Ares V Interstage Composite Panel Concept and Ringframe Spacing Trade Studies

Craig Collier[1], James Ainsworth[2], Phil Yarrington[3], and Ryan Lucking [4]
craig.collier@hypersizer.com
Collier Research Corp., Hampton, VA

The NASA Ares V Advanced Composite Technology Project is evaluating the performance of three primary composite structures for heavy lift vehicles (HLV). They are the Shroud, the Interstage, and the Core Intertank. The HyperSizer® commercial software is being used by a nationwide NASA team for the analysis and design sizing of all three structures. This paper focuses on trade studies performed for the Interstage. The Interstage is a cylindrical barrel that is axially compressed but must also withstand crushing and internal pressure causing compressive and tension hoop panel loads. Weight trends are quantified considering all possible design possibilities in order to determine the most structurally efficient combination of composite layups, panel cross section dimensions, and ring frame spacing to achieve the lightest weight. Included are results obtained with HyperSizer for honeycomb and reinforced core sandwich panels, and Hat, I, Tee, Blade, and PRSEUS stiffened panel concepts. The HyperSizer optimum designs have been analyzed in great detail and independently verified with a multitude of different FEA models. The hat composite stiffened panel is the lightest concept for a HLV and is 20% lighter than honeycomb sandwich for an Ares V Interstage. The composite hat is 30% lighter than the lightest metallic design.

[1] Senior Research Engineer, Hampton, Virginia; AIAA Senior Member, craig.collier@hypersizer.com
[2] Aerospace Structural Engineer, Hampton, Virginia; james.ainsworth@hypersizer.com
[4] Senior Research Engineer, Hampton, Virginia; AIAA Senior Member, phil.yarrington@hypersizer.com
[4] Aerospace Structural Engineer, Hampton, Virginia; ryan.lucking@hypersizer.com

Contents

1 Introduction

NASA's Ares V Advanced Composite Technology Project is evaluating the performance of three primary composite structures for heavy lift vehicles (HLV). They are the Shroud, the Interstage, and the Core Intertank, figure 1. The HyperSizer® commercial software is being used by a nationwide NASA team for the analysis, design sizing, and weight reduction of all three structures. This paper focuses on trade studies performed for the Interstage.

The Ares V Interstage is a 33 foot diameter, 48 foot tall cylindrical (barrel) that is in the early preliminary design phase. It is a cylindrical barrel that is axially compressed but must also withstand crushing and internal pressure causing compressive and tension hoop panel loads. It is essential that as for all launch vehicle structures that it be designed to minimum weight. To establish minimum weight, trade studies are performed to determine weight trends and the most efficient combination of architectural design, panel concept, cross sectional dimensions, material system, and layup sequence.

The HyperSizer® software is used to perform panel optimization for each concept considered, for all manufacturable layups, and as a function of ringframe spacing. This paper presents weight trends for each panel concept as a function of ringframe spacing. In order to establish the correct weights of each design, accurate failure analyses were performed by HyperSizer. All panel concepts reported achieved positive margins of safety for all relevant failure modes and for all load cases.

Included are results obtained with HyperSizer for honeycomb and reinforced core sandwich panels, and Hat, I, Tee, Blade, and Boeing's PRSEUS stiffened panel concepts. Though several different panel designs were considered, the hat stiffened panel is determined to be optimum. Its weight, along with its associated ringframe weight, joints, and fasteners in total is lighter than the honeycomb sandwich panel concept. The hat composite stiffened panel is the lightest concept for a HLV and is 20% lighter than honeycomb sandwich for an Ares V Interstage. The composite hat is 30% lighter than the lightest metallic design.

Many different independent verifications of HyperSizer's failure predictions were performed with FEA and are presented. These include linear static stress analysis, buckling Eigenvalue solutions for full barrel cylindrical buckling, panel buckling, local buckling, and cross section crippling. 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 happened first.

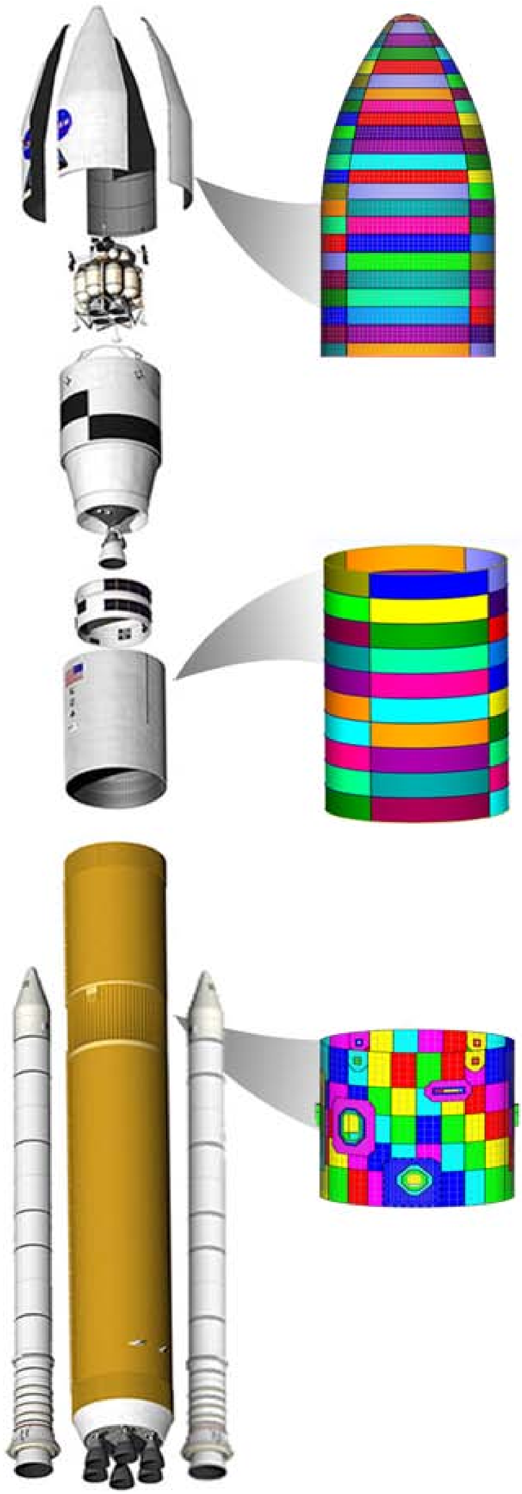
1.1 NASA-HyperSizer National Team

In 2009, NASA formed the Advanced Composites Technology (ACT) program with the objective to study and develop technology to build a light-weight, cost effective space structure from composite materials. Currently the Advanced Composites Team is composed of research engineers from nearly all of NASA's research centers (Langley, Glenn, Marshall, Ames, and Goddard) and they are using HyperSizer to perform weight trade studies for the three composite structures of the Ares V Heavy Lift Vehicle: the Payload Shroud, the Interstage and the Core Intertank [1].

A major accomplishment of the ACT organization in recent months has been the complete design, analysis and documentation of the three Ares V composite structures. By using HyperSizer, the ACT national team members have produced high fidelity panel designs and detailed weight reports for many concepts in a short period of time. During this process new panel concepts were introduced and seamlessly incorporated into the trade space without affecting the schedule.

The results reported here are those from Collier Research Corporation developers of the HyperSizer software [2, 3, and 4]. They are similar in trend and magnitude as produced by the NASA team using HyperSizer. Slight differences between results reported here and those of the NASA team is due to Collier Research's higher level of effort and experience optimizing with HyperSizer. This evaluation is described in section 1.7 and is the basis of the scoring for the Weight Maturity Level (WML) of Table 2.

1.2 The NASA Heavy Lift Vehicle (Ares V)



Payload Shroud
Length = 77’
Diameter = 33’
Lightly loaded by Aerodynamic pressure
Panels sized to minimum gage thickness
Four segments for separation
Panel concepts evaluated:

- Honeycomb, hat, skin stringer, reinforced core sandwich (RCS)

Interstage
Length = 47.5’
Diameter = 33’
Moderately loaded

- Axial compression forces
- Tension/compression hoop forces

Unitized and manufacturing segments considered
Panel concepts evaluated:

- Honeycomb, hat, skin stringer, reinforced core sandwich, PRSEUS,

Core Intertank
Length = 27.5’
Diameter = 33’
Beam and beamless designs considered
Highly loaded

- Axial compression forces
- Tension/compression hoop forces

Unitized and manufacturing segments
Panel concepts evaluated:

- Honeycomb, hat, skin stringer, reinforced core sandwich, PRSEUS,

Fig. 1, NASA teams used HyperSizer for three Ares V Heavy Lift Composite Structures to Perform Structural Weight Trade Studies and Reduce Weight

1.3 Summary Weight Results for three Ares V Structures

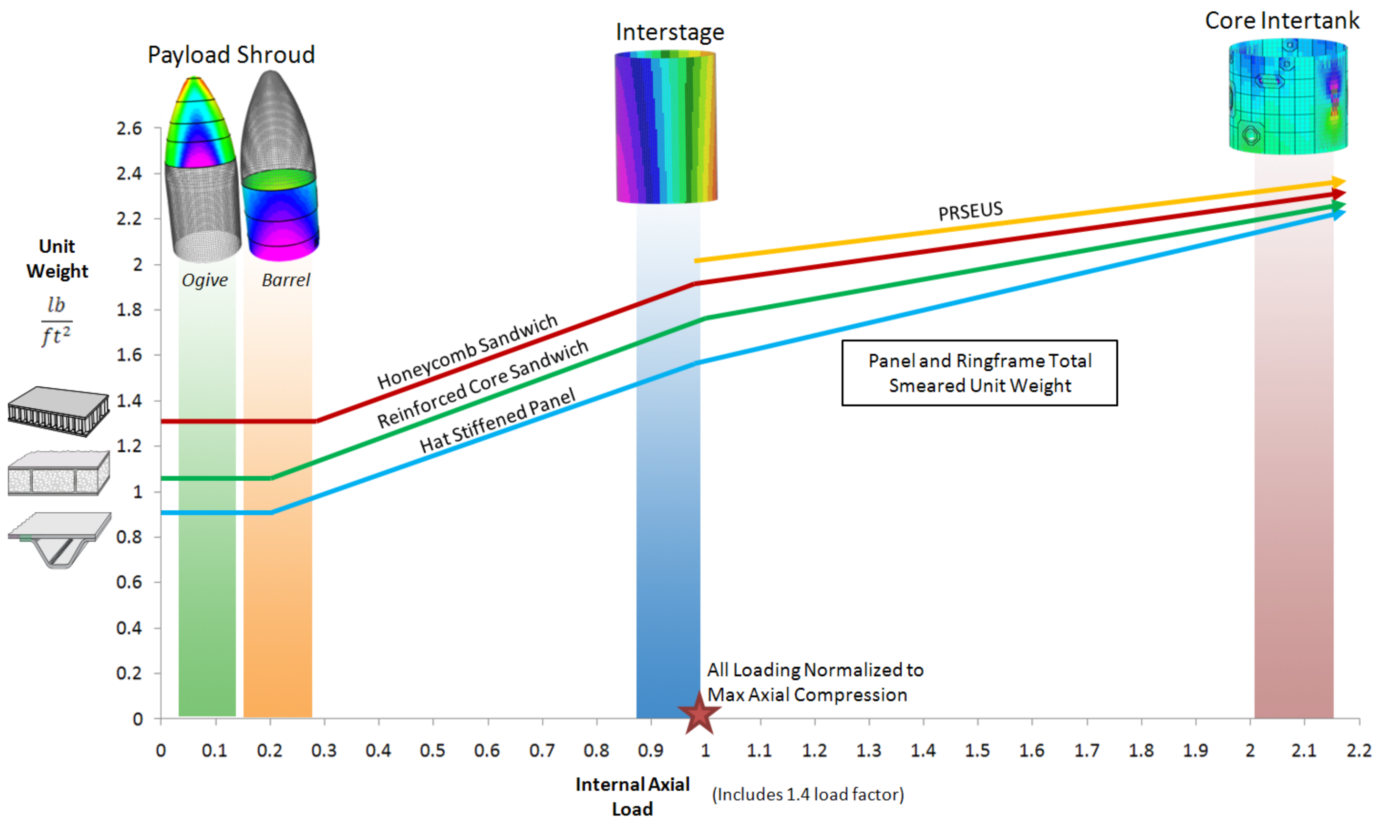


Fig. 2, Total Weight Trends for the Weight Competitive Panel Concepts for the Three Composite Structures of Ares V

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. Hat is the lightest overall panel concept for all three Ares V structures, followed by reinforced core sandwich and honeycomb sandwich, figure 2. The PRSEUS 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 a lightly loaded which causes most panel concepts to optimize to minimum gage. In figure 2, the zero slope of the curve represents min gage. Hat stiffened panels are lighter for this application mainly because they have no parasitic weight. The Interstage is moderately loaded in axial compression. Hats are lighter in this scenario because they are more effective at providing the material strength and stability required to carry the axial compression and shear, and for these loadings the panel weights begin to converge.

1.4 Ares V Interstage Barrel Geometry

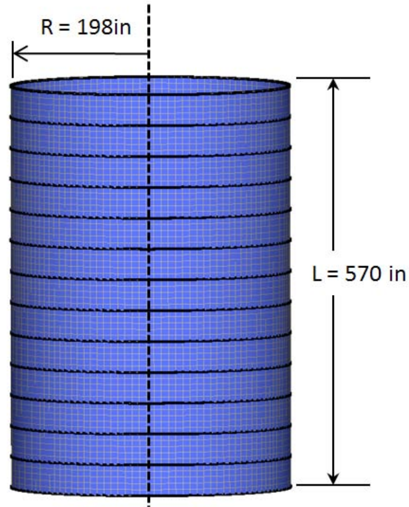


Fig. 3, NASA Ares V Interstage Structural Geometry used for Weight Trade Studies

The Ares V Interstage connects the Earth Departure Stage (EDS) to the lower stage in the vertical stack and is one of the largest composite space structures ever designed. The cylindrical structure stands 570in (47.5ft) tall and has a radius of curvature of 198in (16.5ft). The total surface area is 7.09E5in^2 (4926ft^2).

The length of the structure requires ringframes to provide buckling stability. For this application stiffened panels will require more ringframes than sandwich panels which will contribute to the total weight. Because stiffened panels require more ringframes than sandwich panels the ringframe weight is an important contributor to the acreage design and is quantified for each concept in the following trade studies.

The purpose of this study is to quantify the best panel design for the acreage barrel section of the Interstage. Hence cutouts and local padup regions are not included in any weight statements presented in this document.

1.5 Panel Concepts

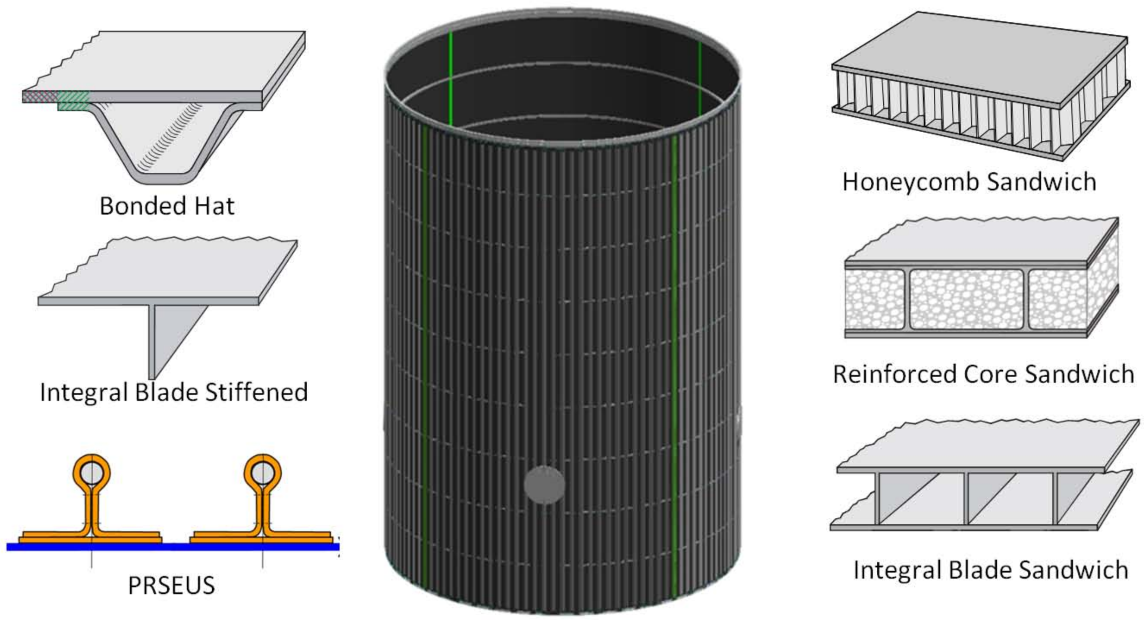


Fig. 4, Panel Concepts Considered for Interstage Structural Optimization.

Many panel concepts are considered and each concept is optimized to find the lightest weight combination of cross sectional dimensions, materials and layups based on ringframe spacing.

From the sandwich panel family, weights are reported for honeycomb sandwich, reinforced core sandwich, and integral blade sandwich. From the stiffened panel family bonded hat stiffened, integral blade stiffened, and Boeing's PRSEUS (Pultruded Rod Stitched Efficient Unitized Structure) stiffened panels are considered [5 and 6].

By plotting the trend lines for each panel concept, the optimal solution is determined from the lightest weight combination of panel and ringframe dimensions. Once a general trend line is determined an estimated optimum solution is obtained. Then the panel designs are matured by iterating HyperSizer with FEA static and buckling solutions, using "master" full scale finite element models.

1.6 Weight Summary

Table 1, Overall Weight Comparison at Optimum Ringframe Spacing

Panel Concept (all composite)	Ringframe Spacing	Panel Unit Weight (lb/ft^2)	Ringframe Unit Weight (lb/ft^2)	Total Unit Weight (lb/ft^2)
Hat Stiffened Panel	57 *	1.38	0.15	**1.53**
Reinforced Core Sandwich	71	1.56	0.16	**1.72**
Honeycomb Sandwich	71	1.77	0.09	**1.86**
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**

* Alternate ringframe spacing of 43.8" is proposed for the hat as a lighter weight design.

1.7 Weight Maturity Level

Table 2, Weight Maturity Level (WML) for Panel Concepts Sized for Ares V Interstage

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%

* The total weight maturity level score is normalized to the highest WML.
# Sandwich panels will have increased weight when ringframe joints and fasteners are included

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. Concepts such as the hat stiffened panel and honeycomb sandwich panel have high WMLs so their weights are not expected to change as the project continues, provided no major load/geometry or design criteria changes are imposed.

Panel concepts with lower WML levels, such as PRSEUS and Reinforced Core Sandwich may show a weight change as the project matures and the design space of each panel concept is fully explored.

1.8 Weight Comparison to Metallic Designs

Removed.

1.9 Design Criteria

The factors used in the Ares V Interstage trade studies are listed in Table 3.

Table 3, Factors used for all Interstage Weight Trade Studies

Allowables Knockdown	**FOS Acreage**	**FOS Discontinuities**	**Knockdown Factor**	**Ref: Temperature**
OHC	1.4	2	0.65	120 F

Composite Materials

An IM7/8552 class composite material system is used for design. The allowables reflect knockdown open hole compression values. The reference temperature defined for the following trade studies is 120F degrees and the material properties are evaluated at this elevated temperature.

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.

Failure Methods

The Max Strain failure criteria is the primary material strength requirement and 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, and 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 preformed for the acreage stiffened 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 ringframe attachments.

Reference Appendix A provides more detail on the failure analysis performed for each panel concept.

Unitized Design

All weight reports presented assume the Interstage is designed as a single, uniform panel concept. That is no panel dimensions changes are permitted around the circumference of the Interstage or along the span.

1.10 External and Internal Element Loads

Primary load supported on the Interstage is axial compression from a combination of vertical acceleration and the bending moment. However, two other loadings must be considered: (1) hoop tension caused by the internal pressurization (2) compressive hoop load caused by crushing pressure. 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. Figure 5 shows how the flight loads are applied to derive the internal loads.

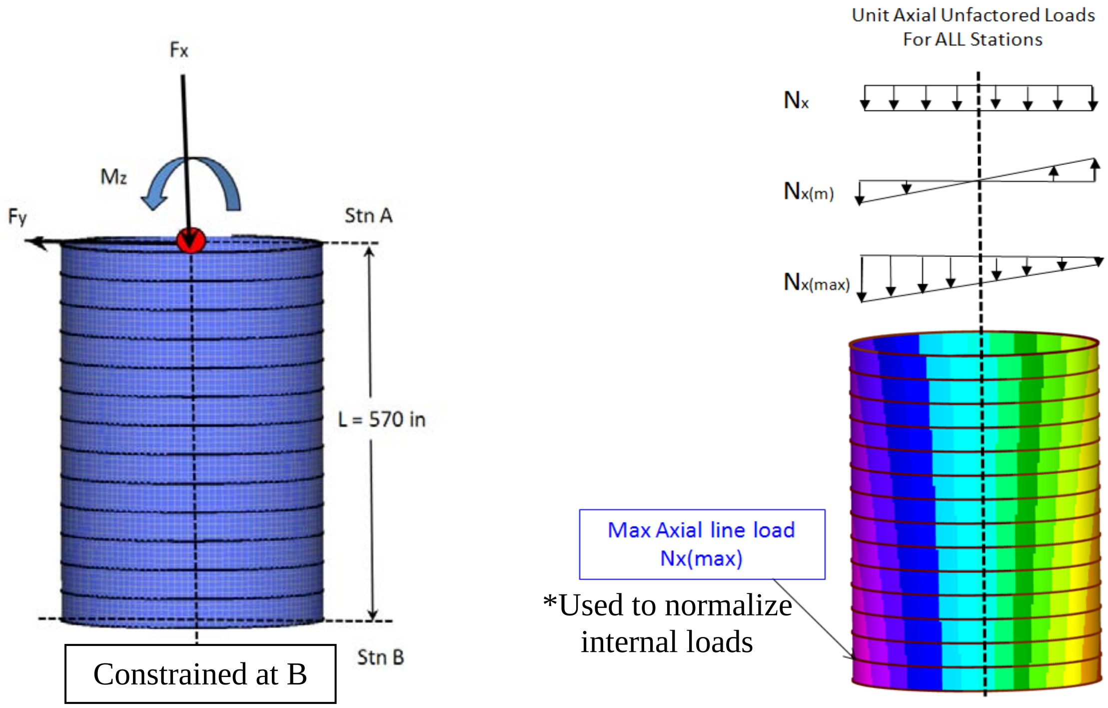


Fig. 5, Ares V Interstage internal axial (Nx) loads due to flight conditions

Though the loading is statically determinate, FEA is used to resolve the external flight loads into internal element loads, that includes the effects of ringframe hoop load sharing. 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 loading. As of now, NASA requires the entire barrel is to be the same design – so the entire barrel from bottom to top is sized to the maximum line load experienced at station B. That is the barrel is not allowed to get thinner at the upper part where the load is less severe. This design criteria causes the maximum line load to be a significant design criteria.

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

For this study two other load conditions must be considered (1) hoop tension caused by the internal pressurization, (2) compressive hoop load caused by crushing pressure. 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 ringframes, the ringframes do present additional internal loads which must be considered. The load sharing between the ringframes and acreage panels causes variance in the hoop load. Additionally, the ringframes will create a pinching effect on the panels as the Interstage is loaded in axial compression. Both effects are studied with FEA to determine the appropriate design-to loads for the trade studies. Figure 6 illustrates the hoop load gradient caused from pressure and ringframe pinching and load sharing.

The uniform Ny hoop loading at the barrel ends is accomplished by setting the end ringframes to ½ the stiffness of the internal ringframes. This is the proper value for both static internal loads and overall barrel buckling. If possible, the mechanical frangible end ringframe joint should be designed to these stiffnesses.

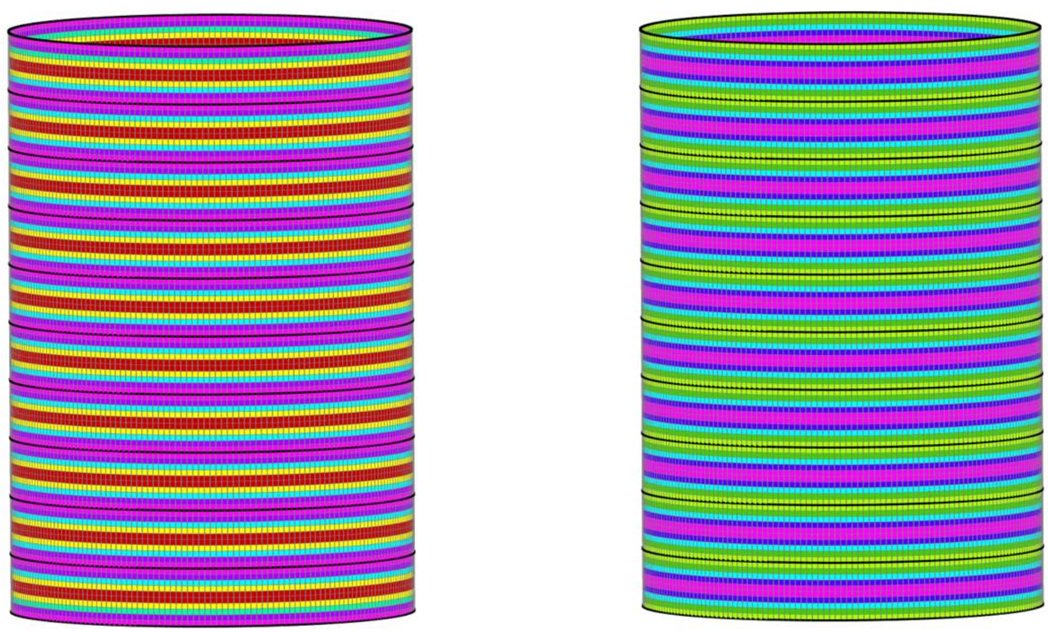


Fig. 6, Internal Load Gradient due to ringframe 'pinch.'

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

The internal pressure case (load case 1) causes hoop tension load in the acreage panels and the crush pressure (load case 2) causes compressive hoop load. The variance in hoop load is caused by the pinching and load sharing effects of the ringframes.

The amount of hoop load depends on the panel properties. Stiffened panels experience less compressive hoop load and less deviation of load. However for initial trade studies this slight reduction in load is ignored and all panels are sized to the same two primary load cases listed in table 4.

Table ,. Summary of Primary Load Cases used for all Pure Panel Sizing Studies

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

2 HyperSizer Software Sizing Optimization and Analysis Process

HyperSizer software automates the optimization process for stiffened panels, sandwich panels and open and closed cross section beams. To use the software the user applies general edge loadings and/or boundary conditions in the software interface and HyperSizer solves for the resulting ply level stresses and strains then evaluates the structural integrity using over 100 different failure analyses. The failure analyses include traditional industry methods, modern analytical and computational solutions, as well as some unique approaches [8]. Methods development has been on-going since the late 1980's to present [9,10,11,12,13].

2.1 FEA Computed Internal Load Paths vs. No FEA Required

A preliminary design criteria for the Interstage is that a uniform design must be established for each panel concept. Even though the axial load will vary along the span of the Interstage, this lesser load is not allowed yet to be considered, and the entire barrel is sized to the maximum compressive line load. For this statically determinate loading approach, FEA is not required and a HyperSizer workspace approach may be used to determine acreage weights for each panel concept. The tension and compression hoop loads caused by pressure are quantified for the panels neglecting load sharing with the ringframe (Ny = pr).

HyperSizer Workspace Sizing

The HyperSizer workspace approach is used to size the Interstage acreage panels. For this sizing approach, the internal design-to loads are entered as a load case. Then the panel geometry is entered, including the radius of curvature and buckling spans for each ringframe spacing. The optimization sizing bounds are set and each panel concepts is automatically sized in HyperSizer. The optimal panel weights are recorded as a function of ringframe spacing.

For this study, 25 possible ringframe spacings are considered for each panel concept that range between 16" spacing (35 ringframes) and 570" spacing (no ringframes). Each panel design is stored in the workspace which becomes a starting point for the FEA coupling process.

2.2 Panel Sizing using HyperSizer

The panel sizing process begins by specifying a minimum and a maximum thickness or width bound, a number of permutations (step size) and available laminates for each sizing variable. This allows the optimizer to choose the best material and panel dimensions to meet the internal loading conditions. During the optimization, HyperSizer generates a margin of safety for each active failure analysis and determines the optimum solution as the lightest panel that passes all active failure criteria.

Composite Laminates

For initial sizing, effective laminates are used for sizing variables. In HyperSizer ***Effective Laminates*** (EL) have 'smeared' material properties based on fiber orientation and thickness. Effective laminates are valuable for preliminary sizing since the laminate thickness is a continuous sizing variable like an isotropic material. The EL approach homogenizes a ply-by-ply layup to achieve smeared Ex and Ey modulus. The orthotropic ratio of Ex and Ey is used, but the bending stiffness for each laminate thickness does not distinguish which ply orientations are on the outer fibers and which are near the midplane. Hence, the true variation of Dij for a given laminate is lost, which is necessary to provide optimal buckling stable skins, a particular issue for stiffened panels, but not necessary for sandwich panels. Actual stacking sequence of the sandwich laminates have little effect on the sandwich analyses. Unlike stiffenend panels which are skin local buckling critical, sandwich panels do not have local buckling modes and therefore the Dij of a facesheet laminate has no impact to the analysis. And because sandwich panels get nearly all of their bending stiffness from the height of the core, the actual ply sequence of the facesheet also has no impact on the panel overall Dij.

Once the appropriate laminate thickness and fiber orientation percents is determined with effective laminates, all panel designs are matured to a discrete laminate design. For detailed sizing ***Discrete Laminates*** (DL) discrete laminates are used and the ply sequence is considered to determine the laminate properties. Since the ply sequence will have a significant effect on the bending properties of the laminate, discrete laminate designs provide higher fidelity buckling results and weight estimates. Going to discrete laminates will reduce the weight of stiffened panels because the actual layup sequence can be a benefit. However, going to discrete laminates will be a weight penalty for sandwich panels. This is because the sandwich will not be able to be made with the ideal laminate thickness and ply percents as quantified with effective laminates. Most likely additional plies will have to be added to achieve symmetric and balanced laminates while meeting fabrication rule of thumbs such as a minimum of 10% in each direction, etc.

For this reason as the panel designs are matured from effective laminates to discrete laminates, the stiffened panel designs will decrease in weight and the sandwich panels will generally increase in weight.

2.3 Optimization Bounds

Honeycomb Sandwich Panel

The honeycomb sandwich panel has the fewest optimization variables and is the easiest to optimize. For sandwich optimizations, the thickness and material for the facesheets and core are the only sizing variables. Due to the limited optimization options the honeycomb panels will usually not decrease in weight from their initial optimal solutions.

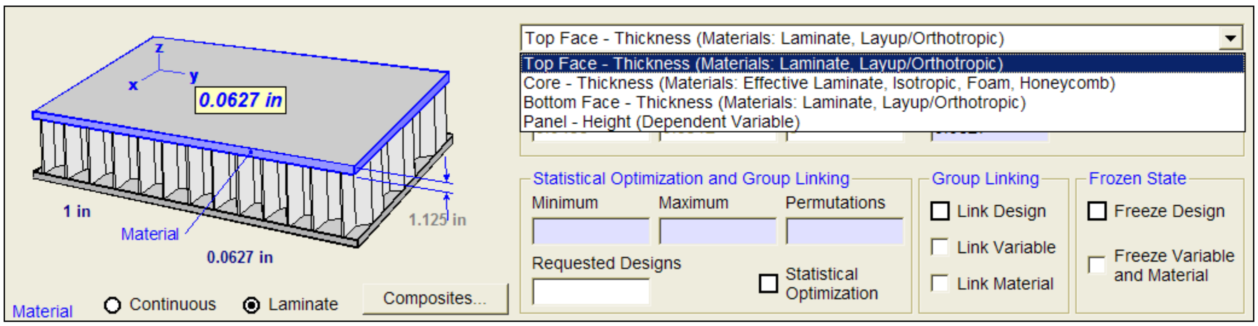


Fig. 7, Honeycomb Sandwich Panel Optimization Variables.

For the Ares V Interstage, the sandwich panel facesheets range from 9 plies to 13 plies and the core height increases from 1" (min gage) to 2.6" as the ringframe spacing increases. The facesheet laminates are determined based on material strength requirements and the core height is chosen to provide buckling stability.

Hat Shaped Stiffened Panel

Unlike sandwich panels, stiffened panels particularly the hat stiffened panel, have many sizing variables. The increased number of sizing variables provide more opportunities for weight savings but this makes the optimization of these concepts increasingly more difficult. To effectively optimize a stiffened panel an automated tool such as HyperSizer is needed to fully explore all the variables in the design space.

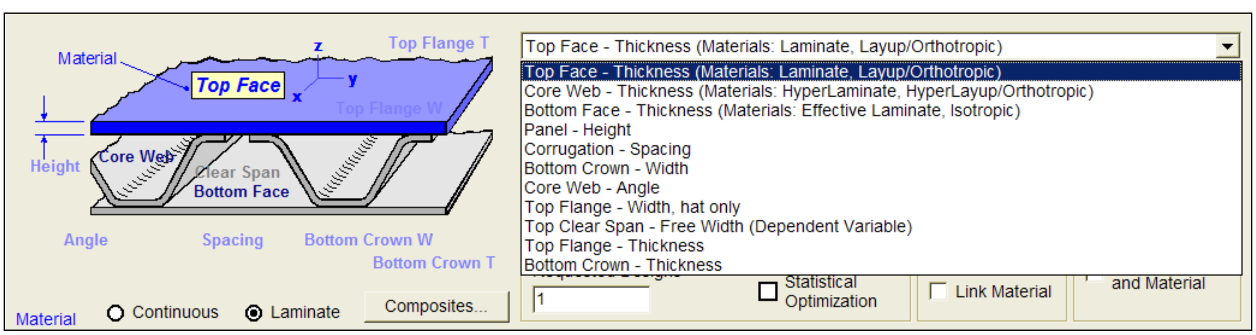


Fig.8, Hat Stiffened Panel Optimization Variables.

2.4 Panel Failure Analysis Margins-of-Safety (MS)

In the software, the active failure methods set the design criteria in that HyperSizer will not choose a panel design unless it passes all active failure methods. The failure methods used during sandwich and stiffened panel optimization are listed in figures 9 and 10.

Honeycomb Sandwich Panel

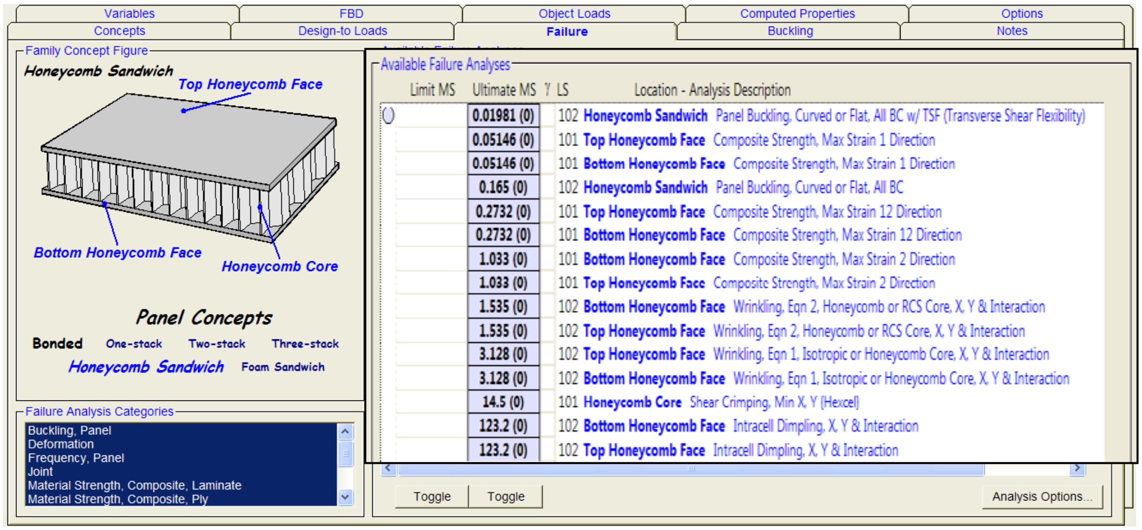


Fig. 9 ,Honeycomb Sandwich Failure Methods Applied During Optimization

Hat Shaped Stiffened Panel

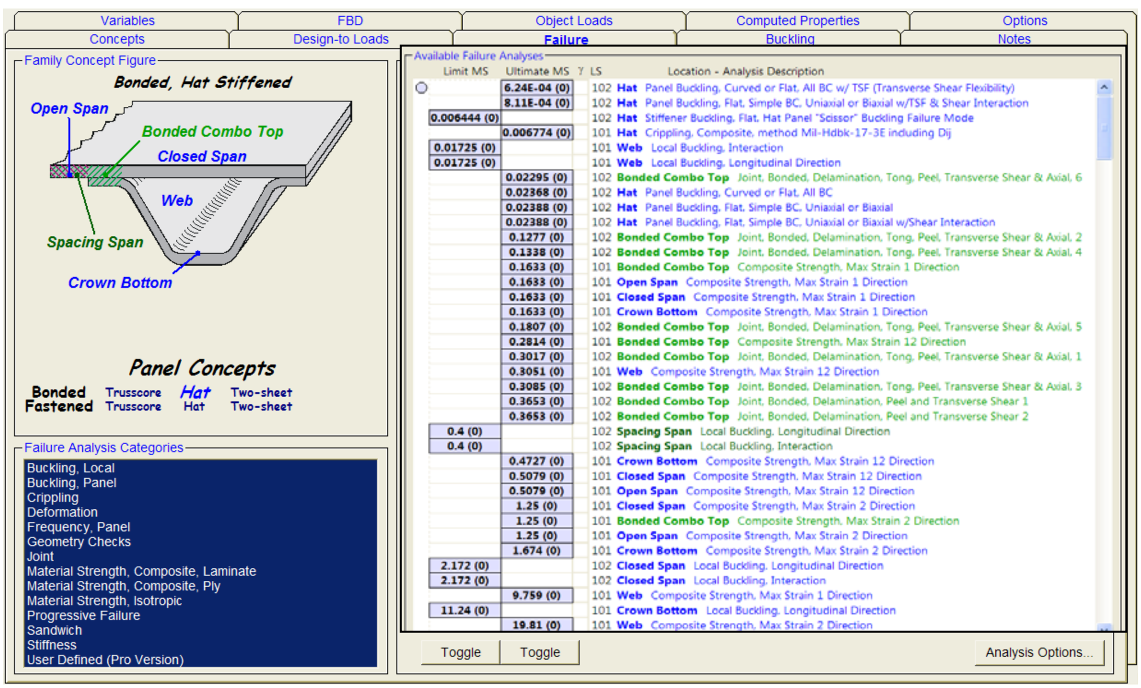


Fig. 10, Hat Stiffened Panel Failure Methods Applied During Optimization

Stiffened panels experience many failure modes not present in sandwich panels. These failures include local buckling of the spacing span and stiffener web, as well as crippling, stiffener "scissor" buckling, bonded flange to skin joint failure and geometric requirements. Each of these failure modes is captured in HyperSizer software.

2.5 Ringframe Sizing and Optimum Spacing

The ringframes are sized to meet a required EI to prevent global buckling. There are two critical ringframe stiffness values which are considered, the first prevents global buckling before ultimate load and the second is more conservative and prevents the buckling wave from passing through the ringframes altogether. 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). The two FEA solutions of figures 11 and 12 verify achieving the required 2.15 eigenvalue for two different important buckling analyses. First is that the ringframes are stout enough to prevent global buckling from occurring before reaching design load, and second that the panel's themselves are stout enough to prevent buckling before reaching design load. Current design criteria requires that only the 2.15 be reached, regardless of the type of mode.

Table 7, 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 Ringframe?
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

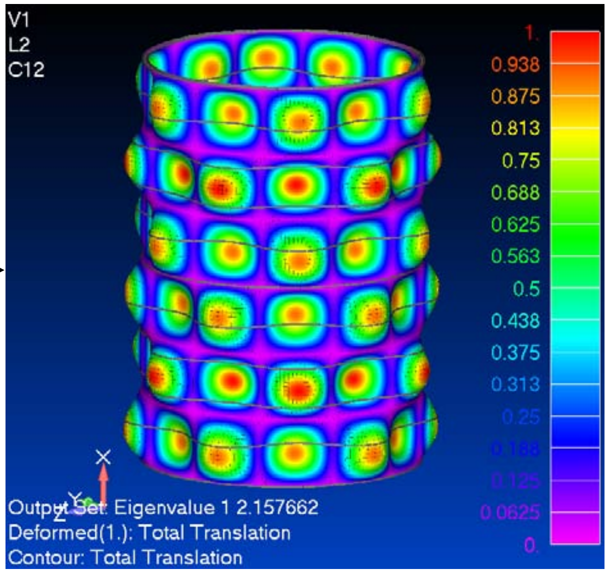


Fig. 11, Buckling Mode Shape for Interstage with Ringframes Sized to Prevent Global Buckling Before Ultimate Load

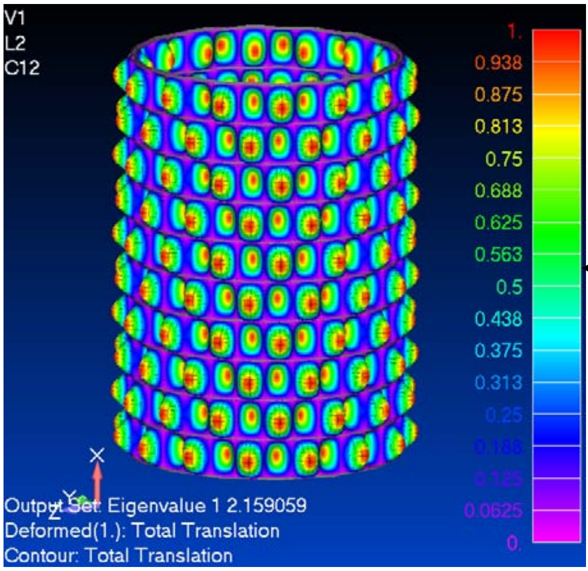


Fig.12, Buckling Mode Shape for Interstage with Ringframes Sized to Prevent Global Buckling from Occurring as First Buckling Mode Shape

Many FEA-ringframe spacing studies were performed to accurately size the ringframes for each panel concept. A summary of the ringframe stiffness studies is shown in figure 13.

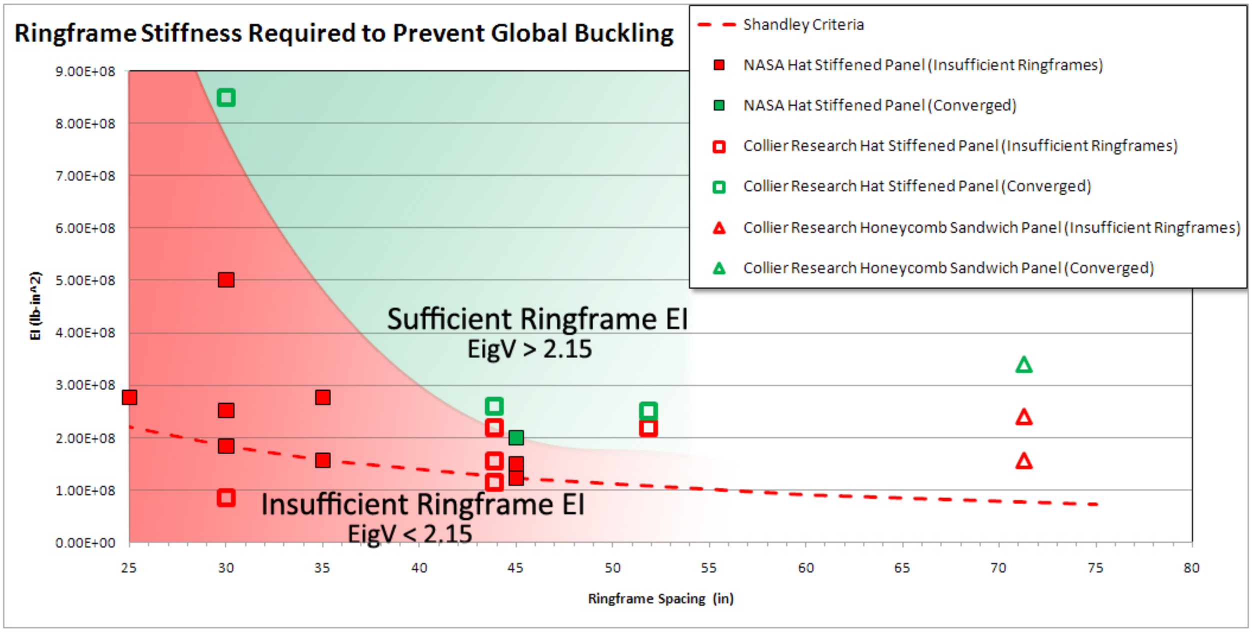


Fig. 13, Ringframe EI Sizing Trade Study

The honeycomb sandwich results are shown as triangles and the hat stiffened panel results are shown as squares. From the general trend we see that the Honeycomb sandwich panels need higher ringframe stiffness to prevent global buckling. We also see the panel designs with shorter ringframe spacings (particularly for ringframe spacing < 43”) to require a higher ringframe EI stiffness to prevent global buckling which is also quantified with the Shanley equation. The Shanley equation is an analytical method for determining the required ringframe stiffness to prevent global buckling and is shown as a dashed red line. Since the Shanley equation has no knowledge of the bending stiffness of the panel it is not an accurate method for estimating the required ringframe stiffness.

Omitted from these studies is the contribution for the ringframes GJ torsional stiffness. A future study should include this term.

Ringframe Failure Analysis Margins-of-Safety (MS)

The controlling failure methods for the Ares V Interstage ringframes include local buckling of the web and flanges and material strength of flanges. The controlling failure mode is the required EI stiffness, the value of which is determined from the process outlined in table 5.

Available Failure Analyses

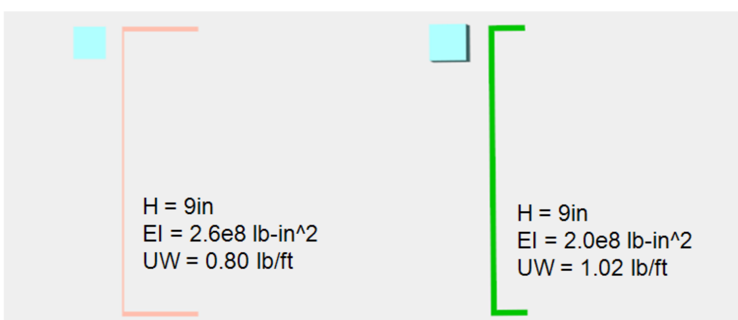
Limit MS	Ultimate MS	γ	LS	Location - Analysis Description
0.001154 (0)			1	**C** Stiffness Requirement, Bending
	0.04588 (0)		4	**Web** Local Buckling, Longitudinal Direction
	1.458 (0)		4	**Flange Top, one sided** Local Buckling, Longitudinal Direction
	2.155 (0)		3	**Flange Top, one sided** Composite 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. 14, Active Failure Analysis for Ringframes

By imposing the stiffness requirement, the ringframes are sized to be tall 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 the ringframes.

Ringframe Laminates

To maximize weight savings in the ringframes the laminates are customized by adding 0 degree fibers in the flanges and keeping the web strictly 45 degree fibers. These cross sections are lighter and provide higher bending stiffness. Figure 15 shows the stiffness and weight impact of customizing the laminates for the ringframes.



Design 1: Extra 0 Degree Fibers in Flanges and 45 Degree Fibers in Web

Design 2: Uniform Laminate for Entire Beam Cross Section

Fig. 15, Stiffness and Weight Impact of Tailoring the Ringframe Laminates to meet the Required Stiffness and Local Buckling Requirements

Notice the first design is 20% lighter and has a 30% higher bending stiffness than the uniform laminate design.

PRSEUS Ringframe Sizing

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

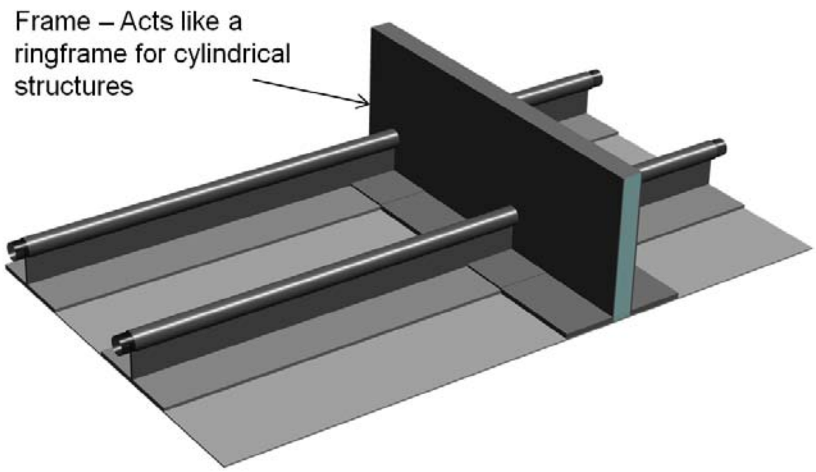


Fig. 16: PRSEUS Panel Geometry

Since the PRSEUS frames are an innate sizing variable within HyperSizer, the entire Interstage can be sized using a simple workspace approach. This optimization approach requires no iterations between HyperSizer and FEA to determine: (1) the ringframe stiffness that prevents global buckling or (2) the transverse (hoop) compression load caused by ringframe pinching. These panel behaviors are captured within HyperSizer which simplifies the optimization process and reduces the level of effort required to perform vehicle level trade studies.

2.6 Sizing for Manufacturing

Geometry checks for fabrication and repair Implemented as failure modes with MS

Three categories of geometric cross-section checks are included in HyperSizer. (1) geometric fabrication rules, (2) geometric analysis rules, and (3) geometric repair rules. These checks are included to ensure that stiffened panels generated by HyperSizer not only have all positive margins of safety (which is automatic), but also that the cross-sections are "reasonable" in that they make sense for fabrication, make sense for design practicality, and provide enough room for a repair angle.

Available Failure Analyses

Limit MS	Ultimate MS	LS	Location - Analysis Description
	PASSED	1	**Hat** Geometry Rule 1, Stiffener Flange Width to Flange Thickness [Ratio Min]
	PASSED	1	**Hat** Geometry Rule 2, Stiffener Flange Width to Stiffener Height [Ratio Min]
	PASSED	1	**Hat** Geometry Rule 40, Panel Width to Stiffener Spacing [Min # of stiffeners]
	PASSED	1	**Hat** Geometry Rule 41, Stiffener to Skin Area [Ratio Min/Max]
	PASSED	1	**Hat** Geometry Rule 72, Stiffener Web/Repair Thickness to Hole Diameter [Ratio Max] (Repair Angle)
	PASSED	1	**Hat** Geometry Rule 73, Stiffener Skin/Flange/Repair Thickness to Hole [Ratio Max] (Repair Angle)
	PASSED	1	**Hat** Geometry Rule 74, Stiffener Height [Min] (Repair Angle)
	PASSED	1	**Hat** Geometry Rule 75, Stiffener Flange Width [Min] (Repair Angle)

Fig.17, Hat Stiffened Panel Geometry Checks

Uniform Stiffener

For stiffened panel and sandwich structures an important manufacturing consideration is maintaining consistent panel variables like stiffener spacing and honeycomb core thickness along the span of the structure. HyperSizer allows the user to link these panel objects across component boundaries to create realistic and manufacturable designs.

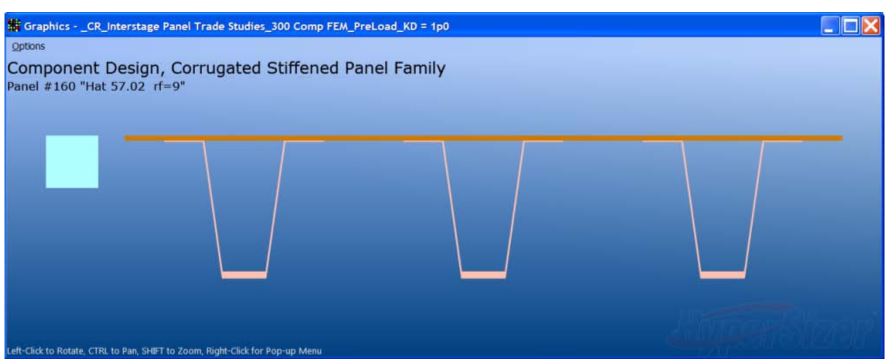


Fig. 18, Optimum Hat Stiffened Panel Scale Cross Section, Uniform Stiffener Dimensions

For the hat stiffened panels presented, a uniform stiffener is defined along the entire length of the Interstage barrel. This is practical because only one mandrel shape is needed to fabricate the barrel section which decreases the manufacturing complexity.

2.7 Sizing Joints

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. Figures 19 and 20 illustrate notational designs. 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 unitized barrel designs.

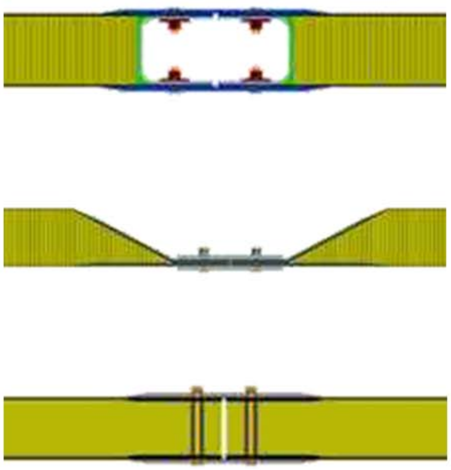


Fig. 19, Honeycomb Sandwich Longitudinal Construction Joint Concepts

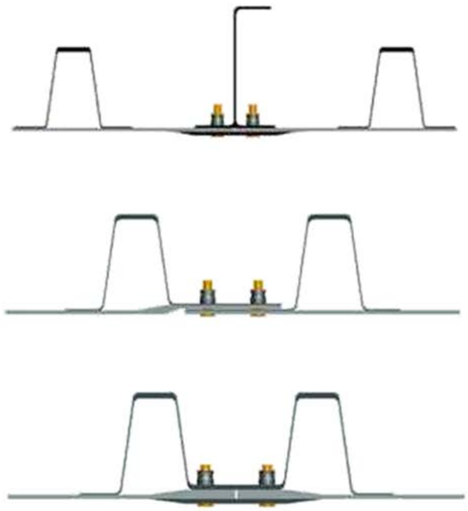


Fig. 20, Hat Stiffened Panel Longitudinal Construction Joint Concepts

Assuming the entire cylinder will have uniform deformation under axial compression implies that the added rigidity provided by the splice joint will reduce the total strain of the cylinder thus reducing the stress in the panels. The effect of the splice plates on the acreage loads of the cylinders are studied by determining a ratio of EA (axial stiffness) between the skin and splice plates.

Table 2.7.1, Longitudinal Stiffness Study for Segmented Hat Stiffened Panel Design

Panel Config (Number of Segments)	EA Splice Joint/EA Panel	Panel Axial Load
1	0.000	100.00%
3	0.008	99.24%
4	0.010	98.99%
6	0.015	98.50%
8	0.020	98.01%

This analysis only considers the uniform axial load and not the flight condition where a large moment is present. 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. Hence for the segmented barrel designs no load is removed from the panels so the panel designs remain constant. Thus the effect of segmenting the structure is simply the added weight of each joint.

Circumferential Assembly Joints

Circumferential End Frames are required for the Ares V Interstage to join the structure to the adjacent components in the vertical stack. Common end frame geometry is illustrated in Figure 21.

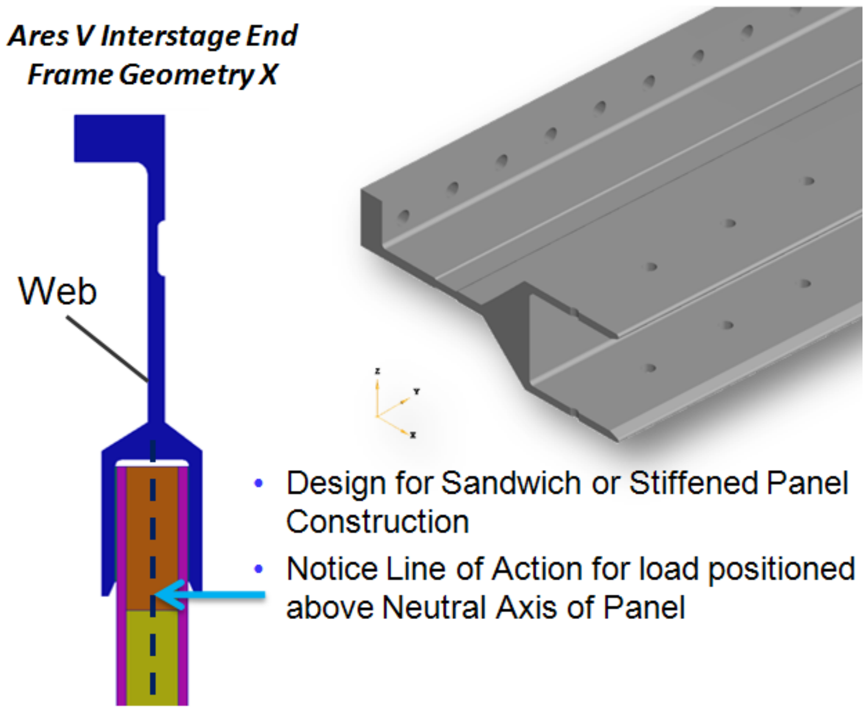
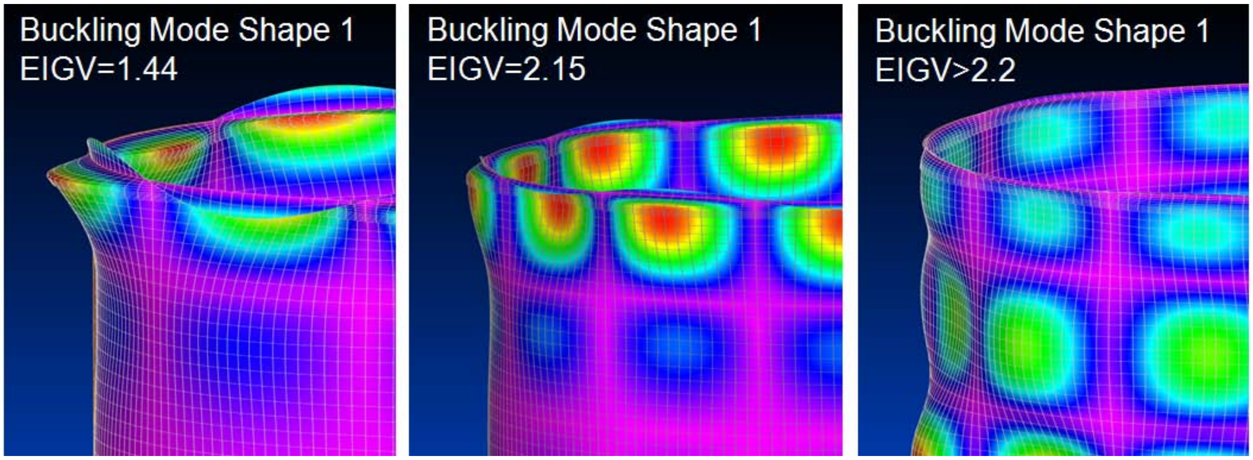


Fig. 21, Common End Frame Geometry for Sandwich and Hat Stiffened Panels

For this design, the web of the metallic end frame (blue) is positioned over the neutral axis of the acreage panel. This is to avoid load eccentricity caused from applying load off the neutral axis of the acreage panels. Extensive trade studies were performed to determine the required end frame design to drive buckling into the acreage of the Interstage for each panel concept.



Design 1: Baseline End frame Design, As Received, Ares I Interstage Dimensions,

Design 2: Modified End frame Design, Increased Frame Web Thickness, 5% Increase in Weight

Design 3: Modified End frame Design, Increased Frame Web Thickness, 13% Increase in Weight

Fig. 22, Global Buckling Results for Optimum Hat Stiffened Panel End Frame Sizing Study

From this study it is determined the Baseline Ares I circumferential joint is not stout enough because localized buckling occurs in the end frame web. By adding a relatively small amount of thickness to the frame web and taking a weight penalty the end frames are redesigned to drive buckling into acreage. Though the end ringframe weights went up to 13%, the overall weight increase to the barrel is insignificant.

3 Weight Trends as a Function of Ringframe Spacing

3.1 Honeycomb Sandwich panel

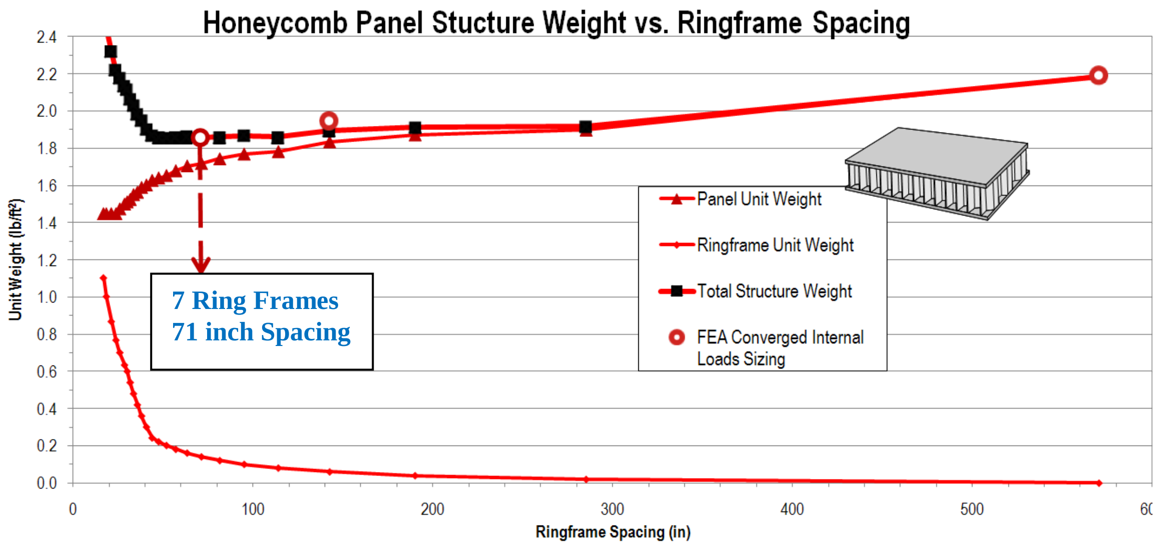


Fig.23, Honeycomb Sandwich Trade Study Results, Weight vs. Ringframe Spacing

3.2 Blade Sandwich panel

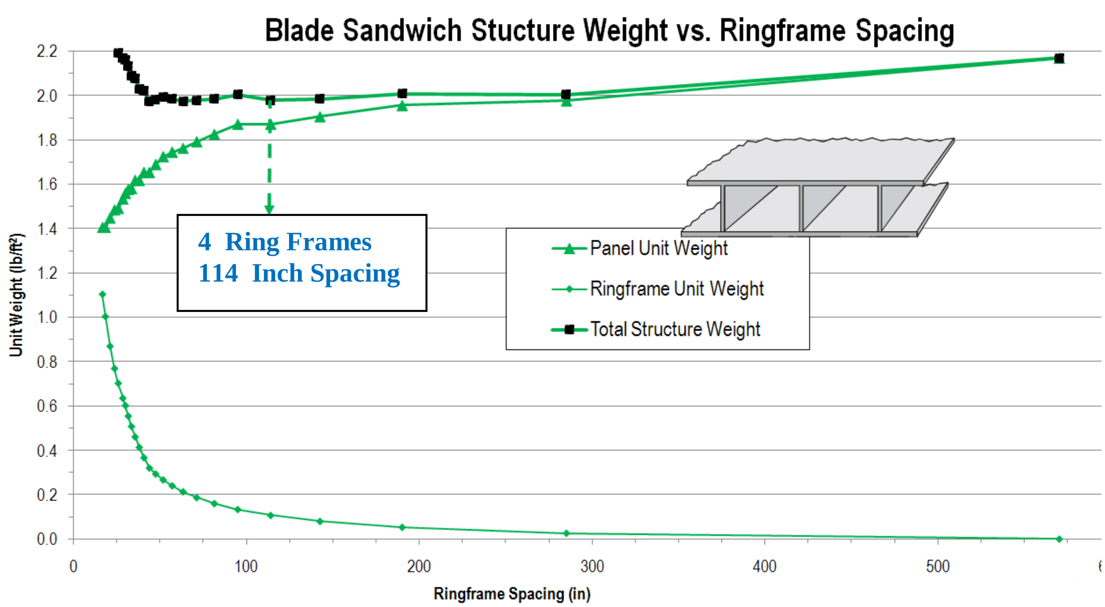


Fig.24, Blade Sandwich Trade Study Results, Weight vs. Ringframe Spacing

3.3 Blade Stiffened panel

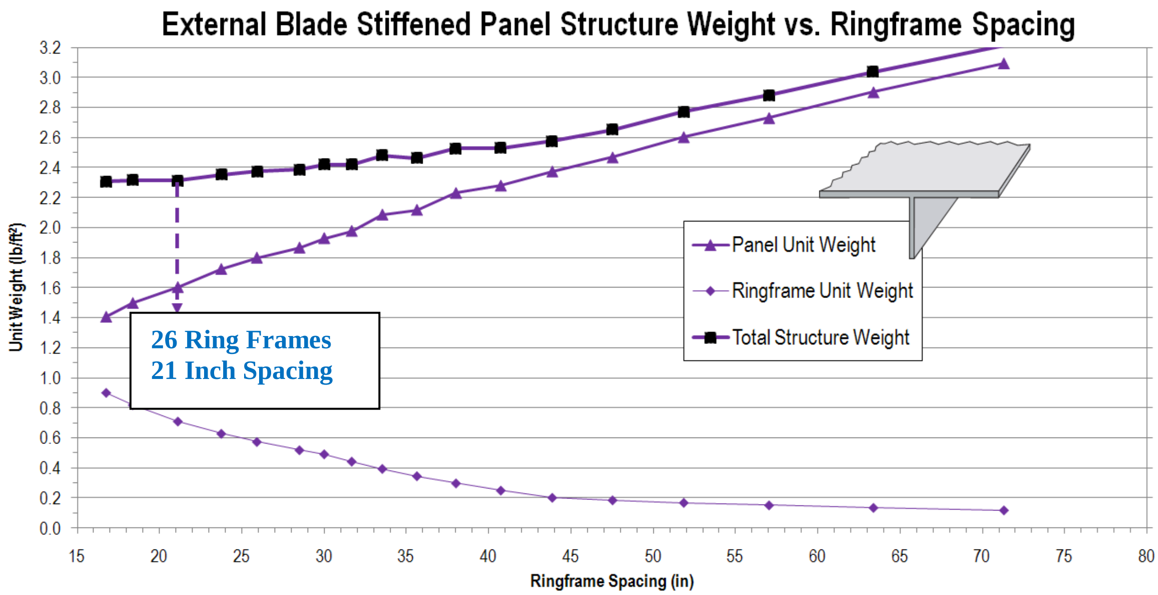


Fig.25, External Integral Blade Stiffened Panel Trade Study Results, Weight vs. Ringframe Spacing

3.4 External Hat Stiffened Panel

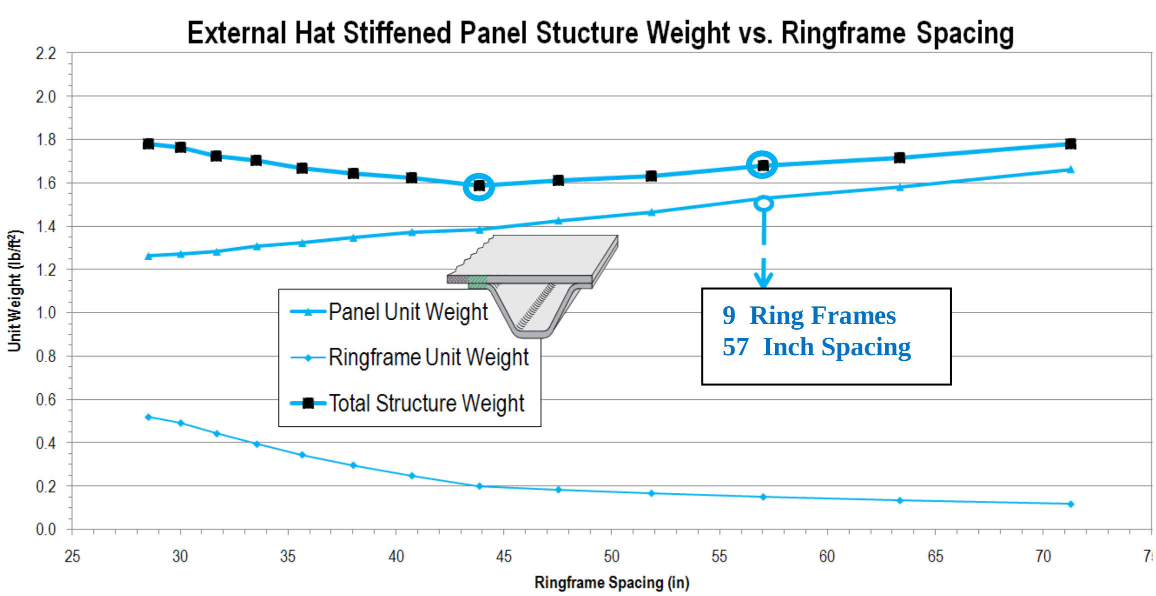


Fig. 26, External Bonded Hat Stiffened Panel Trade Study Results, Weight vs. Ringframe Spacing

3.5 Summary Data

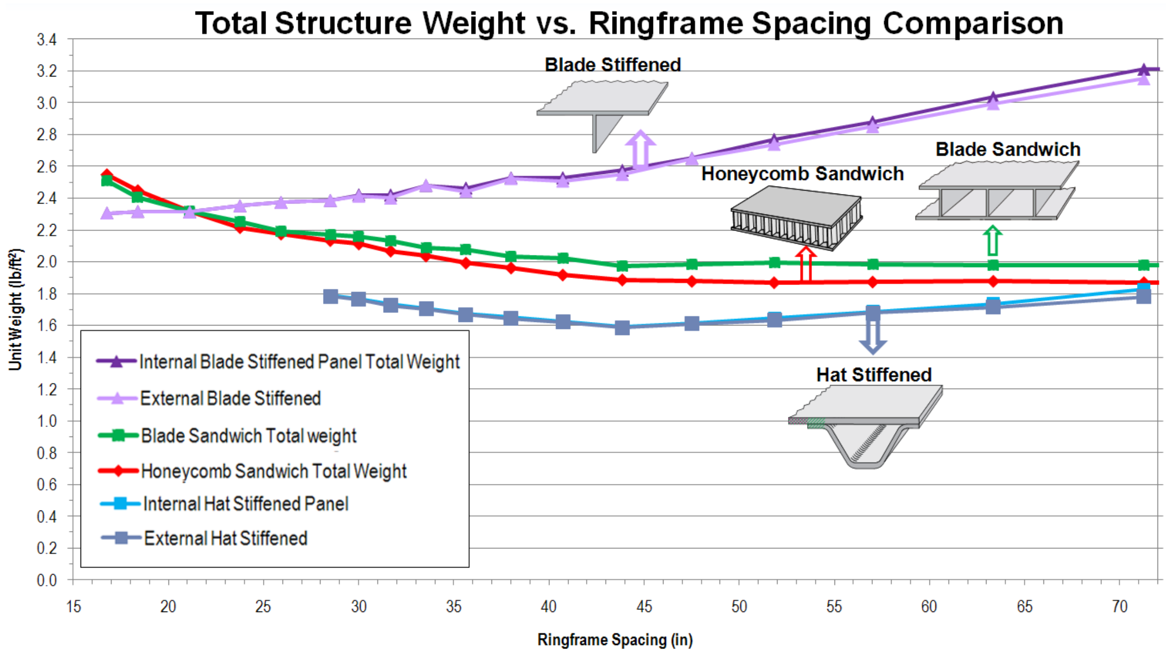


Fig. 27, Comparison of Sandwich and Stiffened Panel, Total Weight vs. Ringframe Spacing

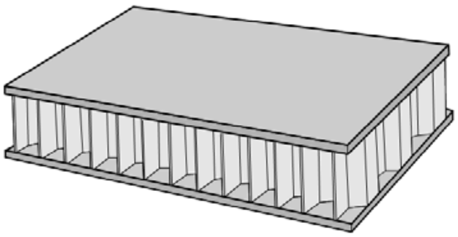
Figure 27 shows the lightest hat spacing is 43” and the optimal honeycomb spacing is 72”. The blade stiffened concept is non-weight competitive. Internal and external stiffeners have minimal impact on weights at ringframe spacing < 57”.

These weight predictions were performed without compression hoop preload. The weights reported in table 1 are more recent and are based on compressive hoop preload. However, the weight trends are nearly the same with or without preload, though the weights of all concepts are slightly less.

In summary, figures 23 to 27 are useful for future cylindrical space launch designs. Though future vehicles may have different loads, diameters, and lengths, the general trends and weight % deltas will hold true for composite designs.

4 Best Design of Each Panel Concept

4.1 Honeycomb Sandwich



Object	Layup/Material
Top Facesheet	[+45/-45/0_3/_90]s
Honeycomb Core	Hexcel 3.1 pcf 1/8" Cell Size
Bottom Facesheet	[+45/-45/0_3/_90]s

71" RF Spacing Honeycomb Sandwich Component Dimensions

Component Type	Facesheet Thickness (in)	Core Thickness (in)	Panel Height (in)	Unit Weight Panel Only (lb / ft^2)	Area (ft^2)	Total Weight Panel Only (lb)
Honeycomb	0.0627	2.2	2.325	1.756	4926	8651

Fig.28, Optimum Honeycomb Sandwich Dimensions and layups

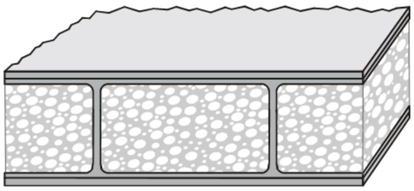
Available Failure Analyses

Limit MS	Ultimate MS	LS	Location - Analysis Description
	0.01981 (0)	102	**Honeycomb Sandwich** Panel Buckling, Curved or Flat, All BC w/ TSF (Transverse Shear Flexibility)
	0.05146 (0)	101	**Top Honeycomb Face** Composite Strength, Max Strain 1 Direction
	0.05146 (0)	101	**Bottom Honeycomb Face** Composite Strength, Max Strain 1 Direction
	0.165 (0)	102	**Honeycomb Sandwich** Panel Buckling, Curved or Flat, All BC
	0.2732 (0)	101	**Top Honeycomb Face** Composite Strength, Max Strain 12 Direction
	0.2732 (0)	101	**Bottom Honeycomb Face** Composite Strength, Max Strain 12 Direction
	1.033 (0)	101	**Bottom Honeycomb Face** Composite Strength, Max Strain 2 Direction
	1.033 (0)	101	**Top Honeycomb Face** Composite Strength, Max Strain 2 Direction
	1.535 (0)	102	**Bottom Honeycomb Face** Wrinkling, Eqn 2, Honeycomb or RCS Core, X, Y & Interaction
	1.535 (0)	102	**Top Honeycomb Face** Wrinkling, Eqn 2, Honeycomb or RCS Core, X, Y & Interaction
	3.128 (0)	102	**Top Honeycomb Face** Wrinkling, Eqn 1, Isotropic or Honeycomb Core, X, Y & Interaction
	3.128 (0)	102	**Bottom Honeycomb Face** Wrinkling, Eqn 1, Isotropic or Honeycomb Core, X, Y & Interaction
	14.5 (0)	101	**Honeycomb Core** Shear Crimping, Min X, Y (Hexcel)
	123.2 (0)	102	**Bottom Honeycomb Face** Intracell Dimpling, X, Y & Interaction
	123.2 (0)	102	**Top Honeycomb Face** Intracell Dimpling, X, Y & Interaction

Fig.29, Optimum Honeycomb Sandwich Margins of Safety

Axial compression requires the honeycomb sandwich facesheets to have a discrete number of 0 degree plies to achieve material strength. Panel buckling analysis requires the facesheets to have a higher % of 45s and relatively thick core heights. The hoop tension from load case 101 requires the laminates to have a set number of 90 degree plies. Both loadcases control as well as both strength and buckling analyses control. The buckling MS = 0.02 for loadcase 102 and the strength MS = 0.05 for loadcase 101. Due to the combination of strength and buckling requirements, the optimal laminate is the same for all sandwich designs for any ringframe spacing and is 55% 0, 36% 45, and 9% 90. Thus the only change in sandwich geometry as the ringframe spacing increases is the increase in core height.

4.2 Reinforced Core Sandwich



Object	Thickness (in)	Layup
Top Facesheet	0.048	[0_5/-45/90/+45] *inverse of bottom facesheet
Stiffener Flange	0.009	[+45/-45]
Stiffener Web	0.018	[+45/-45]s
Foam Core	2.586	Rohacell IG 2.0 pcf
Bottom Facesheet	0.048	[+45/90/-45/0_5] *inverse of top facesheet

71” RF Spacing Reinforced Core Sandwich Component Dimensions

Component	Panel Height	Stiffener Spacing	Web Angle	Unit Weight Panel Only	Area	Total Weight Panel Only
Type	(in)	(in)	(°)	(lb / ft^2)	(ft^2)	(lb)
Reinforced Core	2.7	1.6	90	1.559	4926	7680

Fig. 30 , Optimum Reinforced Core Sandwich Dimensions and layups

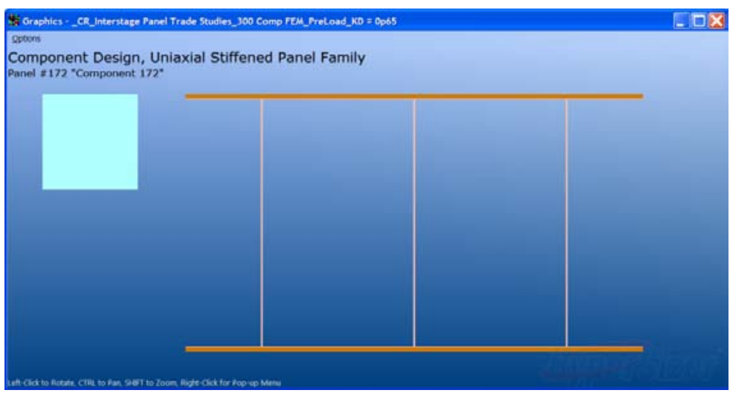
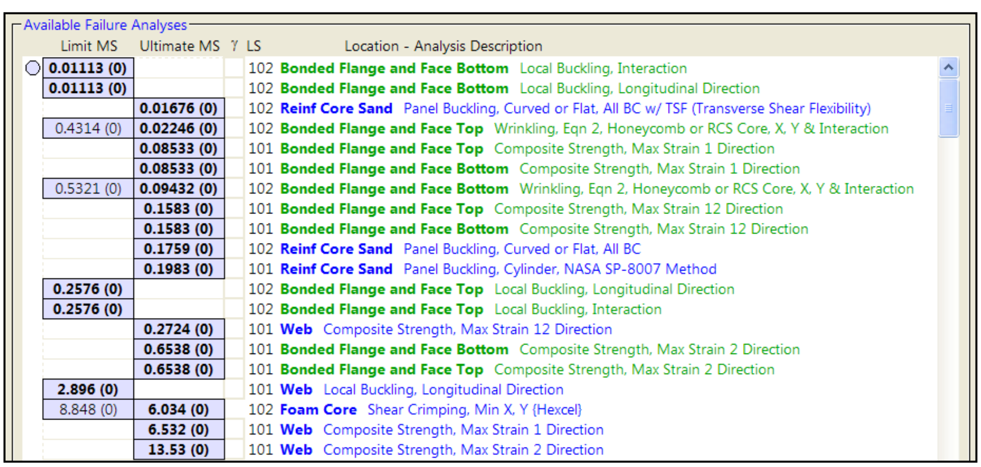


Fig. 31, Optimum Reinforced Core Sandwich Scale Cross Section. Laminates are thin because of stability provided by the foam elastic foundation.

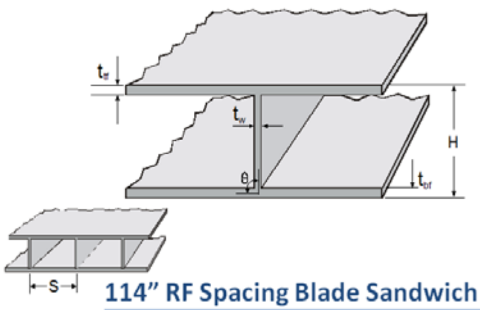


Available Failure Analyses

Limit MS	Ultimate MS	LS	Location	Analysis Description
0.01113 (0)		102	Bonded Flange and Face Bottom	Local Buckling, Interaction
0.01113 (0)		102	Bonded Flange and Face Bottom	Local Buckling, Longitudinal Direction
	0.01676 (0)	102	Reinf Core Sand	Panel Buckling, Curved or Flat, All BC w/ TSF (Transverse Shear Flexibility)
0.4314 (0)	0.02246 (0)	102	Bonded Flange and Face Top	Wrinkling, Eqn 2, Honeycomb or RCS Core, X, Y & Interaction
	0.08533 (0)	101	Bonded Flange and Face Top	Composite Strength, Max Strain 1 Direction
	0.08533 (0)	101	Bonded Flange and Face Bottom	Composite Strength, Max Strain 1 Direction
0.5321 (0)	0.09432 (0)	102	Bonded Flange and Face Bottom	Wrinkling, Eqn 2, Honeycomb or RCS Core, X, Y & Interaction
	0.1583 (0)	101	Bonded Flange and Face Top	Composite Strength, Max Strain 12 Direction
	0.1583 (0)	101	Bonded Flange and Face Bottom	Composite Strength, Max Strain 12 Direction
	0.1759 (0)	102	Reinf Core Sand	Panel Buckling, Curved or Flat, All BC
	0.1983 (0)	101	Reinf Core Sand	Panel Buckling, Cylinder, NASA SP-8007 Method
0.2576 (0)		102	Bonded Flange and Face Top	Local Buckling, Longitudinal Direction
0.2576 (0)		102	Bonded Flange and Face Top	Local Buckling, Interaction
	0.2724 (0)	101	Web	Composite Strength, Max Strain 12 Direction
	0.6538 (0)	101	Bonded Flange and Face Bottom	Composite Strength, Max Strain 2 Direction
	0.6538 (0)	101	Bonded Flange and Face Top	Composite Strength, Max Strain 2 Direction
2.896 (0)		101	Web	Local Buckling, Longitudinal Direction
8.848 (0)	6.034 (0)	102	Foam Core	Shear Crimping, Min X, Y (Hexcel)
	6.532 (0)	101	Web	Composite Strength, Max Strain 1 Direction
	13.53 (0)	101	Web	Composite Strength, Max Strain 2 Direction

Fig. 32, Optimum Reinforced Core Sandwich Margins of Safety

4.3 Blade Sandwich



Object	Thickness (in)	Layup
Top Facesheet	0.0855	[+45/-45/0$_3$/90/0/_0]s
Stiffener Web	0.0513	[+45/-45/+45/-45/_0]s
Bottom Facesheet	0.0855	[+45/-45/0$_3$/90/0/_0]s

114" RF Spacing Blade Sandwich Component Dimensions

Panel Type	Top Facesheet Thickness ttf	Web Thickness tw	Panel Height H	Stiffener Spacing S	Web Angle θ	Unit Weight Panel Only	Acreage Interstage Area	Total Weight Panel Only
	(in)	(in)	(in)	(in)	(°)	(lb / ft^2)	(ft^2)	(lb)
Blade Sandwich	0.0855	0.0513	2.24	1.9	90	1.862	4926	9172

Fig. 33, Optimum Blade Sandwich Dimensions and layups

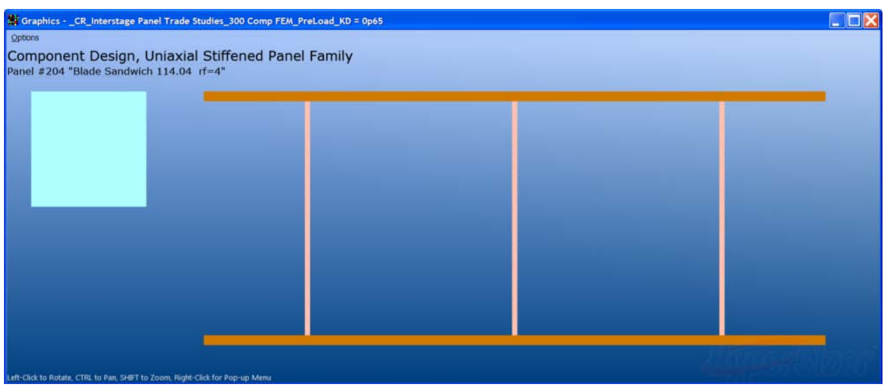


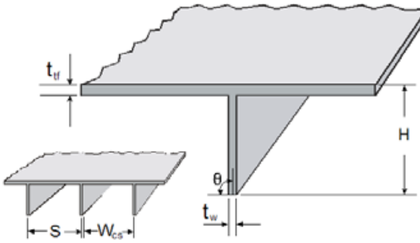
Fig. 34, Optimum Blade Sandwich Scale Cross Section. In this concept, foam is not present and the laminates are thicker.

Available Failure Analyses

Limit MS	Ultimate MS	γ	LS	Location - Analysis Description
	0.006779 (0)		102	**Blade Sand** Panel Buckling, Curved or Flat, All BC w/ TSF (Transverse Shear Flexibility)
	0.01122 (0)		101	**Blade Sand** Crippling, Composite, method Mil-Hdbk-17-3E including Dij
	0.2013 (0)		102	**Blade Sand** Panel Buckling, Curved or Flat, All BC
	0.2899 (0)		101	**Blade Sand** Panel Buckling, Cylinder, NASA SP-8007 Method
	0.665 (0)		102	**Bottom Span** Local Buckling, Interaction
	0.665 (0)		102	**Clear Span** Local Buckling, Interaction
	0.665 (0)		102	**Clear Span** Local Buckling, Longitudinal Direction
	0.665 (0)		102	**Bottom Span** Local Buckling, Longitudinal Direction
	0.71 (0)		101	**Bottom Span** Composite Strength, Max Strain 1 Direction
	0.71 (0)		101	**Clear Span** Composite Strength, Max Strain 1 Direction
	0.9168 (0)		101	**Web** Composite Strength, Max Strain 12 Direction
	1.056 (0)		101	**Bottom Span** Composite Strength, Max Strain 12 Direction
	1.056 (0)		101	**Clear Span** Composite Strength, Max Strain 12 Direction
	1.266 (0)		101	**Web** Local Buckling, Longitudinal Direction
	2.307 (0)		101	**Clear Span** Composite Strength, Max Strain 2 Direction
	2.307 (0)		101	**Bottom Span** Composite Strength, Max Strain 2 Direction
	14.97 (0)		101	**Web** Composite Strength, Max Strain 1 Direction
	29.89 (0)		101	**Web** Composite Strength, Max Strain 2 Direction

Fig. 35, Optimum Blade Sandwich Margins of Safety

4.4 Blade Stiffened Panel



Object	Thickness (in)	Layup
Top Facesheet	0.0855	$[+45/-45/0_2/90/0_2/\_90]s$
Stiffener Web	0.1767	$[+45/-45/0_5/90/0_5/90/0\_0]s$

21" RF Spacing Blade Stiffened Component Dimensions

Panel Type	Top Facesheet Thickness t_{tf} (in)	Web Thickness t_w (in)	Panel Height H (in)	Stiffener Spacing S (in)	Web Height θ (°)	Unit Weight Panel Only (lb / ft^2)	Acreage Interstage Area (ft^2)	Total Weight Panel Only (lb)
Blade Stiffened	0.0855	0.1767	1.375	2.5	90	1.45	4926	7140

Fig. 36, Optimum Blade Stiffened Dimensions and layups

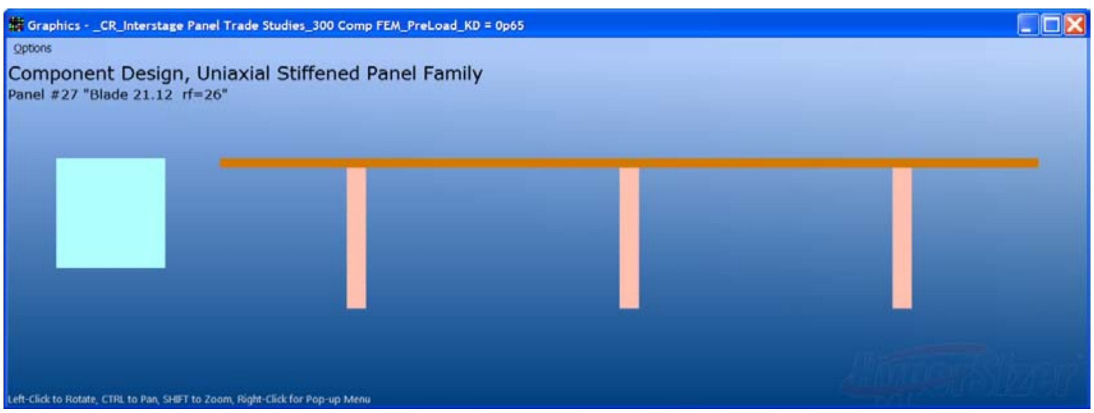


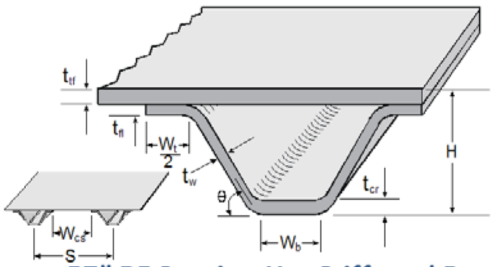
Fig. 37, Optimum Blade Stiffened Scale Cross Section. To achieve panel buckling, the web height needs to be tall. However, this makes the web susceptible to local buckling causing it to be thick.

Available Failure Analyses

Limit MS	Ultimate MS	LS	Location - Analysis Description
	0.05431 (0)	102	**Blade** Panel Buckling, Curved or Flat, All BC w/ TSF (Transverse Shear Flexibility)
0.05451 (0)		102	**Clear Span** Local Buckling, Interaction
0.05451 (0)		102	**Clear Span** Local Buckling, Longitudinal Direction
	0.07383 (0)	102	**Blade** Panel Buckling, Curved or Flat, All BC
	0.09448 (0)	101	**Blade** Crippling, Composite, method Mil-Hdbk-17-3E including Dij
0.6236 (0)		101	**Web, unsupported** Local Buckling, Longitudinal Direction
	0.7599 (0)	101	**Clear Span** Composite Strength, Max Strain 12 Direction
	0.8945 (0)	101	**Clear Span** Composite Strength, Max Strain 1 Direction
	0.8945 (0)	101	**Web, unsupported** Composite Strength, Max Strain 1 Direction
	1.189 (0)	101	**Clear Span** Composite Strength, Max Strain 2 Direction
	1.402 (0)	101	**Web, unsupported** Composite Strength, Max Strain 12 Direction
	3.369 (0)	101	**Web, unsupported** Composite Strength, Max Strain 2 Direction

Fig. 38, Optimum Blade Stiffened Margins of Safety

4.5 Hat Stiffened Panel



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

57” RF Spacing Hat Stiffened Panel Component Dimensions

Component	Panel Height H	Stiffener Spacing S	Crown Width W_b	Web Angle θ	Flange Width W_t	Crown Width W_{cs}	Unit Weight Panel Only	Area	Total Weight Panel Only
Type	(in)	(in)	(in)	(°)	(in)	(in)	(lb / ft^2)	(ft^2)	(lb)
Hat Stiffened	2.73	4.575	0.835	82	1.5	1.522	1.378	4926	6788

Fig. 39, Optimum Hat Stiffened Panel Dimensions and layups

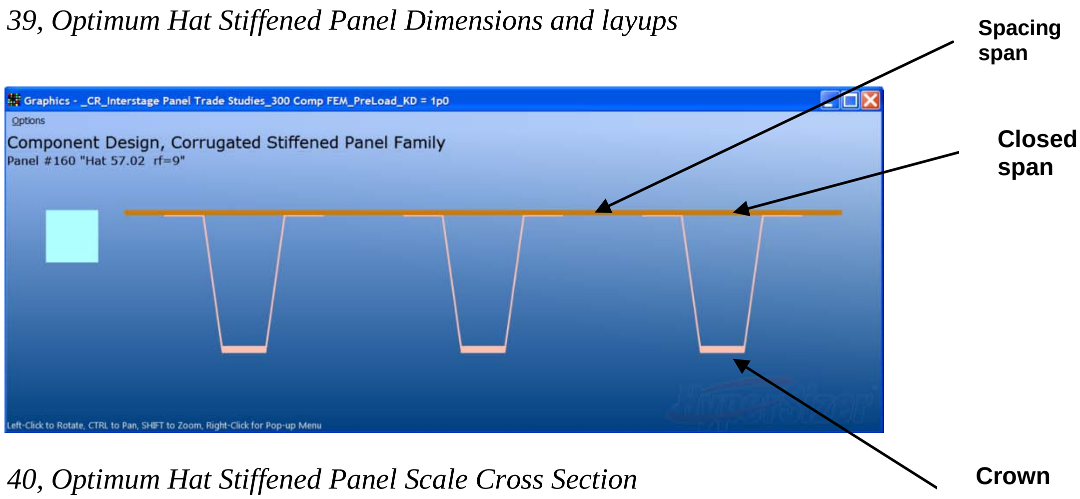


Fig. 40, Optimum Hat Stiffened Panel Scale Cross Section

Biaxial compression loads present in the Ares V Interstage influence the layups of the hat stiffened panels differently than the sandwich panels. The extra 45 and 90 degree fibers are more effective at carrying the compressive hoop load created by the crush pressure and ringframe pinching effect. The stiffened panel has to carry the entire hoop load in one facesheet while providing enough strength to carry 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 % 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	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

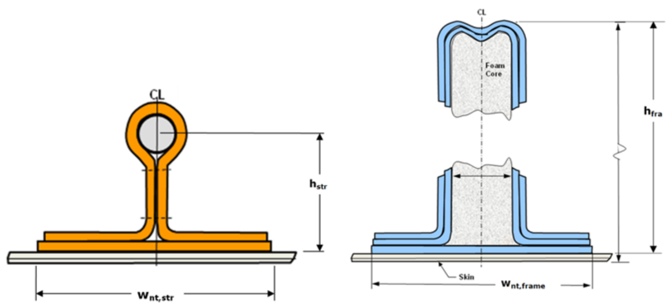
Fig. 41, Optimum Hat Stiffened Panel Margins of Safety

For the hat stiffened panel concept, both load cases are affecting the layups and panel geometry. 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.

Ten different potential failures have a MS from 0.0 to 0.02 with both loadcases controlling.

Reference Appendix A for more information on the failure analysis performed on the Hat stiffened panel.

4.6 PRSEUS



Object	Thickness (in)	Layup/Material
Top Facesheet	0.1140	[+45/-45/0_2/90_2/0_2/-45/+45]s
Stiffener Web	0.0855	[+45/-45/0_3/-45/+45/_90]s
Stringer Flange	0.0399	[-45/+45/0_3/-45/+45]
Tear Strap	0.0456	[+45/-45/0_3/+45/-45/90]
Frame Web	0.1026	[+45/-45/0_2/90/0_2/-45/+45]s
Frame Flange	0.0513	[+45/-45/0_2/_90]s
Frame Cap	0.0513	[+45/-45/0_2/_90]s
Frame Foam	0.50	Rohacell Foam 6.9pcf
Rod Diameter	0.55	Composite Rod (100% 0 deg fibers)

52" RF Spacing PRSEUS Panel Component Dimensions

Panel Type	Stringer Height H_{str} (in)	Stringer Spacing S_{str} (in)	Stringer Flange Width $W_{nt,str}$ (in)	Frame Height H_{fra} (in)	Frame Spacing S_{fra} (in)	Frame Flange Width $W_{nt,fra}$ (in)	Unit Weight Panel and Frames (lb / ft^2)	Acreage Interstage Area (ft^2)	Total Weight Includes Ringframes (lb)
Rod/Bulb Stiffened	2.24	1.9	3.37	6.67	52	52	2.019	4926	9946

Fig. 42, Optimum PRSEUS Panel Dimensions and layups

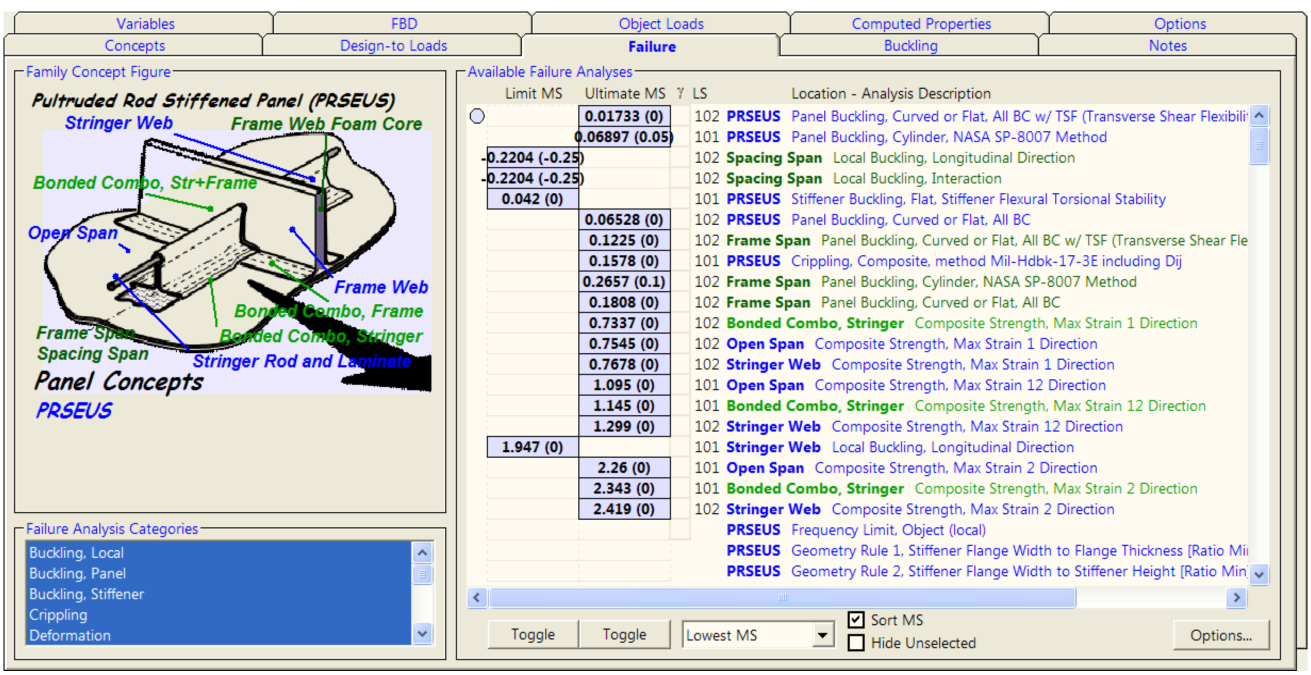


Fig. 43, Optimum PRSEUS Panel Margins of Safety

Since this concept adds stitching to the flange to skin bondline, it is allowed to post buckle (LPB). Initial skin buckling is allowed at 75% limit load.

5 Why Hat Stiffened Panels are the Lightest Panel Concept

NASA SP-5039 reports sandwich panels as lighter than stiffened panels. The results of this paper contradict those findings. This section attempts to describe why hat panels are lighter. 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. The comparison between optimized hat and honeycomb sandwich barrel sections is shown in figure 44.

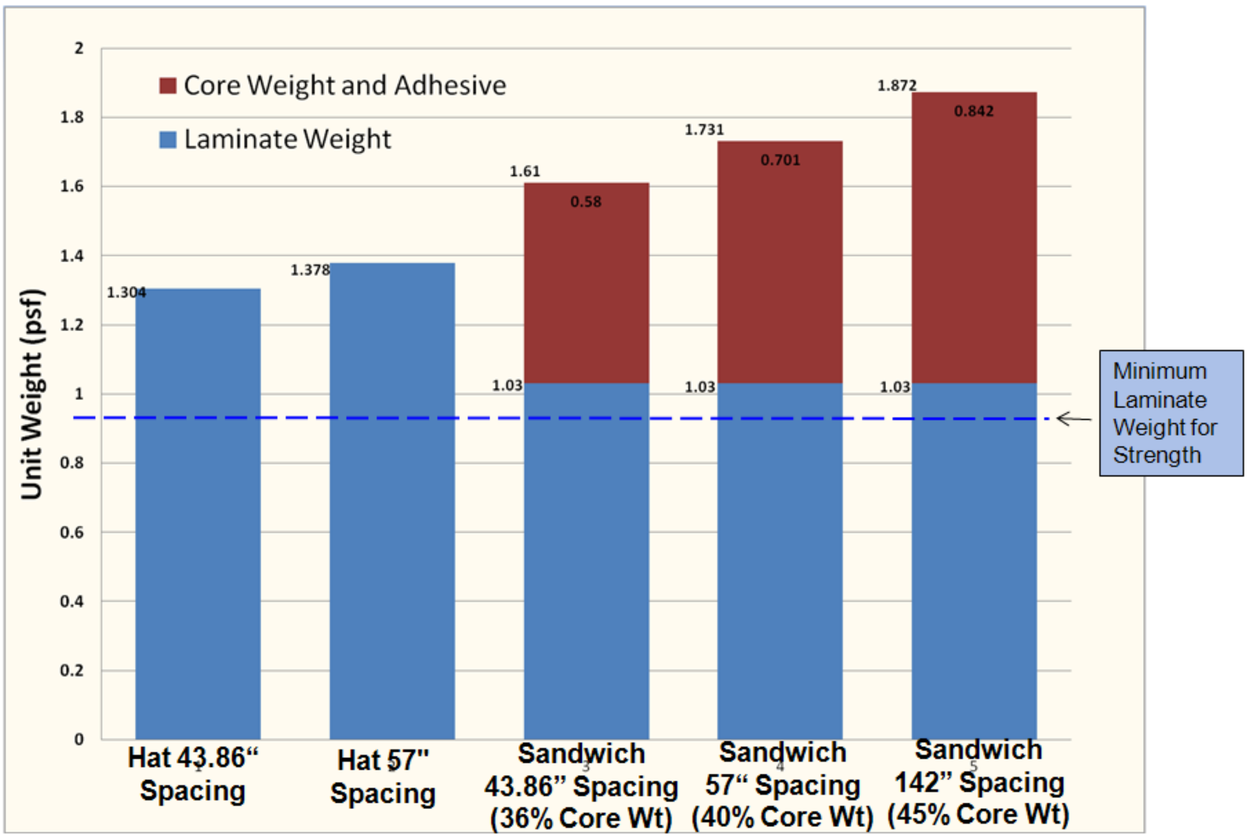


Fig. 44, Hat Stiffened vs. Honeycomb Sandwich, Panel Unit Weight (does not include ringframe weight)

Hat panels are lighter than honeycomb sandwich panels for axially loaded cylindrical structures that have ringframes for buckling support (spaced 40" to 60") and a large diameter (1244"). The blue column represents laminate weight and the red additional weight is for honeycomb core and adhesive weight. At 57” spacing the hat unit weight = 1.38 psf where at the same spacing, the honeycomb UW = 1.73 psf. At this spacing the core and adhesive parasitic weight = .701/1.73 = 40%.

The dashed line indicates the weight of the sandwich laminate to meet material strength. A slight additional facesheet weight is needed to obtain required buckling stability. Primarily the sandwich then achieves additional buckling capability for longer ringframe spacings by increasing the core depth. In this manner, the sandwich laminates weigh is constant at 1.03 psf. In contrast, the hat stiffened panel achieves additional buckling stability by increasing the hat shapes size, which in turn requires thicker and heavier laminates to prevent local buckling.

In short, sandwich core is parasitic in that it does not carry longitudinal nor hoop load. For the optimized honeycomb sandwich panel at 71" ringframe spacing, the parasitic weight includes 0.16 psf for adhesive and the core weight of 0.54 psf. So right from the start the honeycomb sandwich has a 0.7 psf weight disadvantage.

5.1 Hat vs. Honeycomb Panel Buckling

Hats are ideal for cylindrical structures with large diameters and relatively closely spaced ringframes. The panel aspect ratio creates a direct load path which puts the stiffeners into column compression as illustrated in figure 45.

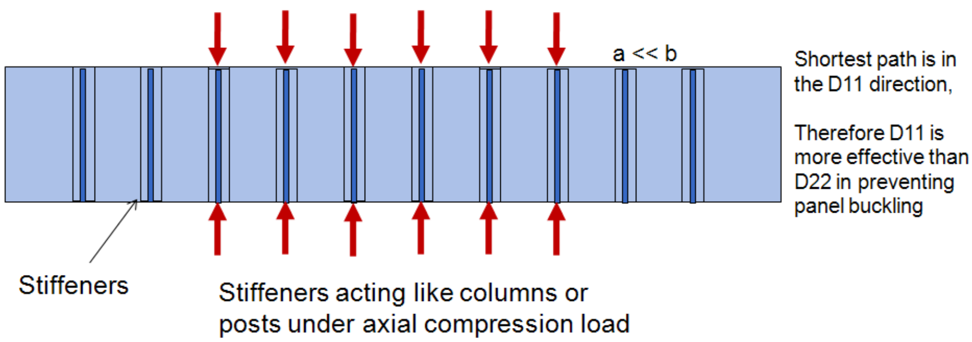


Figure 45, Stiffened Panels with High Width to Height Ratio under Pure Axial Compression

Short ringframe spacing where b (width) is much greater that a (height) makes panel buckling primarily a function of D11. The shortest path is in the D11 direction; therefore the D11 is more effective than D22 in preventing panel buckling. From the flat panel buckling equation, we notice for stiffened panels, where D11 is much greater than D22, the last term in the equation effectively falls out.

$$N_{x,\,crit} = \frac{-\pi^2\left[D_{11}\left(\frac{m}{a}\right)^2 + 2\left(D_{12} + 2D_{66}\right)\left(\frac{n}{b}\right)^2 + D_{22}\left(\frac{n}{b}\right)^4\left(\frac{a}{m}\right)^2\right]}{1+\left(\frac{N_y}{N_x}\right)\left(\frac{a}{b}\right)^2\left(\frac{n}{m}\right)^2}$$

Drops Out

6 Hat Panels in More Detail

Hat stiffened panels have a closed section stiffener that provides high axial membrane stiffness (A11) and high axial bending stiffness (D11). Since the hat stiffener is a closed section, the GJ of the cross section is higher than open-section stiffeners like I's, or Tee's. The closed cell provides torsional rigidity and provides the panel with a higher bending-twisting stiffness (D33). The D33 stiffness is an influential term in the buckling stability. However the transverse bending stiffness (D22) is much lower for all stiffened panels than for a sandwich panel. For this reason ringframes are required for buckling stability *(reference section 5.2)*.

The weight optimum ringframe spacing for the Ares V Interstage is shown at 43.86 inches *(reference figure 26)*. At this ringframe spacing, non-linear studies are performed to determine the collapse load of optimum hat designs.

6.1 Post Buckled vs. Non Post Buckled Hat Designs

Weight savings is possible if stiffened panels are allowed to post buckle. HyperSizer optimizations and analyses were performed for the hat panel allowing the skin to initial buckle at limit load. The FEA buckling mode for initial buckling and into post buckling is illustrated in figure 46. As seen in the figure, the skin between the stiffeners (open span) buckles, and then the web may or may not buckle depending on the current design, but in either case, the additional load is accumulated in the corners of the cross section in the laminates effective widths.

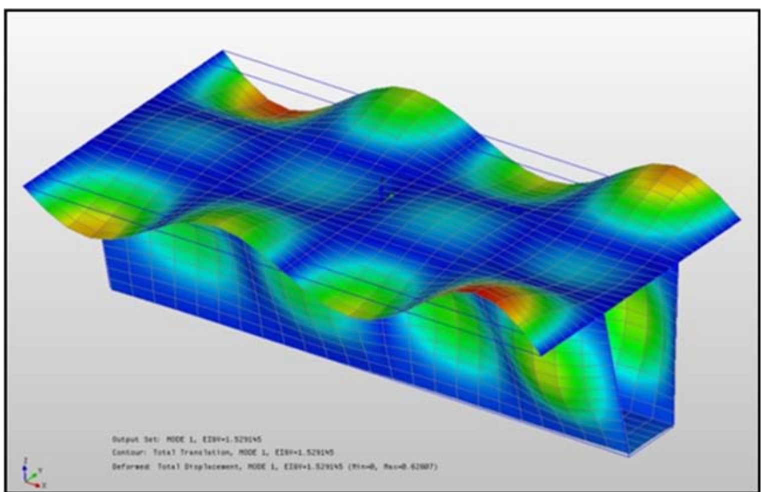


Fig. 47, Local Buckling Deformation of a Hat Stiffened Panel at Limit Load

The stress strain behavior of a post buckled hat design vs. a non-post buckled hat design are shown in figure 47. Blue is the post buckling design and the green is the non-post buckled design. This nonlinear analysis shows the hat design represented by the blue line is capable of carrying load after the first local buckling bifurcation which occurs just after limit load. The ability to carry load after local buckling is a result of the high stiffener stability.

Figure 47 has four main points to make. 1st, both Abaqus and Nastran FEA eigenvalue solutions verify the close agreement of the predicted HyperSizer initial local buckling for post buckled and non post buckled designs. 2nd, the FEA and HyperSizer analyses predict the same load-strain response, 3rd, both post buckled and non-post buckled designs have collapse loads well beyond required ultimate load and coincidentally fail at the same load level, 4th what this means is that the compression allowable of -4900 µin/in when applied allows the non-post buckled stiffer panel to carry more load than the post buckled softer design. Both hat designs can support more load than the sandwich at this strain allowable cutoff.

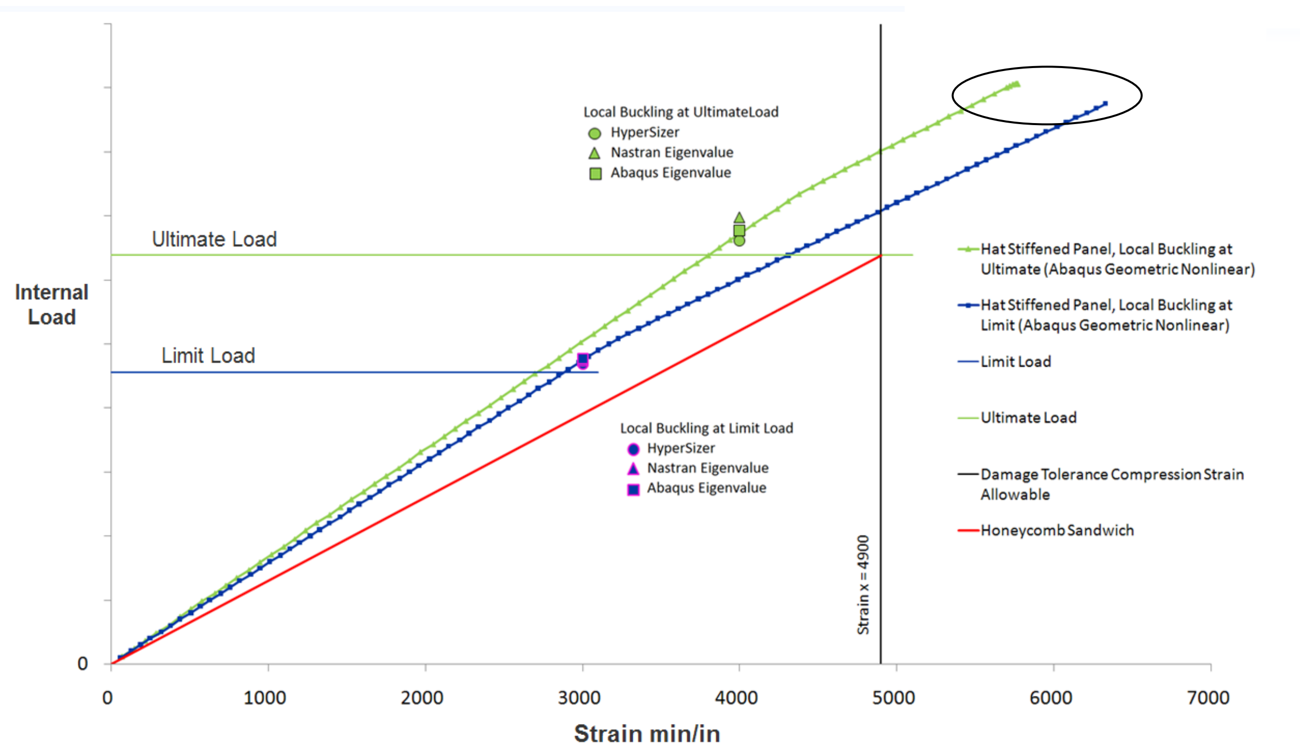


Fig. 46, Strain Response of Two Hat Stiffened Designs due to Axial Compression Loading. Blue Line Represents a Post Buckled Hat Stiffened Panel Design after limit load, while the Green Line Represents a Panel not Allowed to Local Buckle Until Ultimate Load.

As the project matured new design criteria was imposed to allow local buckling at limit load. Since hat panel is also being controlled by 'Scissor' buckling, which is directly related to local skin stability, the new hat design only realized a small weight saving of 1.5%.

6.2 90 Degree Plies on the OML/IML to Prevent Transverse Buckling

Scissor buckling is a stiffener buckling mode only observed in hat stiffened panels. This mode is greatly influenced by the transverse bending stiffness (D22) of the skin *(reference section 12.5.7)*. The transverse bending stiffness in the skin prevents the compressive hoop load from causing transverse buckling waves.

Transverse stiffness is gained in the skin by forcing 90 degree fibers close to the outside of the laminate. This layup sequence challenges the assumption that a +45/-45 tool side stacking sequence be used for the skin laminates. Many trade studies were performed to understand the weight impact of moving the 90 degree fibers off the IML and OML of the facesheet. It was determined that by forcing +45/-45 sublaminates on the toolside, the open span width has to decrease to minimize the transverse buckling span, thus increasing the transverse buckling stability.The current design uses a $[+45/90/-45]_{GSS}$ OML/IML tool side global stack sublaminate.

6.3 Increasing the Crown Width

In attempts to reduce the count of 0° plies in the bottom crown, a hat design with a wider crown is studied. A wider crown allows less 0° plies to achieve the same D_{11} (EI_1), 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 is significantly reduced. The local buckling of the web and crown lead to a significant reduction in bending stiffness causing crippling and panel buckling.

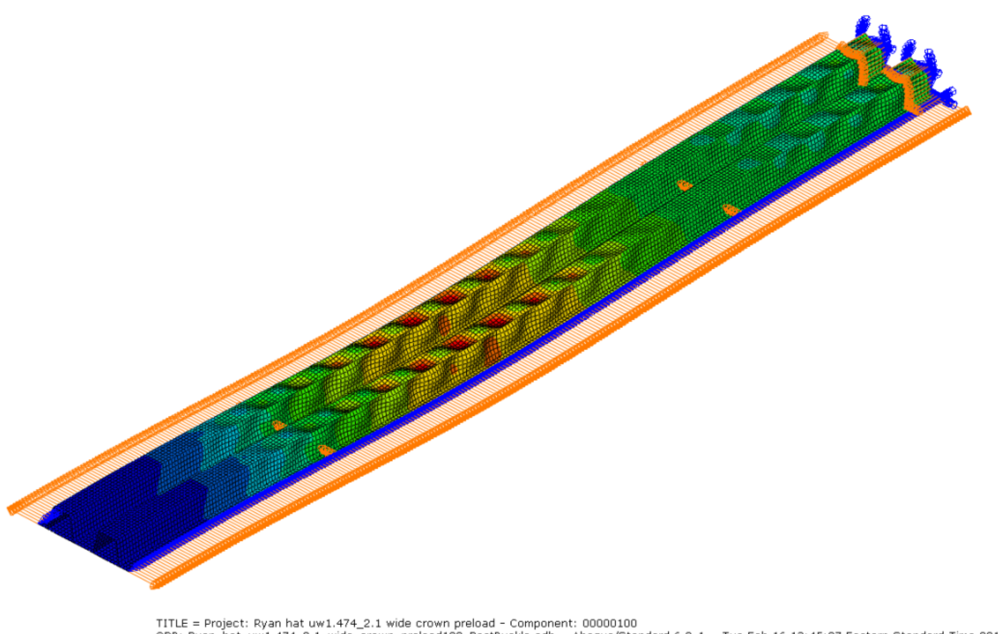


Fig. 48, Buckling Deformation of Hat Stiffened Panel with Wide Crown, Abaqus Non-Linear Analysis Verifies HyperSizer Predictions.

Optimum Hat Stiffened Panels at 57.01in Ringframe Spacing

A temporary design requirement was to set the minimum ringframe spacing to 57 inches. As the ringframe spacing increases, the hat stiffeners become taller to increase the overall bending stiffness of the panel and provide buckling stability. Fortunately the hat stiffened panel layups can be tailored to meet the internal loads. The web and flanges are 100% 45 degree fibers which adds local buckling stability and many 0 degree fibers are added to the crown to provide axial membrane and bending stiffness. A +45/90/-45 tool side sublaminate is applied to the OML and IML of the facesheet. This layup geometry meets the 45 degree fiber on the IML/OML rule and provides the transverse bending stiffness necessary to prevent 'Scissor' buckling.

7 Weight Saving Ideas

7.1 Redefine Components and Use Flight loads

A best practice recommendation is in future work to define components on the Interstage that can possibly be different panel geometry and materials. The components may be defined between ringframes as illustrated in figure 49.

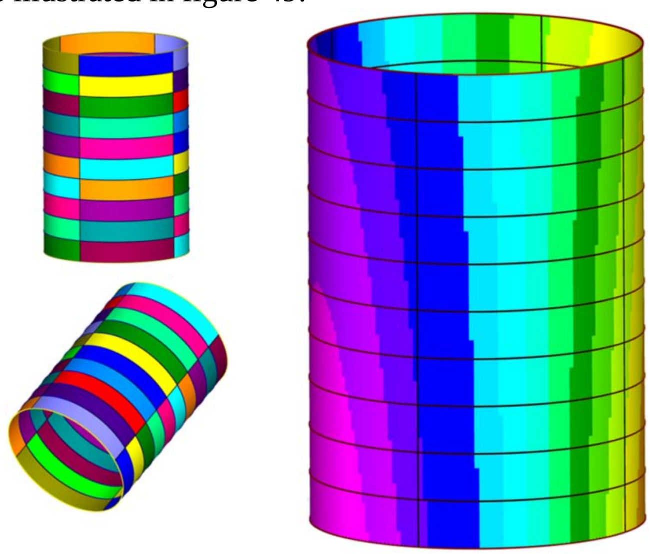


Fig. 49, Component Definition for Interstage Sizing using Flight Loads

By splitting the Interstage into components that span between each ringframe, new design-to loads will be determined for each panel bay, providing more accurate internal loads. Since the flight loads decrease up the span of the barrel, the panels near the top of the Interstage may be lighter than the panels at the bottom.

7.1 Flat Panel Buckling without Knockdown Factor

Most stiffened panels do not benefit from curved panel buckling methods. Due to their strong uniaxial stiffness orientation and their relatively short span between ringframes, their lowest buckling mode is not benefited by the cylindrical nature of the barrel. For this reason, flat panel and curved panel buckling methods produce the same critical buckling load. In contrast sandwich panels do benefit from the additional buckling stability provided by the cylindrical buckling methods. So a weight savings for stiffened panels could be obtained by not using the buckling knockdown factor of 0.65 as paired with cylindrical methods but rather just quantify the critical buckling load based on flat buckling methods without a KD factor.

7.2 Internal versus External Stiffeners

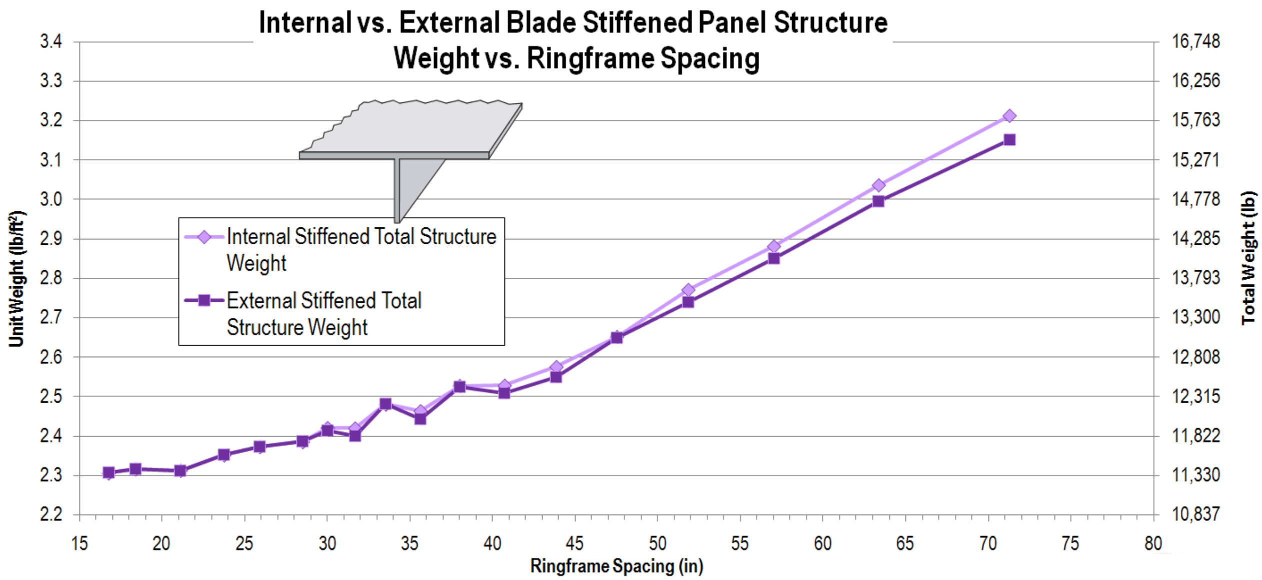


Fig. 50, Internal vs. External Integral Blade Stiffened Panel Trade Study Results, Total Weight vs. Ringframe Spacing

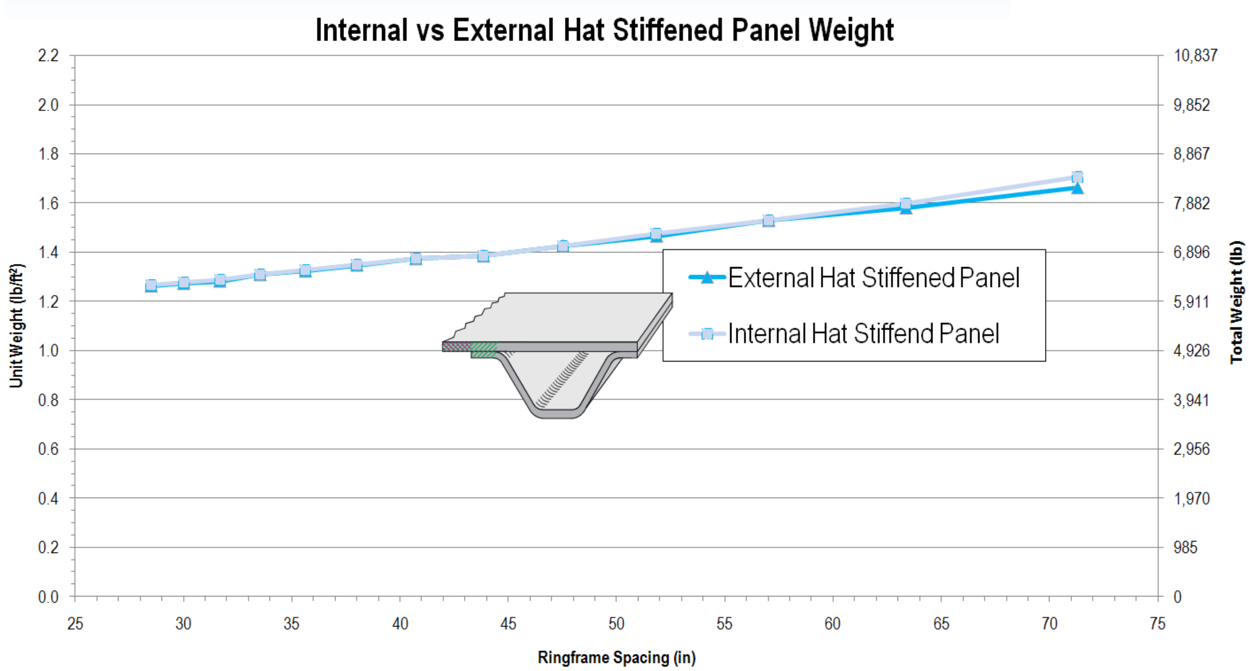


Fig. 51, Internal vs. External Bonded Hat Stiffened Panel Trade Study Results, Total Weight vs. Ringframe Spacing

Internal blade stiffened panels are considered and show little weight difference at low ringframe spacings. As the ringframe spacing increases, the external stiffened panels are slightly more effective at meeting the panel buckling requirement due to the increased EI gained from externally mounting stiffeners. Thus the weight of the external blade stiffened panels is less than the internal blade stiffened panels at higher ringframe spacings.

Internal hat stiffened panel designs are also considered and show a similar total weight trend to the external hat stiffened panel designs. As seen with the blade stiffened panels, the external stiffened panels are lighter at higher ringframe spacings due to the added buckling stability gained from externally mounting the stiffeners. However, at shorter ringframe spacings where panel buckling is not cylindrical but rather flat, mounting stiffeners on the inside or outside makes no difference.

A primary benefit of external stiffeners is the fabrication convenience of mounting internal ringframes to the smoother IML skin surface.

7.3 A lighter core density

A lighter core could be considered for sandwich panel concepts, however, the issue with using a core lighter than the typical 3.1 pcf is the reduction in buckling allowable due to the transverse shear flexibility of the soft core. Also a concern about the sandwich as a whole is not being as damage tolerant.

7.4 Evaluate the use of Pi Preform bonded joining technology

The use of Pi preforms to join the internal ringframes inside the barrel may prove to be a weight savings, and a cost of fabrication savings over bolted joints since there would be less parts and holes to drill and holes to fill. The Pi preform used to bond the ringframe to the IML may more effectively provide continuity in the joint and increase GJ torsional stiffness. The practices used by the NASA NESC Composite Crew Module (CCM) may be of use.

8 Conclusions

These weight studies prove hat stiffened panels are the most efficient panel concept to carry the axial compressive load experienced in the Ares V Heavy Launch Vehicle. From the trends we see the hat stiffened panel concept is 20% lighter than the honeycomb sandwich concept. Even though ringframes are required for buckling stability of stiffened panels the weight savings in the hat panels overcome the added weight of the ringframes, and associated joints and fasteners.

All panel weight trends provided were generated using HyperSizer software and the local and global buckling margins of safety were verified with FEA. Each panel concept has been rated using a weight maturity level scale. The outcome of the study is that the robust panel designs that were produced are ready for the next level of design.

Figures 23 to 27 are useful for future cylindrical space launch designs. Though future vehicles may have different loads, diameters, and lengths, the general trends and weight % deltas will hold true for composite designs.

As the project continues HyperSizer can be used to further reduce the stiffened panel weight and optimize design details like bonded/bolted joints and minimize manufacturing complexity by reducing the laminate ply drops across component boundaries. In the short term as the design criteria changes each concept will adapt to new criteria. It is expected that the stiffened panel weight will decrease and the sandwich weight will remain constant.

Stiffened panels are more complex than sandwich panels and are more difficult to optimize because there are more optimization variables. However, this provides more customization and weight savings opportunities. To effectively optimize stiffened panels to the many complex failure analyses an automated analysis tool like HyperSizer is needed to fully explore the design space.

Acknowledgments
This material is based upon work fully funded mostly by internal Collier Research Corporation funding, the NASA Advances Composites Technology Program, and the Northrop Grumman Ares V Project.

Trademarks
HyperSizer® is a registered trademark of Collier Research Corporation

Abaqus® is a registered trademark

NX NASTRAN® is a registered trademark

NEI NASTRAN® is a registered trademark

9 References

1. Black, Sara. "Optimizing the Ares V Payload Shroud." High Performance Composites November, 2009: 46-48

2. Collier Research Corporation, NASA's Constellation Project Ares V Advanced Composite Technology, NASA SBIR Phase III contract # NNL07AA14C, January 2010

3. Collier Research Corporation, Northrop Grumman Final Report: Ares V Composite Dry Structures Sizing Study, Northrop Grumman contract # 2701923, November 2009

4. Collier Research Corporation, HyperSizer Ares V Composite Design and Analysis Best Practices, NASA SBIR Phase III contract # NNL07AA14C, March 2010

5. Collier Research Corporation, PRSEUS Panel Concept Implementation in HyperSizer Structural Sizing Software Interim Report: Boeing Contract # 280722, November 2009

6. Victor Li and Alex Velicki, Advanced PRSEUS Structural Concept Design and Optimization, AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. Palm Springs, CA: AIAA 2008-5840

7. Bednarcyk, B., Arnold, S., & Hopkins, D. (2009). Design of Fiber Reinforced Foam Sandwich Panels for Large Ares V Structural Applications. AIAA/ASME/ASCE/AHS/ASC Special Session on Ares V Structures:

8. HyperSizer Structural Sizing Software, Collier Research Corp., Hampton, VA, http://www.hypersizer.com, 2009.

9. Collier, C. (1993). Stiffness, Thermal Expansion, and Thermal Bending Formulation of Stiffened, Fiber-Reinforced Composite Panels. 34th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (pp. 93-1569). La Jolla: AIAA.

10. Collier, C. S., "Thermoelastic Formulation of Stiffened, Unsymmetric Composite Panels for Finite Element Analysis of High Speed Aircraft", 35th AIAA/ASME/ASCE/AHS/ACS Structures, Dynamics, & Materials Conference, Hilton Head, SC, April 1994, AIAA 94-1579.

11. Yarrington, Collier, Bednarcyk, "Failure Analysis of Adhesively Bonded Composite Joints", 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin, TX, April 2005

12. Yarrington, P., Collier, C., & Bednarcyk, B. (2008). Analysis of Composite Corrugated Panel Facesheet to Flange Joints. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials. Schaumburg, IL: AIAA.

13. Collier, C., Yarrington, P., & Gustafson, P. B. (2009). Local Post Buckling: An Efficient Analysis Approach for Industry Use. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. Palm Springs, CA: AIAA.

14. NASA SP-5039, Structural Design Concepts, NASA Space Vehicle Design Criteria (Structures), September 1967

15. NASA SP-8007, Buckling of Thin-Walled Circular Cylinders, NASA Space Vehicle Design Criteria (Structures), August 1968