

Composite Structure Modeling and Analysis of Advanced Aircraft Fuselage Concepts

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Abstract: NASA Environmentally Responsible Aviation (ERA) project and the Boeing Company are collaborating to advance the unitized damage arresting composite airframe technology with application to the Hybrid-Wing-Body (HWB) aircraft. The testing of a HWB fuselage section with Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) construction is presently being conducted at NASA Langley. Based on lessons learned from previous HWB structural design studies, improved finite-element models (FEM) of the HWB multibay and bulkhead assembly are developed to evaluate the performance of the PRSEUS construction. In order to assess the comparative weight reduction benefits of the PRSEUS technology, conventional cylindrical skin-stringer-frame models of a cylindrical and a double-bubble section fuselage concepts are developed. Stress analysis with design cabin-pressure load and scenario based case studies are conducted for design improvement in each case. Alternate analysis with stitched composite hat-stringers and C-frames are also presented, in addition to the foam-core sandwich frame and pultruded rod-stringer construction. The FEM structural stress, strain and weights are computed and compared for relative weight/strength benefit assessment. The structural analysis and specific weight comparison of these stitched composite advanced aircraft fuselage concepts demonstrated that the pressurized HWB fuselage section assembly can be structurally as efficient as the conventional cylindrical fuselage section with composite stringer-frame and PRSEUS construction, and significantly better than the conventional aluminum construction and the double-bubble section concept.

Nomenclature

A_f, A_s	=	section area of a stiffener frame and stringer, respectively.
B	=	total breadth of stiffened panel between end supports.
D	=	bending rigidity of plate $Eh^3/12(1 - \nu^2)$.
D_x, D_y	=	bending rigidity of stiffened orthotropic plate about the y axis, and x axis, respectively.
E_x, E_y	=	Young's modulus of orthotropic plate in x and y directions, respectively.
E'_x, E'_y	=	Young's modulus of stiffeners in x and y directions, respectively.
F_{cx}, F_{cy}	=	yield stress in compression along x and y directions, respectively.
F_{tx}, F_{ty}	=	yield stress in tension along x and y directions, respectively.
f_{sp}, s_{sp}	=	spacing between stiffener frame and stringer, respectively.
g	=	acceleration due to gravity
G	=	shear modulus
I_x, I_y	=	area moment of inertia of x - and y -stiffeners about neutral axis, respectively.
L	=	total length of stiffened panel between end supports.
ν_x, ν_y	=	Poisson's ratio along x and y direction.
M_x, M_y	=	running bending moments about y and x axis, respectively (lbs.-inch/inch).
N_x, N_y	=	running in-plane load along x and y directions, respectively (lbs./inch).
P_{cr}	=	compression buckling load.
P	=	cabin internal pressure of 9.2 psi ($2P = 18.4$ psi).
R	=	radius of cylindrical fuselage.
t	=	plate or base skin thickness.
T_{eq}	=	equivalent thickness of unstiffened plate for same bending stiffness D_x or D_y .
w_{max}	=	maximum deflection at panel mid-point.
x, y	=	x and y reference axes of the panel, respectively.
z	=	normal distance from panel neutral plane.
Z_{ox}, Z_{oy}	=	neutral axis location of x - and y -stiffeners from skin mid plane.

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I. Introduction

Pressurized fuselage configuration design for the unconventional Hybrid-Wing-Body¹⁻³ (HWB) and Advanced Mobility Concept⁴ flight vehicles are significantly high-risk compared to the conventional stringer-frame cylindrical fuselage, due to the significantly higher bending stresses⁵, and structural deformation. Many novel structural concepts such as the ribbed-double-shell, multi-bubble stiffened shell, thick composite sandwich shell, and recently the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) construction have been studied under the NASA Environmentally Responsible Aviation (ERA) research project⁶⁻¹⁷ in collaboration with the Boeing Company.

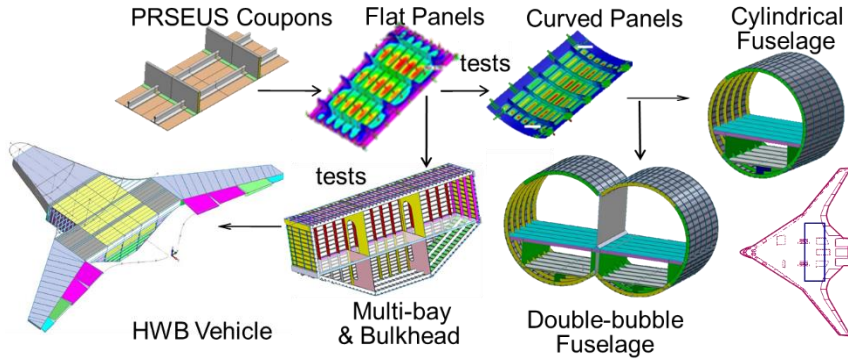


Figure 1. PRSEUS technology development roadmap for the Hybrid-Wing-Body (HWB) vehicle concept.

Figure 1 shows a schematic diagram of the PRSEUS technology development, starting with test coupons, flat and curved PRSEUS panels and progressing towards a HWB fuselage section construction at the Boeing Company and follow-up testing under way at NASA Langley Research Center. Initially detailed finite element models of PRSEUS coupons, flat panels and curved panels were developed and compared with test results of fabricated articles¹⁰⁻¹². Structural analysis of the HWB conceptual vehicles for 100, 200, 300, and 400-passengers were presented by Gern^{14,15}, in order to optimize the full vehicle structural weight at critical design load conditions. The most recent structural analysis of the HWB multi-bay fuselage section test article was presented by Przekop¹⁶. An integrated multi-bay fuselage and bulkhead finite element models (FEM) with flat PRSEUS panels were developed and analyzed for an independent case study and weight estimation^{13,17}. In this paper, the PRSEUS modeling and analyses are applied to a representative cylindrical pressurized fuselage section and a multi-bubble section fuselage for comparison with the HWB concept. Several alternate concepts, which combine sandwich foam-core frame and hat-stringers, as well as conventional extruded frames and hat-stringers are also modeled and analyzed for structural weight/strength benefit analysis.

II. Multi-bay analysis.

Figure 2 shows an improved multi-bay concept model along with the sandwich frame and rod-stringer dimensions. This conceptual model is similar in geometry, compared to the engineering analysis of the test article described in Ref. 16, but many construction features are simplified in order to perform multiple design alternatives studies. This 70% scale HWB multi-bay box model is 360 inch wide in the spanwise direction with a height of 162 in. and a chord-wise length of 80 in. The fuselage section has only four foam-core sandwich frames with spacing increased from 20 to 24 in. The 6 in. high sandwich frames have 0.5 inch thick foam-core, and are wrapped with two stack (0.104 in.) composite laminate. The frame flanges are stitched to skin and frame base cover straps. The rod-stringers are spaced 6 in. apart on top surface of each bay, on the side rib walls, and on the lower cargo bays and are modeled with beam elements. The passenger floor rod-stringers are spaced at 8 inch apart, since they carry mostly passenger weight. The two mid-cabin sandwich walls are modeled with 2 in. thick foam-core sandwich and 0.052 in. composite skin without cutouts. The four critical design load cases are as follows.

Load case 1. 18.4-psi internal static over-pressure at ground level (2P over pressure).

Load case 2. 2.5g climb condition with the cabin operational pressure of 9.2 psi (1P+2.5g)

Load case 3. -1g dive condition with the cabin operational pressure of 9.2 psi (1P-1g)

Load case 4. Linear buckling analysis with load cases 2 and 3 (Buckling).

Out of the four load cases, the 2P over-pressure condition is critical for the HWB type flat structure static test certification. The bending due to the cabin pressure results in significantly higher stress compared to a conventional cylindrical fuselage

that counters cabin pressure with membrane hoop stress. The maximum aerodynamic load for the $1P+2.5g$ case also produces a maximum compression load on the fuselage crown panels and a maximum tensile load on the fuselage keel panels. This bending load is idealized as approximately 5000-lb/in. running compression and tension load along the top and bottom panels, respectively. This in-plane ultimate design load was derived from full-vehicle FEM analysis⁸. Based on the composite material elastic properties for the orthotropic skin and frame wraps, the allowable maximum strains are 0.0059 in tension and 0.0048 in compression. On the rod-stringer, the maximum allowable strain is 0.007 in tension and 0.0058 in compression. The initial basic panel model component sizing and stress analyses were conducted using classical stiffened plate theory¹⁸⁻¹⁹. In this paper, finite element modeling and analyses were conducted with the SolidWorks Finite Element Simulation software²⁰. The parametric case studies with frame spacing (20 and 24 inch) and stiffener spacing (6 and 8 inch) were conducted in Ref. 17. In this paper, 0.104 inch minimum gauge skin (2 stacks), 24 inch frame spacing, and 8 inch rod-stringer spacing (both with two stack wraps) were recommended for a 90x140 panel with 2P over-pressure load condition.

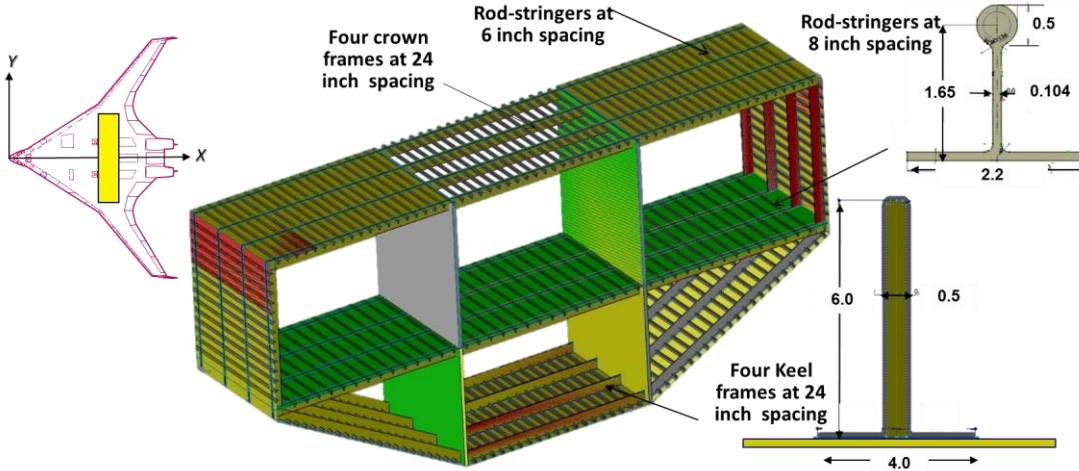


Figure 2. A multi-bay hybrid wing body fuselage section configuration model with four frames, and 8 inch rod-stringer spacing on crown surface.

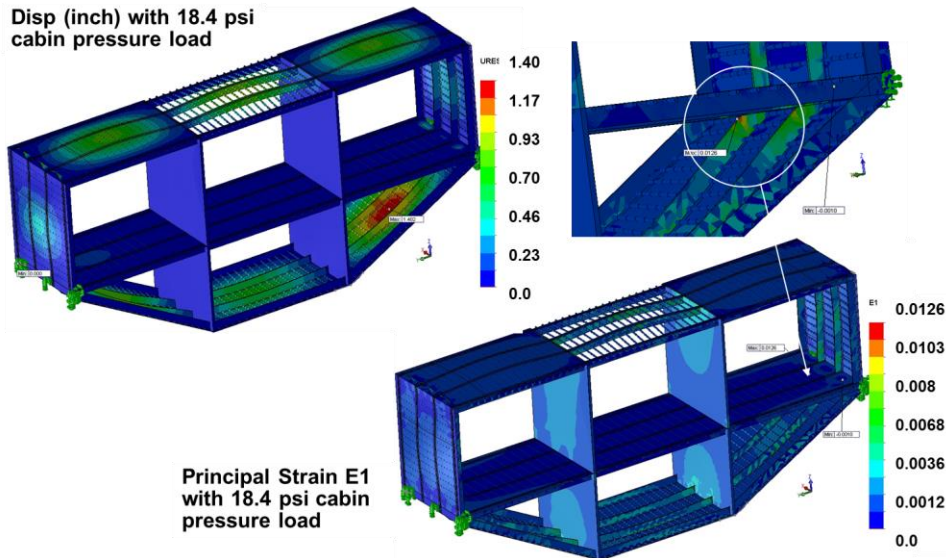


Figure 3. Four-frame multi-bay model displacement and element principal strain E1 under internal cabin pressure of 18.4 psi and passenger-floor pressure of 1 psi.

The details of the finite element model, frame and rod-stringer are also shown in Figure 2. The four sandwich frames are at 24 inch spacing. The foam-cores are modeled with solid elements. The two stack outer frame wraps and flanges are modeled with shell elements. The rod-stringers are at 6 inch spacing on the top crown and bottom keel surfaces. The rod-stringers are at 8 inches apart on the passenger floor. All rod-stringers are modeled as beam elements. Structural deflections and first principal stresses with 18.4 psi internal pressure are shown in Figure 3. The maximum deflection of 1.4 inch occurs at the largest side-keel panels. The maximum deflection on the crown panel is about 1 inch. At the normal operational cabin

pressure of 9.2 psi, this will cause a pillowing of the aerodynamic surface with maximum deflection about 0.5 inch at the center of the panel. The corresponding adverse effect on the aerodynamic flow, such as boundary layer separation, turbulence and increased drag are not known and should be a subject of future research. The principal stresses are generally within the allowable limits except at the joints between the side walls and the main passenger floor and also on cargo keel surfaces. These complex joints would require local corner braces or gusset plates in order to preclude local failure. In the actual test article FEM modeling and analysis¹⁶, the skin is reinforced gradually with layups from 2 to 10 stacks of woven stitched composite, and are seamlessly integrated into the flanges for attachment with side walls or ribs.

Table 1. Finite Element Model weight breakdown of the PRSEUS Multi-bay box section.

1. BAY6A New weight calculation with 2 stack wrap (80 inch width 4 frame version) 120+120+120										
4 frames @24 in. & rods @6, 8 inch spacing with 1.65 2w base-rod center 2.1 in flange, 3.4 in frame strap										
BAY6A New weight calculation with	width/se	length	area	thickness	vol.	density	wt/item		weights	Group
Study-2	inch	in	in^2	in	in^3	lb/in^3	lbs	x no item	lbs	weight
1 and 2 stack skin mixed										491
skin group										
3 top panels	80	120	9600	0.104	998	0.057	57	3	171	
2 side panel	80	96	7680	0.052	399	0.057	23	2	46	
3 floor panels	80	120	9600	0.052	499	0.057	28	3	85	
bottom Keel panel	80	120	9600	0.104	998	0.057	57	1	57	
R+L keel panels	80	140	11200	0.104	1165	0.057	66	2	133	
modified rod 1.65 inch b2c	rod area	web ar	flange a	area	length	density		no of rods		
rod-stringer group	in^2	in^2	in^2	in^2	in^3	lb/in^3	lbs	x no		593
rod_stringer C 8 in spacing	0.20	0.13	0.22	0.55	80	0.057	2.5	143	358	
rod_stringer D@6 in 2 wrap	0.27	0.26	0.33	0.86	80	0.057	3.9	60	234	
Mod Frame group @24	width	length	area	thickness	vol	120 and 200wf	St	x no		1000
2 frame core Rohacell 200	6	120	720	0.5	360	0.008	2.9	19	54	
4 frame wrap+flanges	15.9	120	1908	0.104	198	0.057	11.3	37	422	
side rib frame core	6	96	576	0.5	288	0.004	1.2	8	9	
side rib core wrap+flange	15.9	96	1526	0.104	159	0.057	9.0	8	72	
frame cover strap	4.5	120	540	0.052	28	0.057	1.6	37	60	
end double frames Fib glass	6	120	720	0.5	360	0.057	20.5	19	383	
Inter cabin wall group										236
inter cabin core	80	162	12960	0.396	5132	0.008	41.1	2	82	
inter cabin wrap	80	162	12960	0.052	674	0.057	38.4	4	154	
Total weight (lb)									2320	2320
Projected Surface area with int-cab wall area			129911	in^2		902 sq feet		lb/sq ft	2.57	
without int-cab wall area			103991	in^2		722 sq feet		lb/sq ft	2.89	

Table 1 shows initial breakdown of the structural weight components for the HWB multi-bay fuselage section. With two stack (0.104 inch) outer skin and single stack (0.052 inch) skin on side walls, the skin group weight is 491 lbs. Rod-stringers weight is 593 lbs. with 6 inch spacing on the highly loaded outer skin, and 8 inch spacing on the passenger floor and side rib walls. The frame group which carry and transfer most of the pressure load from the skin to the stringers have a total weight of 1000 lbs. The two inter-cabin wall weight total is 236 lbs. Thus total FEM weight is 2320 lb. The specific FEM structural weight, which is defined as the total FEM structural weight normalized by the total surface area for relative comparison with each of the construction concept is 2.57 lbs. In general all the attachments, bolts and fail-safe splices may add about 30% additional weight. The non-optimal weights such as the resin filling, paint and sealing may contribute an additional 20% weight.

Integrated multi-bay box and bulkhead assembly with horizontal frame: In preparation for extending the multibay model to the full center section passenger bay, design changes were made in the bulkhead frame orientation. Although in the test article, the bulkhead frames were vertical¹⁶, horizontal spanwise frames are advantageous for integration into the full vehicle outer wing. This spanwise frame orientation would allow efficient transfer of load from the outer wing rear spar into the rear bulkhead. Analysis results of the multi-bay and improved bulkhead assembly with spanwise frames are presented in Figure 4, which shows displacement and first principal strain under 18.4 psi internal cabin pressure. In this analysis model, all sandwich frames are at 24 inch spacing, and all rod-stringers are at 8 inch spacing. Both are modeled as beam elements. The outer skin thickness is 0.104 inch. The maximum deflection (pillowing) of the crown surface is about 0.9 inch and maximum deflection of the cargo keel surface is about 1.18 inch. The maximum first principal strain is 0.006 inch/inch at the joints and are generally under 0.004 inch/inch in most areas. These deflections are 15% lower, compared to deflection results shown in Figure 4. This may be due to the beam cores being modeled as solid elements and absence of the bulkhead and corresponding changed edge boundary conditions.

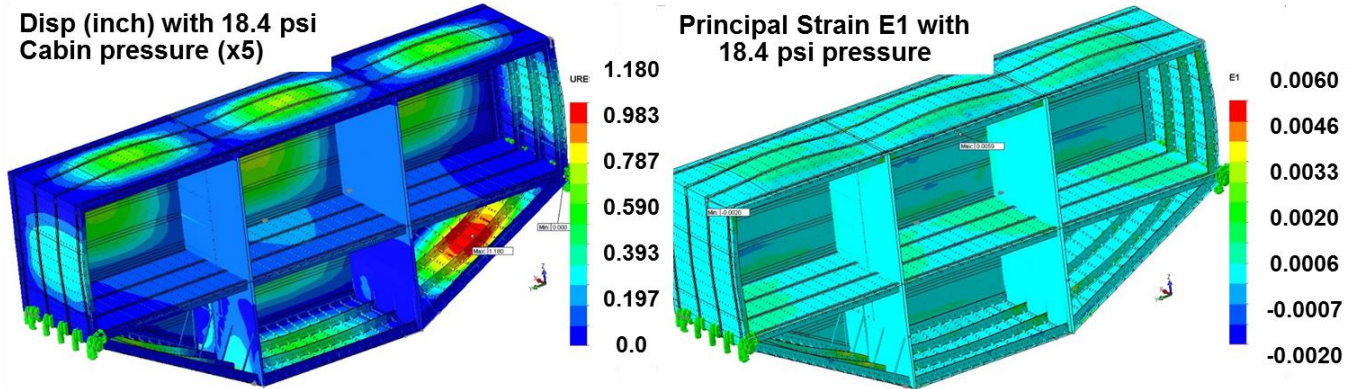


Figure 4. Integrated multi-bay and bulkhead model deflection and first principal stress distribution under 18.4 psi internal cabin pressure.

III. Cylindrical Fuselage Analysis.

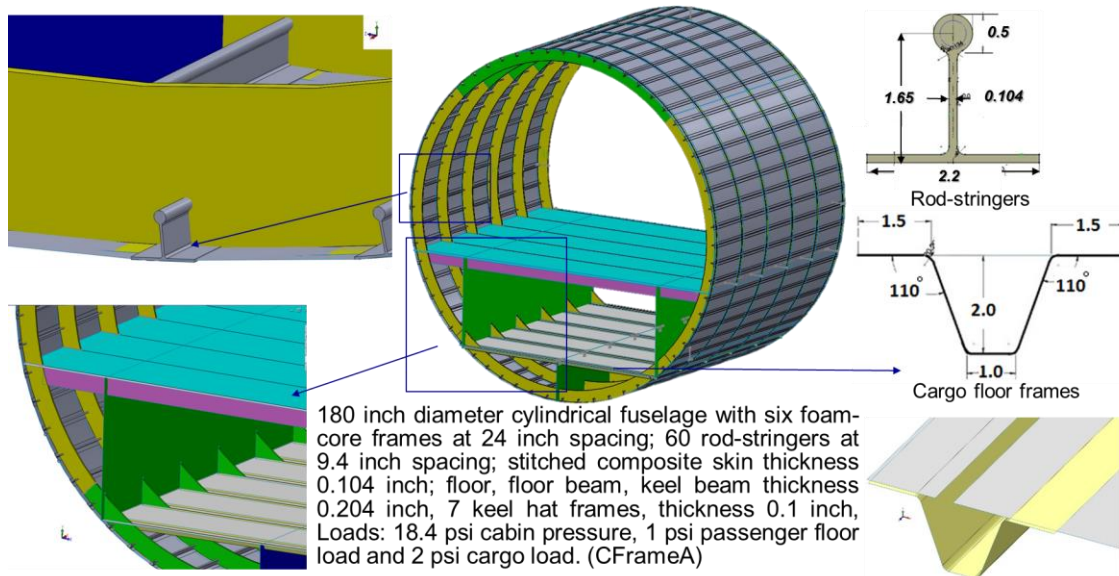


Figure 5. Cylindrical fuselage section assembly model description with curved PRESUS panel construction.

Cylindrical fuselage with pultruded rod-stringer and foam-core frame: Figure 5 shows a cylindrical fuselage assembly with curved PRSEUS panels. The 180 inch diameter fuselage section is assembled from four curved PRSEUS panels, each with six curved frames at 24 inch spacing. There are a total of 60 straight rod-stringers along the axial direction at 9.4 inch spacings. The passenger floors are stiffened with 6 inch high, 0.2 inch thick ribs. The cargo floors are stiffened with hat stiffeners and a vertical keel beam at the center. The advantages of a stiffened cylindrical fuselage are that the cabin pressure load is balanced by hoop (membrane stretching) stress which are much lower than those on the HWB fuselage. The hoop stress PR/t on the 0.1 inch outer skin is of the order 16,000 psi, with 18.4 psi cabin over-pressure. However, the passenger and cargo floors, which are flat stiffened structure, will exhibit significantly higher stresses and deflection, even with 2 psi design cargo load. Figure 6 shows the displacement and first principal strain distribution with 18.4 psi normal cabin pressure load, 1 psi load on the passenger-floor and 2 psi load on the cargo-floor. The maximum deflection is 0.84 inch on the cargo floor with 2 psi cargo load. The maximum first principal strain 0.0053 inch/inch occurs at the junction of the floor and fuselage. The corresponding weight breakdown is shown in Table 2. Total rod-stringer weight is 233 lb. and the total frame group weight is 607 lbs. The total outer skin weight is 416 lbs. and the total passenger-floor and cargo-floor weight is 644 lbs. The total weight of this fuselage segment is 1900 lbs. The specific weight is 2.59 lbs./square feet when divided by the 735 square feet surface area of the outer cylindrical surface, passenger-floor and cargo-floor areas. The specific weight/surface area of the cylindrical PRSEUS fuselage is very close to that for the PRSEUS multi-bay model. However, this

part of the cylindrical fuselage may also include the wing carry-through box, and possibly wheel well. The required reinforcements will significantly increase the overall structural weight.

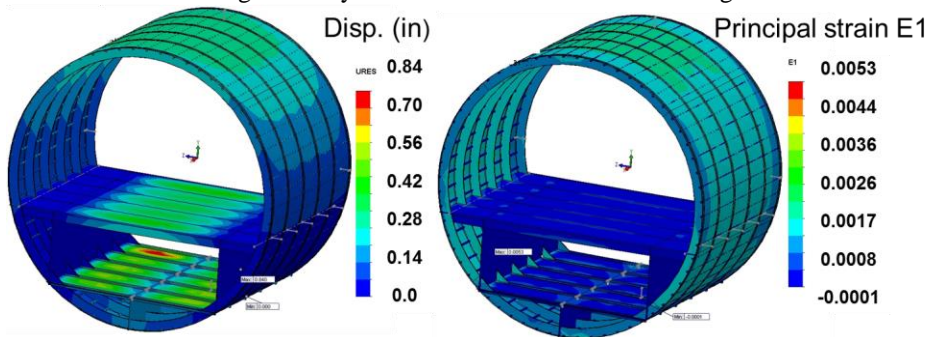


Figure 6. Cylindrical fuselage displacement and principal strain E1 with 18.4 psi cabin pressure, 1 psi load on the passenger floor and 2 psi load on the cargo floor.

Table 2. FEM structural weight breakdown of the cylindrical PRSEUS construction fuselage.

3. Cylindrical fuselage CFrameA	Fuselage 90	length f 124	frames 6	stringers 60	floor 173	
modified rod 1.65 inch b2c	rod area	web art	flange a	area length	density	no items
rod-stringer group (2 stack skin)	in^2	in^2	in^2	in^2	lb/in^3	lbs x no
rod_stringer @ 8 in 1 wrap	0.20	0.13	0.22	0.55	124	0.057 3.9 60 233
cyl Frame group @24	length	length	area	thick vol	120 and 200wf S\	x no
4 frame core Rohacell 200	6	565	3393	0.5	1696	0.0072 12.2 4 49
frame wrap+flanges	15.9	565	8991	0.1	935	0.057 53.3 6 320
frame cover strap	4.5	565	2545	0.1	132	0.057 7.5 6 45
2 end double frames Fib glass	6	565	3393	0.5	1696	0.057 96.7 2 193
skin group	length	length	area	thick vol	density wt	x no items
cyl outer skin	124	565	70120	0.1	7293	0.057 415.7 1 416
floor skin	124	173	21452	0.2	4462	0.057 254.3 1 254
floor frames 6	6	173	1038	0.2	216	0.057 12.3 6 74
frame cover strap	4.5	173	779	0.1	40	0.057 2.3 6 14
floor support	124	45	5580	0.1	580	0.057 33.1 2 66
keel /cargo floor	124	115	14260	0.2	2966	0.057 169.1 1 169
cargo hat stiffeners	124	8.256	1024	0.1	106	0.057 6.1 6 36
keel vertical beam	20.8	124	2579	0.2	536	0.057 30.6 1 31
Total weight (lbs)						lbs 1900 1900
Loaded surface area	105832 in^in	735 ft^ft				lb/sq f 2.59

Cylindrical Fuselage with stitched composite hat-stringers and foam-core frames: Figure 7 shows an alternate cylindrical fuselage concept in which the pultruded rod-stringers are replaced by stitched composite hat-stringers. This

Cylindrical fuselage with composite stitched hat-stringers at 9.4 inch spacing and foam-core frames at 24 inch spacing, Skin thickness 0.104 inch (CFrame3C)

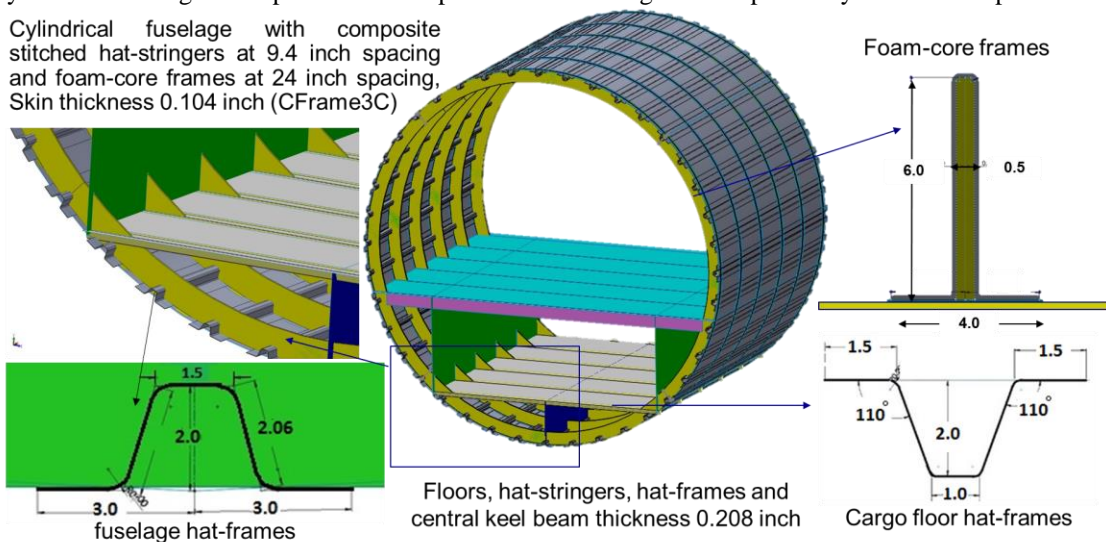


Figure 7. Cylindrical fuselage concept with foam-core frames and stitched composite hat-stringers.

construction is similar to the B787 composite fuselage construction, and may reduce fabrication time and cost associated with the pultruded rod-stringers. Sixty hat-stringers are spaced at 9.4 inches around the fuselage rim. Passenger floors are stiffened with 0.208 inch thick, 6 inch high ribs. The cargo floors are stiffened with hat-frames and a vertical keel beam at the center.

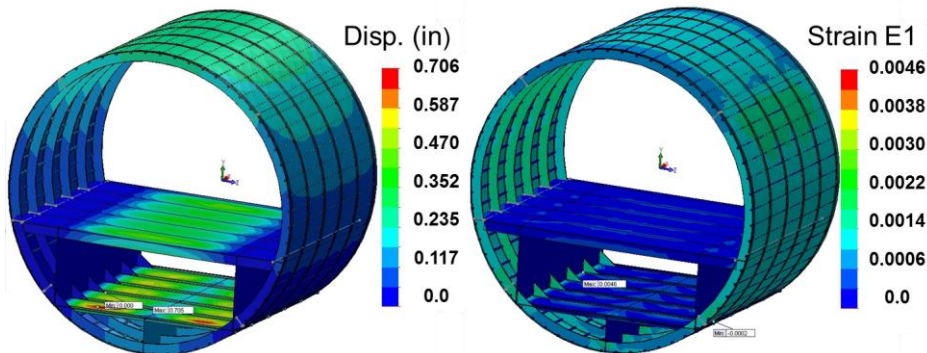


Figure 8. Displacement and first principal stress distribution with 18.4 psi internal pressure on the cylindrical fuselage with foam-core frame and stitched composite hat-stringers shown in Figure 7.

Table 3. FEM weight breakdown of cylindrical fuselage with hat-stringers and foam-core frames (90 inch radius).

4. Cylindrical fuselage CFrame3C	Fuselage 90		length 124		frames 6		stringers 60		floor 173	
	length	length	area	thickness	vol	density	weight	no items		
units	in	in	in^2	in	in^3	lb/in^3	lbs	x no		lbs
fuselage hat stringers mod	10.12	124	6.20	0.05	62.744	0.057	3.6	60	215	215
cyl Frame group @24	length	length	area	thickness	vol	120/200wf SW	x no			
4 frame core Rohacell 200	6	565	3393	0.5	1696	0.0072	12	4	49	
frame wrap+flanges	15.9	565	8991	0.104	935	0.057	53	6	320	
frame cover strap	4.5	565	2545	0.052	132	0.057	8	6	45	
2 end double frames Fib glass	6	565	3393	0.5	1696	0.057	97	2	193	607
skin group	length	length	area	thickness	vol	density	wt	x no items		
cyl outer skin	124	565	70120	0.104	7293	0.057	416	1	416	416
floor skin	124	173	21452	0.208	4462	0.057	254	1	254	
floor frames 6	6	173	1038	0.208	216	0.057	12	6	74	
frame cover strap	4.5	173	779	0.052	40	0.057	2	6	14	
2 vert floor support	124	45	5580	0.104	580	0.057	33	2	66	408
keel /cargo floor	124	115	14260	0.208	2966	0.057	169	1	169	
cargo hat stiffeners	124	8.256	1024	0.104	106	0.057	6	6	36	
keel vertical beam	20.8	124	2579	0.208	536	0.057	31	1	31	236
Total weight (lbs)							lbs		1882	1882
Loaded surface area	105832	in*in	735	ft*ft			lb/sq ft	2.56		

The corresponding displacement and principal stress distributions with 18.4 psi internal cabin pressure are shown in Figure 8. In this analysis, the fuselage skin thickness is 0.104 inch, and the passenger and cargo floor skin thicknesses are 0.208 inch. The maximum deflection is 0.7 inch on the cargo-floor and the maximum principal strain is 0.0046 at the cargo floor junction. The maximum stresses on the fuselage skin are of the order 16,000 psi. The corresponding weight breakdown of the FEM model is shown in Table 3. The weight of the 60 hat-stringers with 0.05 inch thickness is 215 lb. which is slightly lower from that of the rod-stringer (233 lbs., Table 2). The maximum stresses on the hat-stringers are about 35,000 psi, which are well under the allowable limit. Thus the rod-stringers in the PRSEUS construction shown in Figure 5 can be safely replaced by stitched composite hat-stringers with some reduction in the weight. However, the hat-stiffeners may need a foam-core to avoid local crippling.

Cylinder with inverted hat-stringers and composite C-frames: Figure 9 shows a conventional cylindrical fuselage with inverted hat-stringers replacing pultruded rod-stringers, and with composite C-frame replacing foam-core sandwich frames. This type of construction is similar to the B737 and B747 stiffened aluminum alloy fuselage, but with stitched composite material. Figure 10 shows the displacement and first principal strain distribution with 18.4 psi internal cabin pressure. In this analysis fuselage skin thickness is 0.104 inch. The passenger-floor and cargo-floor thicknesses are 0.208 inch. This cargo floor has additional L-shaped lengthwise stringers. The maximum deflections on the flat cargo floor skin is 0.57 inches, with 2 psi cargo load. The maximum first principal strain is 0.0051 on the inverted hat-stringer which are modeled with 0.104 inch thin shell elements. The corresponding weight breakdown of the FEM model is shown in Table 4. The total FEM weight of

C-frames and hat-stringers

Cargo floor hat-frames

Cylindrical fuselage with hat-stringers at 9 inch spacing and C-frame at 24 inch spacing similar to the B747 and B737 fuselage. Skin thickness 0.104 inch. Passenger & Cargo floors, support, central keel beam thickness 0.208 inch

CFrame3Conv[5]

Two finite element analysis plots of a dome structure. The left plot shows displacement (Disp. in inch) with a color scale from 0.0 to 0.57. The right plot shows principal strain (E1) with a color scale from -0.0001 to 0.0051. Both plots include a legend and a color bar.

Table 4. FEM weight of composite cylindrical fuselage with inverted hat-stringers and C-frames (90 inch radius).

5. Cylindrical fuselage CFrameConv[5]	Fuselage rad 90	length F 124	frames 6	stringers 60	floor 173				
	length	length	area	thicknevol	density	weight	x no	items	lbs
units	in	in	in^2	in	in^3	lb/in^3	lbs	x no	lbs
Conv C Frame group @24	11	565	6220	0.104	647	0.057	36.9	6	221
fuselage inv hat stringers	124	9	1116	0.104	116	0.057	6.6	60	397
fail safe strap circumferential	5	565	2827	0.052	147	0.057	8.4	6	50
fail safe strap axial	4	124	496	0.050	25	0.057	1.4	60	85
skin group	length	length	area	thicknevol	density	wt	x no	items	
cyl outer skin	124	565	70120	0.104	7293	0.057	416	1	416
floor skin	124	173	21452	0.208	4462	0.057	254	1	254
floor frames	6	173	1038	0.208	216	0.057	12	4	49
floor frame cover strap	4.5	173	779	0.052	40	0.057	2	6	14
2 vert floor support	124	45	5580	0.104	580	0.057	33	2	66
keel /cargo floor	124	115	14260	0.208	2966	0.057	169	1	169
cargo hat stiffeners	124	8.26	1024	0.104	106	0.057	6	6	36
keel vertical beam	20.8	124	2579	0.208	536	0.057	31	1	31
Total weight (lbs)							lbs		1789
Loaded surface area		105832 in^in		735 ft^ft			lb/sq ft		2.43

Double-bubble fuselage with rod-stringer and foam-core frame: An alternative configuration for the hybrid-wing-body fuselage is a double-bubble structure with a central cabin wall as shown in Figure 11. The advantage of a double-bubble

fuselage is that the fuselage hoop (membrane) stress resultant is balanced by the inter-cabin wall in-plane tension, since the three segments meet at 120 degrees angle. The passenger-floor and cargo-floor constructions are similar to those for the cylindrical fuselage, but without the lengthwise L-stringers. With this geometric configuration, the total fuselage width is 268.5 inch. A FEM model of this double-bubble concept was developed and preliminary results with 18.4 psi cabin pressure are also presented in Figure 11. The design passenger load of 1 psi and a cargo load of 2 psi are also applied. Detailed stress analysis results and weight analysis are presented for comparison with those of the HWB concept. The maximum deflection is 0.9 inch on the cargo-floors, and the maximum first principal strain is 0.0036 at the cabin wall and cargo floor junction, which are reinforced with triangular stringers for structural continuity and load transfer. The corresponding FEM model weight analysis is shown in Table 5. The specific weight/unit loaded area is 2.95 lbs. /sq. ft., which is considerable higher than those of the cylindrical section concepts.

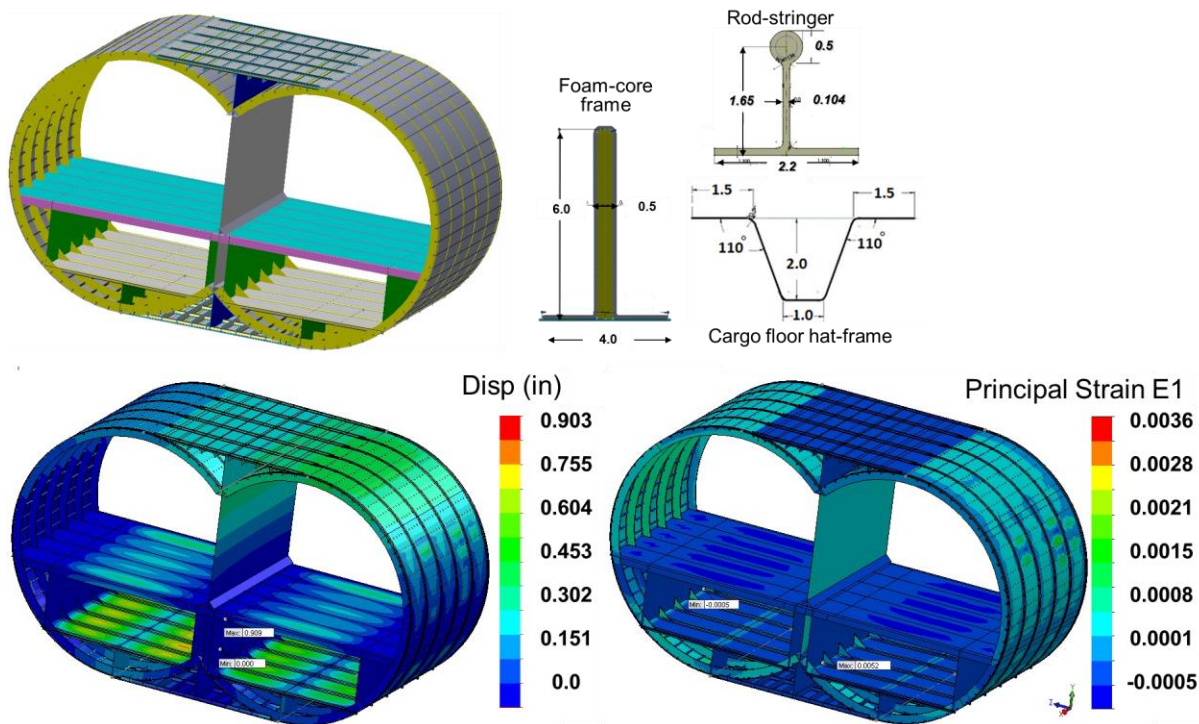


Figure 11. Analysis of PRSEUS double-bubble fuselage section model with 18.4 psi cabin pressure load.

Table 5. FEM model weight breakdown of PRSEUS double-bubble fuselage section model (90 inch radius).

6. DoublebubbleCFRAME Fuselage8DB[3]	Fuselage 90	length 124	frames 6	stringer 80	floor 302	
modified rod 1.65 inch b2c	rod area	web ar	flange area	length	density	no items
rod-stringer group (2 stack skin)	in^2	in^2	in^2	in^3	lb/in^3	lbs x no
rod_stringer @ 8 in 1 wrap	0.20	0.13	0.22	0.55	124	0.057 3.9 80
cyl Frame group @24	length	length area	thickness vol	120 and 200w	f 5 x no	
4 frame core Rohacell 200	6	565 3393	0.5	1696	0.0072	12 5 65
frame wrap+flanges	15.9	565 8991	0.104	935	0.057	53 8 426
frame cover strap	4.5	565 2545	0.052	132	0.057	7.5 8 60
2 end double frames w Fib glass core	6	565 3393	0.5	1696	0.057	97 2.7 258
skin group	length	length area	thickness vol	density wt	x no items	
cyl outer skin	124	565 70120	0.104	7293	0.057	416 1.3333 554
floor skin	124	302 37448	0.208	7789	0.057	444 1 444
floor frames 6	6	302 1812	0.208	377	0.057	21.5 6 129
frame cover strap	4.5	302 1359	0.052	71	0.057	4.0 6 24
floor support	124	45 5580	0.104	580	0.057	33 4 132
keel /cargo floor	124	230 28520	0.208	5932	0.057	338 2 676
cargo hat stiffeners	124	8.3 1024	0.104	106	0.057	6.1 12 73
keel vertical beam	21	124 2579	0.208	536	0.057	30.6 2 61
intercabin wall	124	128 15872	0.208	3301	0.057	188 1 188
inter cabin wall joints	124	16.4 2029	0.208	422	0.057	24.1 6 144
upper surface and vertical wall	124	153 19007	0.052	988	0.057	56 1 56
Upper+lower L stiffeners	127	6 764	0.052	40	0.057	2.26 10 23
Upper+lower hat stiffeners	124	8.3 1024	0.052	53	0.057	3.0 12 36
lower surface and vertical wall	124	153 19007	0.052	988	0.057	56.3 1 56
Total weight (lbs)					lbs	3719 3719
Loaded surface area w/o incab wall	181451 in*in	1260 ft*ft			lb/sq ft	2.95

Conventional Aluminum Cylindrical Fuselage: A conventional cylindrical fuselage model similar to the Boeing 737 construction²¹ with 7075-T6 aluminum fuselage was developed and analyzed with 18.4 psi over-pressure condition. The construction is same as that shown in Figure 9. All the outer skins, fail-safe frame cover straps, C-frames and inverted hat-stringer thicknesses are assumed to be 0.06 inches which is typical for this size fuselage²¹. The hoop stress is about 28,000 psi. The passenger floor thickness is 0.208 inch. Floor frames, cargo floor skin, hat-frames and L-stringers are all made of 0.104 inch thin aluminum extrusions. The component thicknesses and FEM weight breakdown are shown in Table 6. The structural deflection and von-Mises stress distributions are shown in Figure 12. The deflections, stress and strain distributions of the aluminum alloy cylindrical fuselage section are similar to those shown in Figure 10 with composite construction.

Figure 12. Conventional aluminum fuselage displacement and von-Mises stress distribution at 18.4 psi cabin pressure.

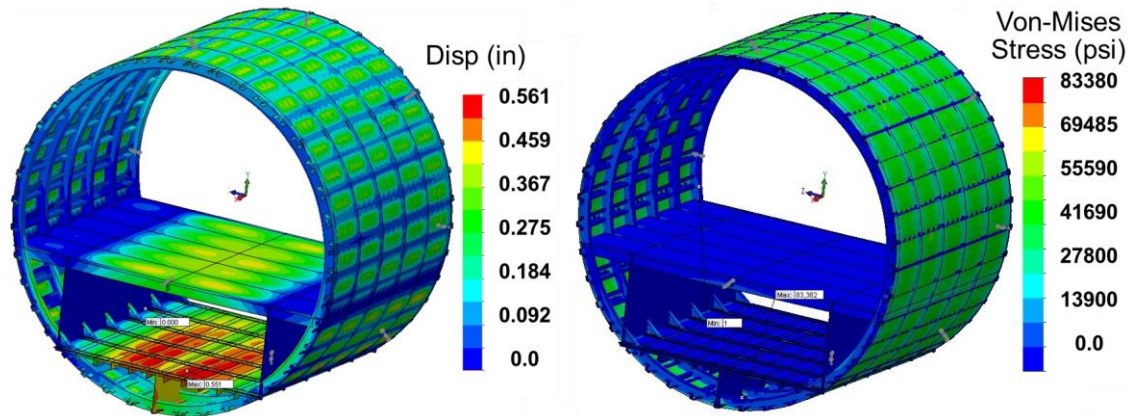


Table 6. FEM model weight breakdown of the aluminum 7075-T6 baseline cylindrical fuselage.

7. Cylindrical fuselage CFrameConv[6]	Fuselage 90 length			124	Cframe 6 stringe			60 floor	173
AL 7075-T6	length	length	area	thickness	vol	density	weight x no	items	lbs
units	in	in	in^2	in	in^3	lb/in^3	lbs	x no	lbs
Conv C Frame group @24	11	565	6220	0.06	373	0.101	37.7	6	226
fuselage inv hat stringers	124	9	1116	0.06	67	0.101	6.8	60	406
fail safe strap circumferential	5	565	2827	0.05	141	0.101	14.3	6	86
fail safe strap axial	4	124	496	0.06	30	0.101	3.0	60	180
skin group	length	length	area	thickness	vol	density	wt	x no	items
cyl outer skin	124	565	70120	0.06	4207	0.101	424.9	1	425
floor skin	124	173	21452	0.208	4462	0.101	450.7	1	451
floor frames	6	173	1038	0.1	104	0.101	10.5	4	42
floor frame cover strap	4.5	173	779	0.104	81	0.101	8.2	6	49
2 vert floor support	124	45	5580	0.104	580	0.101	58.6	2	117
keel /cargo floor	124	115	14260	0.104	1483	0.101	149.8	1	150
cargo hat stiffeners	124	8.26	1024	0.06	61	0.101	6.2	6	37
keel vertical beam	20.8	124	2579	0.1	258	0.101	26.0	1	26
Total weight (lbs)								lbs	2195
Loaded surface area	105832 in*in	735 ft*ft						lb/sq ft	2.99

V. Structural Model Weight Comparison

Table 7 shows FEM weight of each of the seven concepts analyzed in this paper. Although the multi-bay, cylindrical double-bubble section fuselage concepts are different in size and construction architecture, a relative structural weight comparison can be established by normalizing the computed weight with the total pressurized surface area, passenger-floor and cargo-floor area. The last two columns in Table 7 show the normalizing surface area and corresponding specific weights, and is plotted as a bar chart in Figure 13. The FEM structural specific weight per unit loaded surface area varies from 2.57 lbs. /sq. feet for the multi-bay and bulkhead, to 2.95 lbs. /sq. feet for the double-bubble fuselage. With PRSEUS construction, the HWB fuselage section specific weight of 2.57 lbs. /sq. ft. is slightly higher than 2.43 lbs. /sq. ft. for PRSEUS cylindrical fuselage, although the maximum stress level on the outer skin are lower in the cylindrical case. It may be noted that if the rod-stringers and sandwich foam-core frames are replace by hat-stringers and C-frames (Figure 9) the specific weight is reduced to 2.43 lbs. /sq. ft. Comparing the cases 3, 4 and 5, it may be possible to replace the foam-core frames and pultruded rod-stringers with hat-stringers and C-frames in order to save weight and reduce construction complexity. The double-bubble PRSEUS construction have a specific weight of 2.95 lbs. /sq. ft., which is heavier than all other concepts. This is due to the additional aerodynamic surface panel weights above and below the inter-bubble joints. It is also interesting to note that the conventional aluminum fuselage specific weight is 2.99 lbs. /sq. ft. which is about 13% higher than the PRSEUS Multi-bay

and the PRSEUS cylindrical fuselage specific weights (2.57 lbs. /sq. ft. and 2.59 lbs. /sq. ft., respectively). Thus the present structural system analysis indicates that the PRSEUS HWB multi-bay fuselage can be structurally as efficient as the conventional composite cylindrical fuselage and superior that the conventional aluminum alloy construction.

Table 7. Structural model weight comparison of multi-bay, bulkhead, cylindrical and double-bubble fuselage concepts.

Analysis Model Description			weight	area	wt/area		
units			lbs	ft^2	lb/ft^2		
1. BAY6A 2 stack skin 2/1 stack wrap rods @6+8, 2+2 frames at 24			1	2320	902	2.57	
2. Bulkhead1b/4 (2 stack skin, 2 stack wrap, 8 inch rod spacing, Hor frame)			2	818	350	2.34	
3. Cylindrical fuselage CFrameA		PRSEUS	Frame	3	1900	735	2.59
4. Cylindrical fuselage CFrame3C		Hat-stringer	Frame	4	1882	735	2.56
5. Cylindrical fuselage CFrameConv[5]		IHat-stringer C-Frame comp		5	1789	735	2.43
6. DoublebubbleCFrame Fuselage8DB[3]		PRSEUS	Frame	6	3719	1260	2.95
7. Cylindrical fuselage CFrameConv[6]		IHat-stringer C-frame Aluminum		7	2195	735	2.99

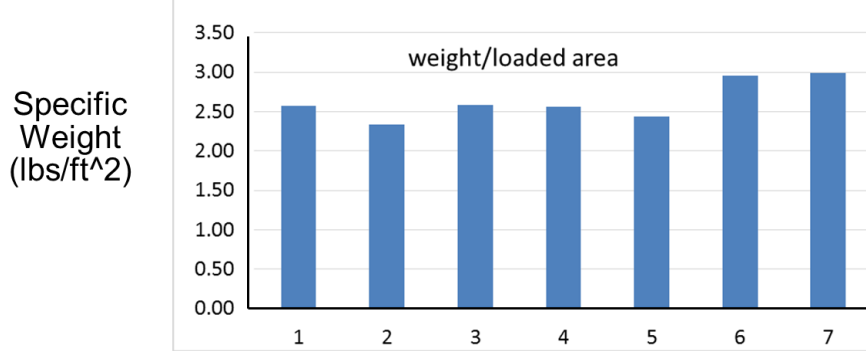


Figure 13. Relative conceptual FEM configuration weights per unit loaded surface area for PRSEUS concepts and stiffener alternatives: 1. Multi-bay; 2. Bulkhead; 3. Cylindrical PRSEUS 4. Cylindrical with hat-stringers; 5. Cylindrical with inverted hat-stringers and C-Frames; 6. PRSEUS Double-bubble, 7. Conventional aluminum cylindrical fuselage with inverted hat-stringers and C-Frames.

VI. Extended Vehicle Model

Figure 14 shows preliminary finite element assembly model of an extended multi-bay, rear bulkhead and inter-bay joints along with outer wing extensions. All frames are modeled as 6 inch deep ribs. For initial trial result, the skins and frames are assumed to have 0.5 inch thickness. However, in these simplified model, the PRSEUS rod-stringers or hat-stringers are replaced by equivalent smeared thickness, that provide same stiffness for a given stiffener spacing. The computation of equivalent skin thickness that provide same plate bending stiffness for a given rod-stiffener geometry and spacing is explained next.

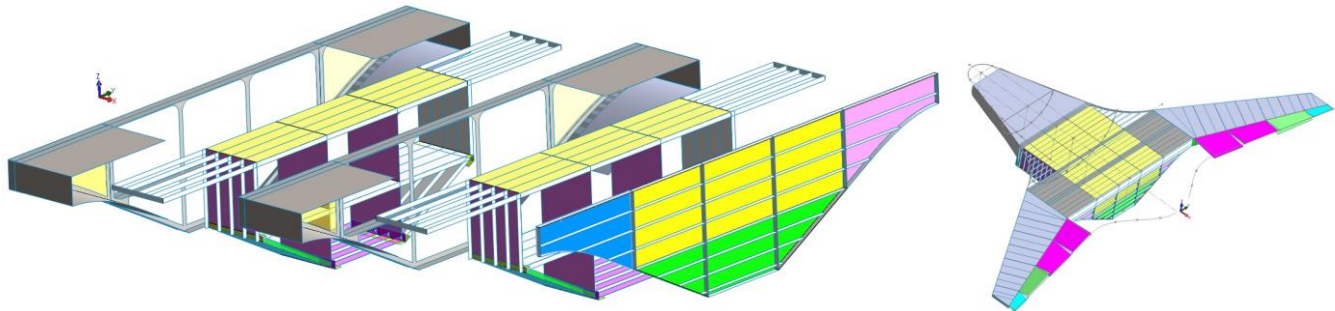


Figure 12. Extended multi-bay, bulkhead and inter-bay joint model exploded view, and vehicle assembly.

Equivalent thickness computation for flat plate bending: For an isotropic thin rectangular plate of uniform equivalent thickness T_{eq} , length L and width B , the maximum deflection may be expressed by Eq. 1 which is a function of the pressure load q , plate bending stiffness D and the factor k that is calculated from analytical solution for each boundary condition. The factor k can be presented in tabular form¹⁸⁻¹⁹, as a function of the ratio B/L . For example, for a square plate with built-in edges, $k=0.00126$ for $B/L=1$. For a simply supported isotropic square plate, $k = 0.00406$.

$$w_{max} = k.q.L^4/D \quad \text{where} \quad D = E.T_{eq}^3/12(1-\nu^2) \quad (1)$$

From ideal orthotropic plate theory¹⁸, for a simply supported stiffened rectangular plate of thickness t , a good closed form maximum deflection is given by

$$w_{max} = \frac{16q}{\pi^6} \frac{1}{\left(\frac{D_x}{L^4} + \frac{2H}{L^2B^2} + \frac{D_y}{B^4}\right)} \quad (2)$$

The flexural rigidity D_x , D_y and H can be approximately defined by the Eqs. (3-5).

$$D_x = \frac{E_x t^3}{12(1-\nu_x \nu_y)} + \frac{E_x t Z_{ox}^2}{12(1-\nu_x \nu_y)} + \frac{E'_x I_x}{b} \quad (3)$$

$$D_y = \frac{E_y t^3}{12(1-\nu_x \nu_y)} + \frac{E_y t Z_{oy}^2}{12(1-\nu_x \nu_y)} + \frac{E'_y I_y}{a} \quad (4)$$

$$H = \sqrt{D_x D_y} \quad (5)$$

For an orthotropic bi-axially stiffened plate, D/L^4 in Eq. (1) is replaced by $[D_x/L^4 + 2H/(L^2B^2) + D_y/B^4]/4$ with k factors for the specific B/L ratio ($L < B$) from Ref. 18. This approximation, shown in Eq. (6) is applied to bi-axially stiffened orthotropic plate.

$$w_{max} = \frac{4kq}{\left(\frac{D_x}{L^4} + \frac{2H}{L^2B^2} + \frac{D_y}{B^4}\right)} \quad (6)$$

For simplification of a full vehicle model development with PRSEUS construction, the foam-core frames may be replaced by beam elements with same wrap thickness. However, it may be necessary to use equivalent shell thickness that provides the same bending stiffness of shells with rod-stringer. Thus by equating D and D_y from Eq. (1) and (4) one can write the equivalent thickness as

$$T_{eq} = [D_y * 12(1-\nu^2)/E_y]^{1/3} \quad (7)$$

Table 8. Composite material properties and allowable stresses.

Component	symbol	property	direction	value	unit
Composite	Ex	Elastic modulus	x	9.75E+06	psi
Skin cover and frame wrap	Ey	Elastic modulus	y	4.86E+06	psi
	Gxy	Shear modulus		2.27E+06	psi
	nux	Poisson's ratio		0.39	
	nuy	Poisson's ratio		0.2	
	rho	density		0.057	lb/in^3
	Ftx	allowable stress x	tension	105100	psi
	Fty	allowable stress y	tension	79200	psi
	Fcx	allowable stress x	comp	46500	psi
	Fcy	allowable stress y	comp	37900	psi
	Fs	allowable stress	shear	30000	psi
rod-stringer	E'y	Elastic modulus		1.90E+07	psi
	ny	Poisson's ratio		0.29	
WF110 core	E	Elastic modulus		21000	psi
Rohacell	G	Shear modulus		8250	
	rho	density		0.0036	lb/in^3
WF220 core	E	Elastic modulus	Rohacell	39150	psi
	G	Shear modulus		14500	psi
	rho	density		0.0074	lb/in^3

Table 8 shows the general material properties for the FEM analysis and the analytical orthotropic plate analysis. In order to develop the FEM model of the full vehicle with PRSEUS construction, it was necessary to compute the equivalent thickness of the PRSEUS panel with the rod-stringer and their spacing. If the rod-stringers are 1.4 inch base to center to height and 6 inch spacing, the equivalent thickness is 1.18 inch. If the frames at 20 inch spacing are also smeared into the single-stack 0.052 inch skin, the equivalent thickness is 1.76 inch. Considering that the frames are modeled appropriately, for the rod-stringer configuration with 1.65 inch base to center to height and at 6 inch spacing as shown in Figure 2, the equivalent thickness is 1.33 inch. With two stack skin and 8 inch rod-stringer spacing, the equivalent smeared thickness is 1.25 inch. The detail stiffness properties and equivalent thickness values for one and two stack skin and rod-stiffener at 6 and 8 inch spacing are shown in Table 8. Figure 15 shows initial deformation with 18.4 internal cabin pressure.

Table 9. Equivalent skin thickness computation for one or two stack skin, and rod-stiffeners with 6 or 8 inch spacing.

rod-stringer 1.65 inch base to rod- center with 1 stack wrap						
One stack skin t=	0.052 inch	Dy (lb-in)	cg from	t=0.052	max axial load	Teq (in)
c/s area w/o skin	0.66 in^2		0.65 in	tension lb/ir	comp lb/in	
area w skin 6 inch	0.97 in^2	1,034,182 lb-in	0.45 in	13630	-11294	1.33
area w skin 8 inch	1.08 in^2	805,089 lb-in	0.41 in	11313	-9374	1.22
Two stack skin t=	0.104 inch	Dy (lb-in)	cg from	t=0.104	max axial load	Teq (in)
c/s area w/o skin	0.66 in^2		0.67 in	tension lb/ir	comp lb/in	
area w skin 6 inch	1.28 in^2	1,087,872 lb-in	0.37 in	17922	-14850	1.35
area w skin 8 inch	1.49 in^2	861,121 lb-in	0.32 in	15622	-12944	1.25

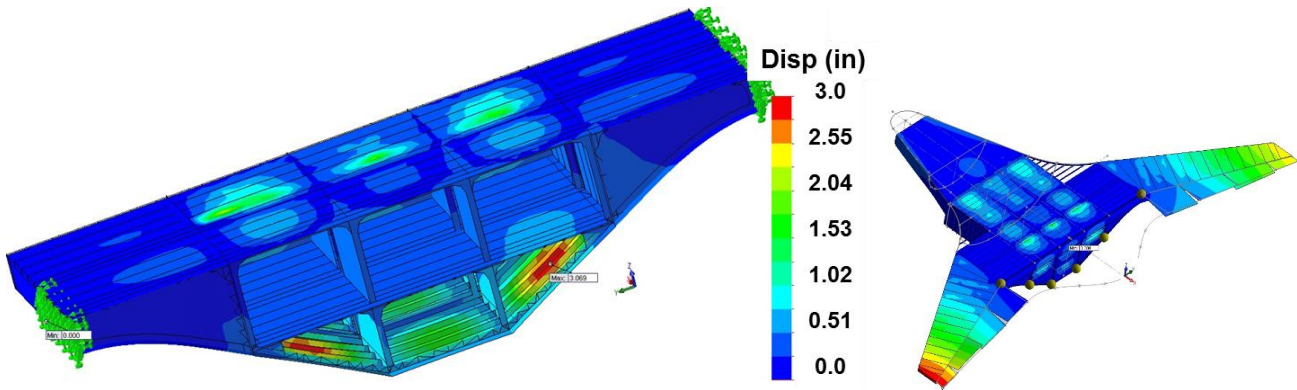
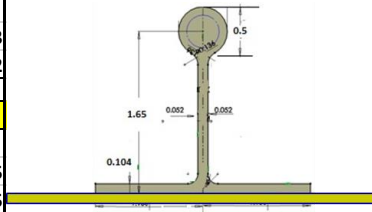


Figure 15. Extended vehicle model assembly deformation with 0.5 inch skin and frames with 18.4 psi cabin pressure load.

VII. Conclusions

Based on lessons learned from previous Hybrid-Wing-Body (HWB) structural design studies, high fidelity finite-element models (FEM) have been developed to evaluate the performance benefits of the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) construction. In order to assess the comparative weight/strength benefits, PRSEUS composite FEM models of a cylindrical fuselage and a double-bubble section concept have also been developed. Stress analysis and scenario based case studies at the 18.4 psi over-pressure load condition were conducted for design improvement. Several alternative construction concepts with hat-stringers and C-frames were also developed and analysed for the cylindrical section fuselage. This type of frame-stringer construction will reduce the weight and fabrication complexity associated with the foam-core sandwich frame and pultruded rod-stringer construction. The FEM structural analysis results and component weights were presented for relative performance benefit assessments. The HWB model specific-weight values per unit loaded surface were compared to that of the composite cylindrical and the double-bubble section fuselage concepts. The structural stress analysis and specific weight comparison of these stitched-composite advanced aircraft fuselage section concepts demonstrated that the pressurized HWB fuselage section assembly can be structurally as efficient as the conventional cylindrical fuselage section with PRSEUS and composite stringer-frame construction, and significantly better than the conventional aluminum construction. The specific weight of the HWB section is 14% lower than the conventional cylindrical aluminum fuselage, and 13% lower than the double-bubble PRSEUS construction. However, the maximum stress and strain levels of the HWB fuselage at the 18.4 psi over-pressure condition are generally higher than those for the cylindrical fuselage. Also, the adverse aerodynamic effect due the deformation (or pillowing) of the HWB outer-surface at operational cabin pressure need to be investigated.

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