig. 34.



Nx - Max Axial Compression = 500% axial line load of Interstage



Nxy - Max Shear = 220% axial line load of Interstage

*Fig. 34 - Internal Load for Ares V Intertank - LC 103 - On Pad Load Case, Full. Note that modeling extensions were used to simulate the adjacent structure for proper load introduction into the Core Intertank, however they were removed from the above images.*

Since most of the load is concentrated near the SRB attachments, both Core Intertank constructions require very stiff panel designs in this area. The beamed Intertank has metallic orthogrid thrust panels and the beamless Intertank has stiff, solid laminate, vertical pylons which carry the high axial compression.

The internal load in the Intertank is highly dependent on the location on the structure, chosen panel concept, composite layups, and load sharing between the thrust panels/pylons and the acreage panels. To characterize the loads in the composite acreage panels, the approximate controlling internal limit loads are summarized in Tables 6 and 7.

*Table 6 – Approximated Average Internal Acreage Load for Beamed Intertank Trade Studies*

| Load Case | Description | Acreage Panel Nx Load (lb/in) | Acreage Panel Ny Load (lb/in) | Acreage Panel Nxy Load (lb/in) | Comments |
|---|---|---|---|---|---|
| **101** | AFT END PINNED – MAX. Q-A | 220% High Moment Side | 20% | 45% Near Thrust Panels | Max. Acceleration at angle of attack |
| **102** | AFT END PINNED – MAX. G | 110% | 10% | 15% | Max. Acceleration |
| **103** | SRB PINNED - ON-PAD: PRE-LAUNCH | 150% | 20% | 60% Near Thrust Panels | On Pad Load Case, Full |

*Table 7 – Approximated Average Internal Acreage Load for Beamless Intertank Trade Studies*

| Load Case | Description | Acreage Panel Nx Load (lb/in) | Acreage Panel Ny Load (lb/in) | Acreage Panel Nxy Load (lb/in) | Comments |
|---|---|---|---|---|---|
| **101** | AFT END PINNED – MAX. Q-A | 260% High Moment Side | 20% | 50% Near Thrust Panels | Max. Acceleration at angle of attack |
| **102** | AFT END PINNED – MAX. G | 110% | 10% | 15% | Max. Acceleration |
| **103** | SRB PINNED - ON-PAD: PRE-LAUNCH | 150% | 20% | 80% Near Thrust Panels | On Pad Load Case, Full |

# 8 Weight Summary

## 8.1 Acreage Panel and Ring Frame Weight Summary

### Payload Shroud

*Table 8 - Acreage Weight Summary of Payload Shroud Panel Concepts*

| Panel Concept (all composite) | Ring frame Spacing (in) | Panel Unit Weight Barrel ($lb/ft^2$) | Panel Unit Weight Ogive ($lb/ft^2$) | Ring frame Unit Weight ($lb/ft^2$) | Acreage Unit Weight ($lb/ft^2$) |
|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 45 | 0.704 | 0.709 | 0.0616 | **0.77** |
| **Corrugated Sandwich** | 45 | 0.810 | 0.928 | 0.0851 | **0.95** |
| **Dark Horse (Hat/Corr)** | 45 | 0.704 | 0.928 | 0.0544 | **0.88** |
| **Reinforced Core Sandwich** | N/A | 1.010 | 0.912 | N/A | **0.96** |
| **Honeycomb Sandwich** | N/A | 1.140 | 1.140 | N/A | **1.14** |

### Interstage

*Table 9 - Acreage Weight Summary of Interstage Panel Concepts. Acreage panel and mid-bay ringframe weights included*

| Panel Concept (all composite) | Ring frame Spacing (in) | Panel Unit Weight ($lb/ft^2$) | Ring frame Unit Weight ($lb/ft^2$) | Baseline Acreage Unit Weight ($lb/ft^2$) |
|---|---|---|---|---|
| **Hat Stiffened Panel** | 57 | 1.38 | 0.103 | **1.48** |
| Hat Stiffened Panel | 44 | 1.30 | 0.138 | **1.44** |
| **Reinforced Core Sandwich** | 71 | 1.56 | 0.087 | **1.64** |
| **Honeycomb Sandwich** | 71 | 1.76 | 0.087 | **1.85** |
| **Blade Sandwich** | 114 | 1.82 | 0.05 | **1.87** |
| **Blade Stiffened Panel** | 21 | 1.45 | 0.46 | **1.91** |
| **PRSEUS (rod stiffened)** | 52 | 2.02 | Included | **2.02** |

For the Ares V Interstage, the optimum honeycomb sandwich concept is 28 percent heavier than the hat stiffened panel. The composite hat stiffened panel weight savings will increase as the design details required to attach ring frames and end frames to the acreage are considered, as accounted for in Table 13.

### Core Intertank

*Table 10 - Acreage Weight Summary of Beamed Intertank Panel Concepts*

| Panel Concept (all composite) | Ring Frame Spacing (in) | Acreage Panel Unit Weight (lb/ft$^2$) | Metallic Orthogrid Unit Weight (lb/ft$^2$) | Metallic Ring Frame Unit Weight (lb/ft$^2$) | *Total Unit Weight (lb/ft$^2$) |
|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 66 | 2.09 | 8.05 | **0.79** | **4.19** |
| **Reinforced Core Sandwich** | 66 | 2.23 | 9.09 | **0.79** | **4.68** |
| **Honeycomb Sandwich** | 66 | 2.21 | 9.13 | **0.79** | **4.32** |
| **PRSEUS (rod stiffened)** | 66 | 2.28 | 8.42 | **0.79** | **4.72** |

*Includes weight of padup areas around cutouts

*Table 11 - Acreage Weight Summary of Beamless Intertank Panel Concepts*

| Panel Concept (all composite) | Ring Frame Spacing (in) | Acreage Panel Unit Weight (lb/ft$^2$) | Pylon Unit Weight (lb/ft$^2$) | Metallic Ring Frame Unit Weight (lb/ft$^2$) | *Total Unit Weight (lb/ft$^2$) |
|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 55 | 2.19 | 6.35 | **0.94** | **4.42** |
| **Reinforced Core Sandwich** | 55 | 1.99 | 6.77 | **0.94** | **4.38** |
| **Honeycomb Sandwich** | 55 | 2.28 | 6.74 | **0.94** | **4.61** |
| **PRSEUS (rod stiffened)** | 55 | 2.26 | 6.28 | **0.94** | **4.43** |

*Includes weight of padup areas around cutouts

## 8.2 Total Weight Summary (Design Details)

### Shroud

*Table 12 - Total Weight Summary of Payload Shroud Panel Concepts*

| Panel Concept (all composite) | Total Acreage Panel Weight (lb) | Total Ring Frame Weight (lb) | Ring Frame Connection Weight (lb) | Total End frame Weight (lb) | Total Weight (lb) |
|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 4823 | 434 | 180 | 433 | **7340*** |
| **Corrugated Sandwich** | 5950 | 536 | 240 | 433 | **8400*** |
| **Dark Horse (Hat/Corr)** | 5608 | 371 | 90 | 433 | **8125*** |
| **Reinforced Core Sandwich** | 6540 | N/A | N/A | 447 | **8740*** |
| **Honeycomb Sandwich** | 7780 | N/A | N/A | 447 | **10290*** |

*Non-opt Factor 1.25 included

## *Interstage*

*Table 13 - Total Weight Summary of Interstage Panel Concepts*

| Panel Concept (all composite) | Ring Frame Spacing (in) | (1) Acreage Panel Weight (lb) | (3, 4) Total Ring Frame Weight (lb)* | (5) Ring Frame Joint Weight (lb) | (6, 7) End Frame Joint Weight (lb) | (8) Longitudinal Splice Joint Weight (lb) | Total Weight (lb) |
|---|---|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 57 | 6788 | 575 | 180 | **866** | **180** | **8590** |
| Hat Stiffened Panel | 44 | 6423 | 745 | 240 | **866** | **180** | **8455** |
| **Reinforced Core Sandwich** | 71 | 7680 | 490 | 385 | **894** | **330** | **9780** |
| **Honeycomb Sandwich** | 71 | 8650 | 490 | 1120 | **815** | **350** | **11425** |
| **Blade Sandwich** | 114 | 8965 | 310 | 239 | **894** | **330** | **10850** |
| **Blade Stiffened Panel** | 21 | 7142 | 1525 | 520 | **866** | **180** | **10230** |
| **PRSEUS (rod stiffened)** | 52 | 9950 | Included | N/A | **866** | **180** | **11000** |

*Includes ½ Stiffness Ringframes at both ends

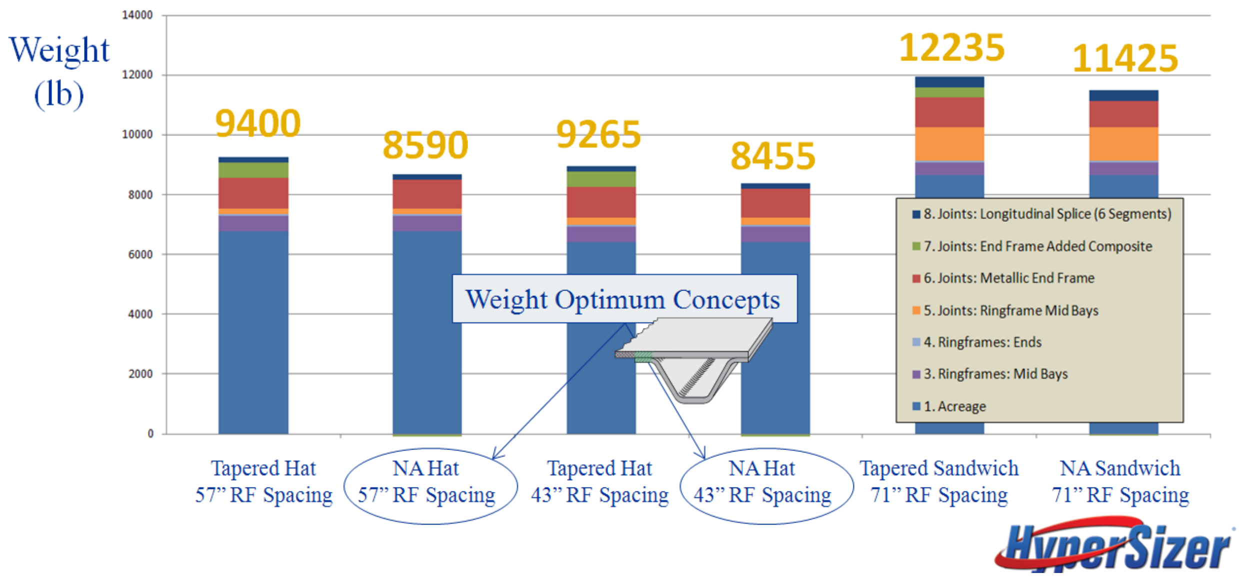



*Fig. 35 – Total weight comparison chart. Line items numbered 1-8 correspond with the weights reported in table 13.*

The studies performed by Collier Research on the Ares V Interstage show the weight delta between hat and honeycomb acreage is 27%. After including the additional weight items and corrections listed in table 13 and figure 35, the total weight delta increases to 33%

## *Core Intertank*

*Table 14 - Total Weight Summary of Beamed Intertank Panel Concepts*

| Panel Concept (all composite) | Ring Frame Spacing (in) | Total Barrel Weight (lb) | Thrust Beam Weight (lb) | End Frame Weight (lb) | Ring Frame Attachment Weight (lb) | *Total Weight (lb) |
|---|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 66 | 11440 | 2600 | **866** | **120** | **15030** |
| **Reinforced Core Sandwich** | 66 | 12800 | 2600 | **894** | **220** | **16515** |
| **Honeycomb Sandwich** | 66 | 11820 | 2600 | **894** | **760** | **16070** |
| **PRSEUS (rod stiffened)** | 66 | 12880 | 2600 | **866** | **120** | **16470** |

*Weight of metallic thrust adapter not included (~2650 lb.)

*Table 15 - Total Weight Summary of Beamless Intertank Panel Concepts*

| Panel Concept (all composite) | Ring Frame Spacing (in) | Total Barrel Weight (lb) | End Frame Weight (lb) | Ring Frame Attachment Weight (lb) | Total Weight (lb) |
|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 55 | 13170 | **866** | **150** | **14190** |
| **Reinforced Core Sandwich** | 55 | 13050 | **894** | **275** | **14220** |
| **Honeycomb Sandwich** | 55 | 13750 | **894** | **950** | **15600** |
| **PRSEUS (rod stiffened)** | 55 | 13195 | **866** | **150** | **14215** |

## 8.3 Weight Maturity Level

*Table 16 - Weight Maturity Level (WML) for Ares V Payload Shroud Panel Concepts*

| Panel Concept (all composite) | Analysis Foundation | Industry Use | FEM/FEA | Sizing Time (LOE) | Adhering to Best Practices | Total WML | Weight impact of Increasing WML from current level |
|---|---|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 10 | 10 | 5 | 10 | 10 | 100 | Lighter by 2% |
| **Corrugated Sandwich** | 10 | 8 | 5 | 8 | 10 | 64 | Lighter by 2% |
| **Dark Horse (Hat/Corr)** | 10 | 6 | 5 | 8 | 10 | 48 | Lighter by 2% |
| **Reinforced Core Sandwich** | 8 | 2 | 5 | 9 | 10 | 14.4 | Heavier by 4% |
| **Honeycomb Sandwich** | 10 | 10 | 5 | 10 | 10 | 100 | Heavier by 4% |

*Table 17 - Weight Maturity Level (WML) for Ares V Interstage Panel Concepts*

| Panel Concept (all composite) | Analysis Foundation | Industry Use | FEM/FEA | Sizing Time (LOE) | Adhering to Best Practices | Total WML | Weight impact of Increasing WML from current level |
|---|---|---|---|---|---|---|---|
| **Hat Stiffened** * | 10 | 10 | 5 | 10 | 10 | 100 | Lighter by 2% |
| **Reinforced Core Sandwich** | 8 | 2 | 5 | 9 | 10 | 14.4 | Heavier by 4% |
| **Honeycomb Sandwich** * | 10 | 10 | 5 | 10 | 10 | 100 | Heavier by 4% |
| **Blade Sandwich** | 8 | 2 | 5 | 5 | 10 | 8 | Lighter by 3% |
| **Blade Stiffened** | 10 | 10 | 5 | 5 | 10 | 50 | Lighter by 3% |
| **PRSEUS (rod stiffened)** | 8 | 1 | 5 | 7 | 10 | 5.6 | Lighter by 10% |

*Table 18 - Weight Maturity Level (WML) for Ares V Core Intertank Panel Concepts*

| Panel Concept (all composite) | Analysis Foundation | Industry Use | FEM/FEA | Sizing Time (LOE) | Adhering to Best Practices | Total WML | Weight impact of Increasing WML from current level |
|---|---|---|---|---|---|---|---|
| **Hat Stiffened Panel** | 10 | 10 | 5 | 7 | 10 | 70 | Lighter by 10% |
| **Reinforced Core Sandwich** | 8 | 2 | 5 | 7 | 10 | 11.2 | Lighter by 5% |
| **Honeycomb Sandwich** | 10 | 10 | 5 | 10 | 10 | 100 | Heavier by 4% |
| **PRSEUS (rod stiffened)** | 8 | 1 | 5 | 7 | 10 | 5.6 | Lighter by 10% |

*The total weight maturity level score is normalized to the highest WML (50,000).

The weight maturity level is a measure of confidence in the weight statements and is comparable to a technology readiness level (TRL) or a manufacturing readiness level (MRL). Higher fidelity panel designs are represented with a higher total WML, see three tables listed above (Table 16-18).

### 8.4 Weight Comparison to Metallic Designs

#### *Interstage*

*Table 19 - Weight Summary of Interstage Panel Concepts with Different Materials.*

| Material | Panel Concept | Acreage Panel Unit Weight ($lb/ft^2$) | Total Weight (lb) | Lightest Total Weight Design (normalized) |
|---|---|---|---|---|
| **Gr/Ep** | Stiffened panel (Hat)* | 1.515 | 8590 | 1.0 |
| **Gr/Ep Skin/Al 5052 Core** | Honeycomb sandwich | 1.76 | 11425 | 1.33 |
| **Alum 2219, 6061-T6, or 7075** [1] | Stiffened panel (Hat) | 2.18 | 13290 | 1.54 |
| **Alum 2219 Skin/Al 5052 Core** | Honeycomb sandwich [2] | 2.28 | 14800 | 1.72 |
| **Alum Lithium 2195** | Orthogrid (isogrid) | 3.73 | 22152 | 2.58 |

* Weight basis is the 2010 composite hat design that is less producible and more costly to manufacture (UW = 1.515). The newer 2011 design came after this assessment was made.

[1] Weight estimates are based on metallic skin stringer designs with friction stir welded (FSW) stiffeners. No post buckling is allowed before 100 percent limit load. Non-linear, post buckling reduced stiffness analysis was performed for crippling and buckling at ultimate loads. The metallic analysis is at an FAA certification analysis maturity.

Standard sheet stock sizes could have been used in HyperSizer, but were not. Skin thicknesses were allowed to freely optimize to achieve the lightest weight metal designs possible. To achieve the reported costs, optimization should be performed again using each materials standard stock sizes. There is little performance benefits using different aluminum alloys. Since the rocket structures are buckling critical, the higher stress allowables of the more advanced aluminum alloys only marginally improve weights.

## 9 Affordability: Weight vs. Cost Comparisons

*Table 20 – Weight to cost metric*

| Material | Panel Concept | Lightest Total Weight Design (normalized) | Total Cost - material and labor (normalized) |
|---|---|---|---|
| **Gr/Ep** | Stiffened panel (Hat) | 1.0 | 2.5 |
| **Gr/Ep Skin/Al 5052 Core** | Honeycomb sandwich | 1.33 | 2.3 |
| **Alum 2219, 6061-T6, or 7075** | Stiffened panel (Hat) | 1.67 | 1.0 |
| **Alum 2219 Skin/Al 5052 Core** | Honeycomb sandwich | 1.65 | 1.8 |

Affordability is the most important concern in 2011 for NASA's heavy lift launch vehicles. With this in mind, a weight to cost metric is presented for informational purposes in Table 20. A metallic skin stringer design fabricated using friction stir welding (FSW) of the hat shaped stiffener onto the skin is relatively inexpensive. Any cross-sectional shape (within a aproximately a 5" diameter) of aluminum can be extruded at a very low cost. The least expensive and most readily available aluminum is suitable for these large barrel structures, see Section 8.4, and the reported cost is based on such (6061-T6).

The above table data is placed into a graph, Fig. 35, for showing the range of the coupled weight-cost metrics. The blue curve represents a metallic skin stringer design with a friction stir welded (FSW) hat shaped stiffener. The orange curve represents the narrow weight-cost metric and limited design flexibility of the honeycomb sandwich with aluminum facesheets. The red curve represents a honeycomb sandwich with composite facesheets and the green curve substantiates the wide ranging weight-cost metric and design flexibility provided by the composite hat. By inspection, it appears that the hat shaped composite panel can better meet any target weight-cost metric better than any other panel concept including composite honeycomb sandwich. Weights are known to a high level of accuracy and confidence. The cost numbers are approximate – the point is the trends.

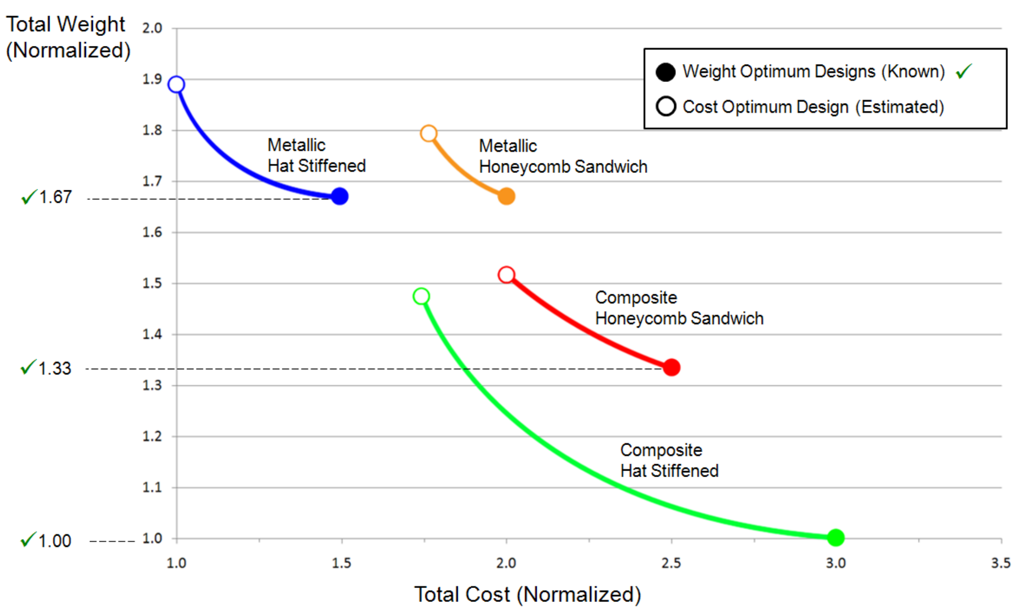



*Fig. 35 - Hat composite stiffened panel has the most weight-cost opportunities.*

# 10 Conclusions

The hat shaped composite stiffened panel with its broadest range of weight-cost performance metrics provides the most design flexibility for axially loaded space launch structure. The graph shows composite hat is the proper choice for weight and metallic skin stringer hat for cost. And for any combination of weight-cost required in between these extremes, the composite hat appears to be the best choice over other panel concepts including honeycomb sandwich.

Future work should be directed toward designing the hat to be more manufacturable (less expensive) and quantifying and minimizing the weight impact. This is the direction Collier Research Corporation is pursuing.

### *Acknowledgments*
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