



**AIAA 2005-2349**  
**Blended-Wing-Body (BWB) Fuselage**  
**Structural Design for Weight Reduction**

**V. Mukhopadhyay**  
**NASA Langley Research Center**  
**Hampton, VA**

**46th AIAA/ASME/ASCE/AHS/ASC**  
**Structures, Structural Dynamics and**  
**Materials Conference,**  
**18-21 April 2005,**  
**Austin, TX**

For permission to copy or to republish, write to American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston VA 20191-4344

## **BLEND-ED-WING-BODY (BWB) FUSELAGE STRUCTURAL DESIGN FOR WEIGHT REDUCTION**

V. Mukhopadhyay\*

*NASA Langley Research Center, Hampton, VA*

### **Abstract**

Structural analysis and design of efficient pressurized fuselage configurations for the advanced Blended-Wing-Body (BWB) flight vehicle is a challenging problem. Unlike a conventional cylindrical pressurized fuselage, stress level in a box type BWB fuselage is an order of magnitude higher, because internal pressure primarily results in bending stress instead of skin-membrane stress. In addition, resulting deformation of aerodynamic surface could significantly affect performance advantages provided by lifting body. The pressurized composite conformal multi-lobe tanks of X-33 type space vehicle also suffered from similar problem. In the earlier BWB design studies, Vaulted Ribbed Shell (VLRS), Flat Ribbed Shell (FRS); Vaulted shell Honeycomb Core (VLHC) and Flat sandwich shell Honeycomb Core (FLHC) concepts were studied. The flat and vaulted ribbed shell concepts were found most efficient. In a recent study, a set of composite sandwich panel and cross-ribbed panel were analyzed. Optimal values of rib and skin thickness, rib spacing, and panel depth were obtained for minimal weight under stress and buckling constraints. In addition, a set of efficient multi-bubble fuselage (MBF) configuration concept was developed. The special geometric configuration of this concept allows for balancing internal cabin pressure load efficiently, through membrane stress in inner-stiffened shell and inter-cabin walls, while the outer-ribbed shell prevents buckling due to external resultant compressive loads. The initial results from these approximate finite element analyses indicate progressively lower maximum stresses and deflections compared to the earlier study. However, a relative comparison of the FEM weight per unit floor area of the segment unit indicates that the unit weights are still relatively higher than the conventional B777 type cylindrical or A380 type elliptic fuselage design. Due to the manufacturing concern associated with multi-bubble fuselage, a Y braced box-type fuselage alternative with special resin-film injected (RFI) stitched carbon composite with foam-core was designed by Boeing under a NASA research contract for the 480 passenger version. It is shown that this configuration can be improved to a modified multi-bubble fuselage which has better stress distribution, for same material and dimension.

### **I. Introduction**

Structural analysis and design of efficient pressurized fuselage configurations for the advanced Blended-Wing-Body (BWB) flight vehicle has been a challenging problem for many years with no clear solution. Unlike a conventional cylindrical pressurized fuselage, stress level in a non-cylindrical shoebox type BWB fuselage is an order of magnitude higher, because internal pressure primarily results in bending stress instead of skin-membrane stress. The pressurized composite conformal multi-lobe tanks of X-33 type space vehicle also suffered from similar problem. Thus, the primary objective is to specially design the primary highly loaded structure and geometry such that the load path leads to mostly membrane stress, thus minimizing the overall structural weight of the vehicle, while satisfying stress, deflection and buckling safety factors, under the critical flight and ground loads. However, due to

manufacturing consideration, large under-carriage retraction bay, pressure bearing main rear spar and additional flat pressure bulkheads, a non-traditional design approach and material are required, in order to increase bending moment of inertia, without paying significant weight penalty. The first and second-generation 800 passenger BWB concepts were developed at Boeing Phantom Works through NASA contract and internal research. Additional conceptual design of an efficient fuselage configuration concept was developed under NASA R&D funding.

In this paper, the lessons learned from the early structural design studies of the BWB 800 passenger version are summarized. Progresses towards recent 480 passenger version of BWB structural analysis are described. Use of rapid finite element analysis tools and results of several geometric configurations of the Y-braced fuselage

derivatives are presented. Design improvements are suggested.

## II. Lessons learned from early design studies:

Unlike the traditional aircraft tubular fuselage, the high stress and weight problem associated with BWB pressurized cabin can be explained using the sketch in Figure 1. This figure illustrates a cylindrical and a square box fuselage under internal pressure  $p$ . In a cylindrical pressure vessel of radius  $R$  and skin thickness  $t$ , the pressure is resisted by uniform stretching resulting membrane stress is equal to  $p(R/t)$ . In BWB box like fuselage, the nearly flat upper cabin wall resists the pressure by bending deformation. Let us model it as a simply supported beam or plate of length  $l$ , thickness  $t$ , then the maximum bending stress is equal to  $0.75p(l/t)^2$ . Assuming  $R$  is of same order as  $l$ , the bending stress is one order of magnitude higher. The problem is aggravated by the non-linear effect of compressive load acting on the deflected beam or plate. So in order to obtain an efficient structure, one must increase the bending stiffness using deep sandwich shell with light weight high-strength composite skin with composite deep stiffener. The alternative is to use a multi-bubble concept shown in the inset sketch. With proper design, the adjacent bubble membrane stress resultant is balanced by tension in the intra-cabin wall.

### Non-Cylindrical Pressure Vessels

*It is difficult to contain pressure in a shoebox!*

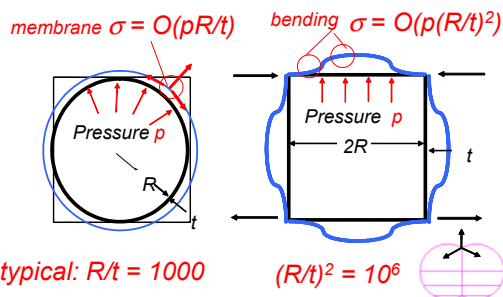


Figure 1. High bending stress associated with a non-cylindrical pressure vessel.

The first and second generation 800 passenger BWB concepts were developed at Boeing Phantom Works (formerly McDonnell Douglas) through NASA contract and internal research (Ref. 1-3). A conceptual design of an efficient fuselage configuration concept was developed under NASA R&D funding and research findings were reported in Refs. 4 and 5.

In Ref. 4, an isolated fuselage bay-3 of the early 800 passenger version of the BWB design

was analyzed. A schematic diagram of the vehicle platform and the bay-3 cross section of two fuselage concepts are shown in Figure 2. Four structural concepts were studied, namely, Vaulted Ribbed Shell, Flat Ribbed Shell; Vaulted shell with Light and Heavy Honeycomb Core; Flat sandwich shell with Light and Heavy Honeycomb Core. A relative comparison of bay-3 weight and component non-optimal weight breakdown were made.

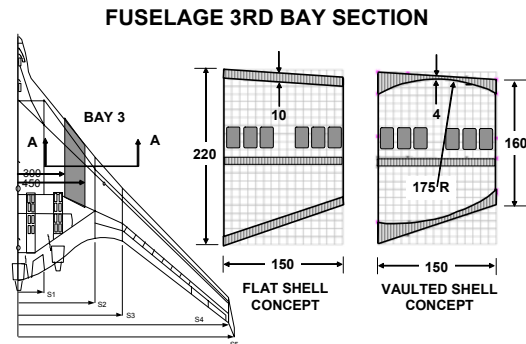


Figure 2. BWB fuselage bay-3 section, flat ribbed and vaulted ribbed shell concepts of first generation BWB 800 passenger version.

Based on the design load definition developed in Ref. 1, a beam-column based sizing calculation, a set of coarse finite element model (FEM) were developed in Ref. 4. The vaulted shell radius was chosen so as to provide a minimum of 4 inch depth at the mid-arch. From this early FEM analysis, the vaulted ribbed shell and flat ribbed shell concepts appeared to be significantly better than the deep sandwich concept. The vaulted concept offered the advantages of cylindrical pressure vessel, but was not preferred due to manufacturing complexity. The deep sandwich concept was eliminated due to weight and maintenance considerations. The pressure bearing front and rear spar were modeled as deep sandwich honeycomb flat shell and contributed significantly to the overall weight. The elastic modulus and allowable stress properties of an orthotropic resin-film injected (RFI) stitched carbon composite material were used. The initial sizing was based on the composite material allowable stress, but no optimization or buckling analysis was performed.

From the isolated bay-3 FEM analysis results, a comparison of weight components of these four concepts is shown in Figure 3. From this study, the double skin vaulted ribbed shell concept appeared to have the least FEM structural weight. Hence, a coarse finite element model of the vehicle super structure was developed and analyzed using the double skin vaulted ribbed shell concept for the pressurized fuselage section and the outer wing.

The vehicle element von-Mises stress distribution and deformation at the critical 2.5 g pull-up load case are shown in Figure 4.

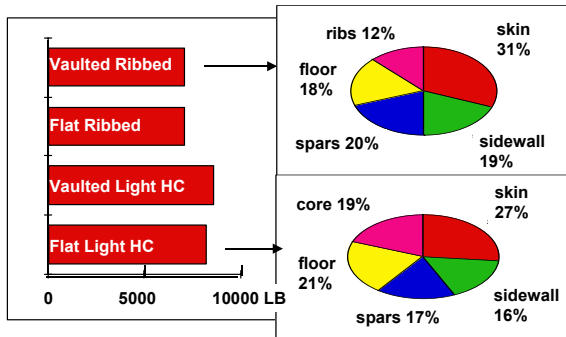


Figure 3. Weight component comparison of bay-3 fuselage concepts.

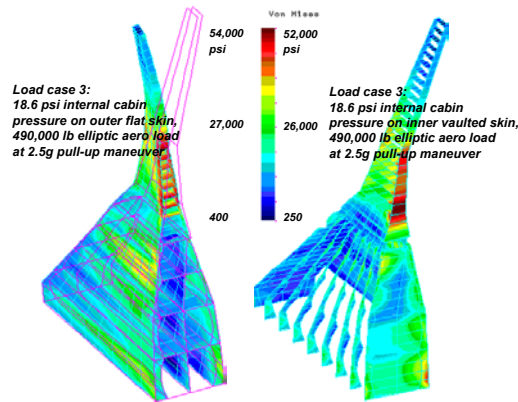


Figure 4. Von-Mises stress and deflection of double skin ribbed vaulted shell fuselage and primary wing structure.

In this FEM analysis, the stress levels at the wing-fuselage junction and wing rear spar were well above the allowable limit and needed to be resized and redesigned. The pressure bearing front and rear spar also needed to be modeled properly. Moreover, no sizing study or bucking analysis was performed. The FEM weight of this configuration of half the vehicle structure was 29200 lbs (13245 kg). The actual as built weight of the airframe with all the fasteners, doublers, are usually twice the FEM weight. In later design, the front pressure bearing spar was eliminated and the wing leading edge curved surface was designed to bear the cabin internal pressure load.

Based on the full vehicle FEM analysis from Ref. 1-3, a set of critical design loads were developed for detailed design and optimization of the most highly loaded central section fuselage

panel. These load definition was used in Ref. 5, for the following three structural analyses models and design study.

- (a) Idealized beam-column model stress and bucking analysis:
- (b) Top surface panel plate model FEM analysis and optimization of rectangular composite plates:
- (c) Multi-bubble model concept FEM analysis of a representative section of the BWB fuselage:

### III. a) Idealized beam-column model

An idealized beam-column model stress and bucking analysis including the nonlinear effect of bending deflection was performed using closed form solution. Analysis equations and sample results of this idealized deep sandwich with aluminum skin are shown in Figure 5.

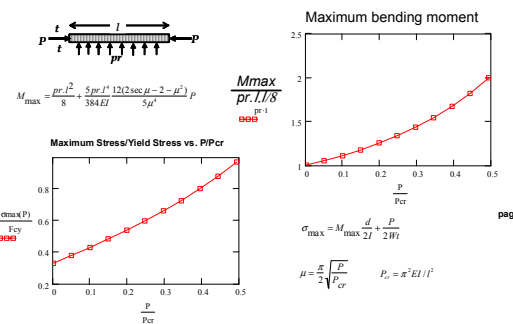


Figure 5. Idealized beam-column analysis with nonlinear effect of bending deflection.

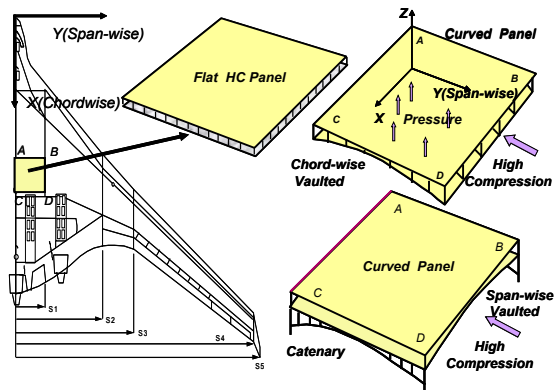


Figure 6. Top surface ribbed and vaulted plate panel models at a highly loaded fuselage section.

### b) Top surface panel plate models

The top surface panel models at a highly loaded fuselage section are shown in Figure 6. A

rectangular composite sandwich plate model, a cross-ribbed flat panel, a vaulted ribbed panel, and a catenary's supported panel were analyzed in Ref.

5. A summary of FEM analysis and optimization results are presented in Table 1.

Concept	Initial				Optimized					
	depth meter	skin t meter	p/pcr	wt/area kg/sq.m	depth meter	skin meter	P/Pcr	wt/area kg/sqm.	max disp. meter	material
2D HC Beam	0.15	0.006	0.4	42.4	0.264	0.0045	0.18	37.9	0.03	AL
2D HC Beam	0.1524	0.0064	0.42	25.55	0.1778	0.0051	0.37	21.3	0.048	SRFI
flat HC	0.137	0.003	0.5	15.3	0.201	0.0046	0.66	24.1	0.0086	SRFI
flat ribbed	0.152	0.003	0.5	13.5	0.184	0.0058	0.66	25.6	0.0064	SRFI
flat HC+cat	0.167	0.003	0.5	15.4	0.201	0.0046	0.71	24.2	0.009	SRFI
vaulted HC	0.2	0.003	0.5	17	0.17	0.0033	0.66	25.4	0.0112	SRFI

Table 1. Summary of beam column and plate analysis and optimization results.

### c) Multi-bubble models

The multi-bubble fuselage configuration concept was developed for balancing internal cabin pressure load efficiently, through membrane stress in inner-stiffened shell and inter-cabin walls. An outer-ribbed shell was designed to prevent buckling due to external resultant compressive loads. For comparison purposes, FEM based structural analysis results were also presented for conventional B777 type cylindrical fuselage section and A380 type elliptic section fuselage. Figure 7 shows a schematic view of the three vehicle fuselage sections.

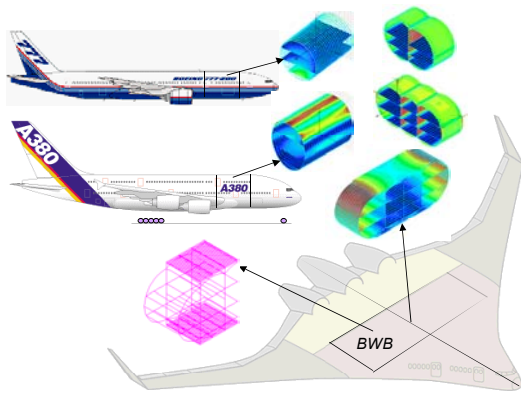


Figure 7. Conceptual Fuselage section analyzed for B777, A380 and BWB 800 class vehicles.

#### Double-bubble design:

As explained earlier, and from the design results described in Ref. 5, the rectangular composite sandwich plate and cross-ribbed panel designs were found to be structurally inefficient to carry the internal cabin design pressure and compressive load simultaneously. Based on the lessons learned from these analyses, 3-floor load-

balanced multi-bubble stiffened-shell pressure vessel concepts were developed. Diameters of the cylindrical segments were almost same as a typical B777 cylindrical fuselage.

In this design shown in Figure 8, the two merging bubble-sections meet with the inter-cabin vertical wall at an angle, so that surface in-plane membrane forces are in self-equilibrium. Thus in an ideal case, the resulting membrane stresses on the cylindrical section skin are balanced by tension in the inter-cabin walls. This geometrical arrangement could reduce undue bending at these joints, thereby preserving the advantage of a cylindrical section fuselage, under internal cabin pressure.

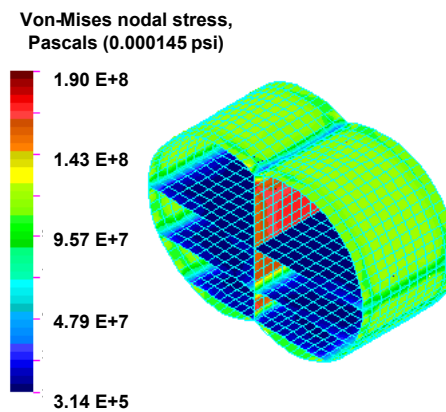


Figure 8. Double-bubble concept: Nodal Von-Mises stress in due to 127530 Pascal (18.6 psi) internal pressure.

#### Triple-bubble design:

This special geometry was extended to a triple-bubble 3-floor multi-aisle fuselage, shown in Figure 9. These force-balanced double and triple bubble configurations were extended to a four-bubble 3-floor concept with additional outer

stiffened double panels, at top and bottom of the fuselage, as shown in Figure 10. In this and subsequent FEM models, cylindrical skin segments were stiffened with ring stiffeners, which are generally typical for commercial transport aircrafts.

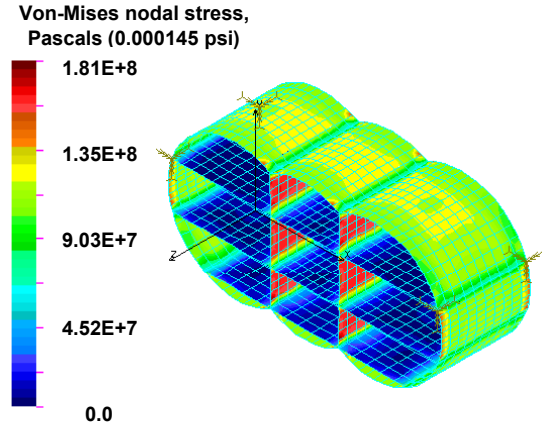


Figure 9. Triple bubble force balanced three floor fuselage configurations: Nodal Von-Mises stress due to 127530 Pascal (18.6 psi) internal pressure

These outer panels initially consisted of two stiffened shells supported by the cylindrical inner fuselage sections at midpoint. These outer shells were not connected to the inter-cabin vertical walls directly at top. The outer shell was added to provide bending and buckling stiffness to span-wise bending loads that were not considered in the double- and triple-bubble concepts. This model was subjected to the standard 12.3 psi (84835 Pascal) internal cabin pressure as load case 1. For load case 2, top stiffened panels were subjected to 164350 kg/meter (9200 lbs/in) span-wise compressive loads. Equal and opposite tensile loads were applied at bottom panels, to represent an equivalent maximum estimated bending moment.

Four-bubble-design:

The four-bubble configuration, shown in Figure 10 was analyzed with internal design pressure loads, as well as with estimated equivalent compressive loads on top panels (and equal tensile load on bottom panels) due to fuselage bending, in order to obtain acceptable stress, deflection and buckling stability safety factor.

Five-bubble-design:

In the five-bubble fuselage concept, shown in Figure 11, the radius of inner cabin vaulted ceiling was reduced from 3.875m to 3.75 meters. Radius of the outer cabin was reduced to 3.248 meters in order to get approximate

membrane stress equilibrium at outboard joints. Additional span-wise running tie-rods were also used at the top and bottom of the cabin. Since only half the fuselage was modeled, symmetric clamped boundary conditions were assumed at the plane of symmetry.

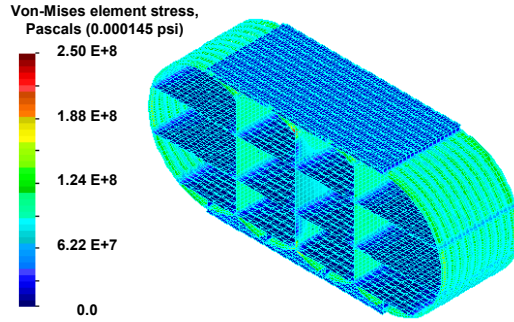


Fig. 10 Element nodal Von-Mises stress at top due to 84835 Pascal (12.3 psi) internal cabin pressure and 164350 kg/meter (9200 lbs/in) span-wise compressive load on top panel and equal tensile load at bottom panel.

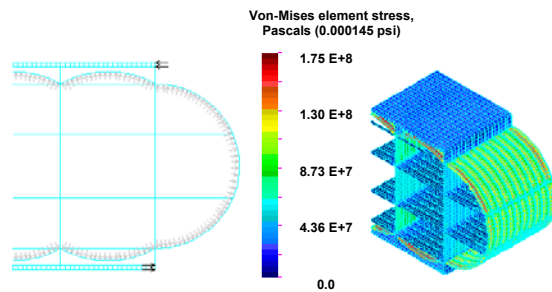


Fig. 11 Five-bubble force-balanced stiffened fuselage concept with vented double outer skin: Element nodal Von-Mises stress at top surface due to 84835 Pascal (12.3 psi) internal cabin pressure and 164350 kg/meter (9200 lbs/in) span-wise compressive load on top panel and equal tensile load at bottom panel.

**IV. Unit weight comparison.**

Initial results of the redesigned multi-bubble fuselage appear to be significantly better compared to the flat shell design. Figure 11 shows Von-Mises stress distribution at element nodes computed on top surface due to combined internal cabin pressure and span-wise compressive load on top panel and equal tensile load at bottom panel. These stresses were well within allowable limits and about 25% lower than the four-bubble design with about 10% increase in unit weight/floor area.

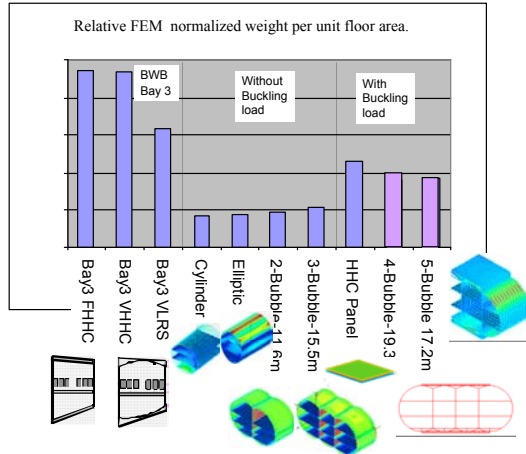


Figure 12. Relative Finite Element Model weight of fuselage configurations per unit floor area: (Ref. 4: FHHC- flat sandwich shell with heavy honeycomb core; VHHC- vaulted shell with heavy honeycomb core; VLRS- vaulted ribbed shell; HHC- heavy honeycomb core flat shell).

Figure 12 shows a relative non-optimal FEM weight comparison from Ref. 5. These relative unit weights were computed as ratio of total finite element weight of the structure divided by floor areas inside the fuselage section. First three concepts labeled BWB bay-3 weights of vaulted shell with heavy honeycomb (VHHC); flat sandwich shell with heavy honeycomb core (FHHC); and vaulted ribbed shell (VLRS) also included side walls, front and rear pressurized spar of similar construction<sup>4</sup>. It should be noted that these previous designs were not optimized or analyzed for buckling stability, although sizing was done using 2-D nonlinear beam-column analysis similar to that described earlier in the paper.

## V. BWB Derivative Vehicle Sizing

The weight comparison shown in Figure 12 provided a trend of fuselage FEM weight per unit floor area. These FEM models contained beam elements for stringers and stiffeners and shell elements for skin. Since these FEM models used for the multi-bubble concept were too detailed to extend into a full vehicle FEM, Bradley (Ref. 6) recently developed a simple methodology for sizing a conceptual derivative BWB vehicle using an approximate equivalent thickness property with plate finite element analysis. Equivalent plate thickness was obtained from the bending stiffness of skin-stringer combination and equivalent isotropic plate.

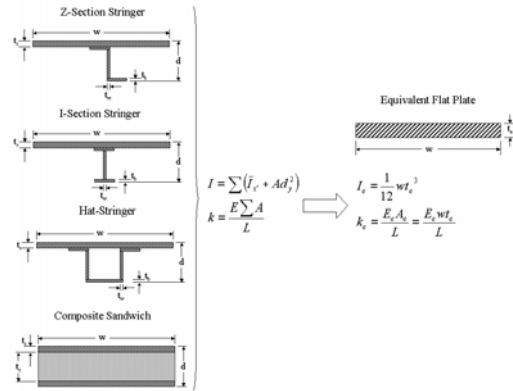


Figure 13 Equivalent flat plate thickness and elastic property estimation scheme (Ref. 6).

The equivalent plate thickness and Young's modulus were obtained as shown in Figure 13. The extensional stiffness,  $k$ , and bending stiffness,  $E \cdot I$ , were equated for the skin/stringer arrangement and the equivalent flat plate. The figure also shows the equations used to determine the thickness and modulus of elasticity of the equivalent flat plate. Although this scaling did not use standard non-dimensional parameters for plate bending and buckling equations, this simplification enabled sizing of a series of scaled FEM model of 200 to 480-passenger version vehicles with design variables such as Cabin Area (5 models), take-off gross weight (to provide aerodynamic load distribution), and Skin/stringer depth and spacing arrangement modeled with equivalent flat plate. However this study did not take advantage of the multi-bubble geometric configuration and its stress balancing property, since it was intended for projecting a weight trend based on the number of passengers, with 480 passenger version as a baseline. Moreover, material modulus of elasticity property scaling resulted in under estimation of the weight. The weight regression equations had to be scaled using baseline vehicle weight data.

## VI. Y braced box fuselage

In a recent study of a 480 passenger version of BWB by Boeing under a NASA research contract (Ref. 7), box-type Y braced fuselage alternative was designed and analyzed with special resin-film injected (RFI) stitched carbon composite skin with foam-core. The Y brace reduces the bending at the joint of the roof and cabin walls. The stitched foam-core with RFI skin provides higher bending stiffness without

adding significant weight penalty. The design also considered span-wise I-section and J-section stiffeners with RFI-foam construction.

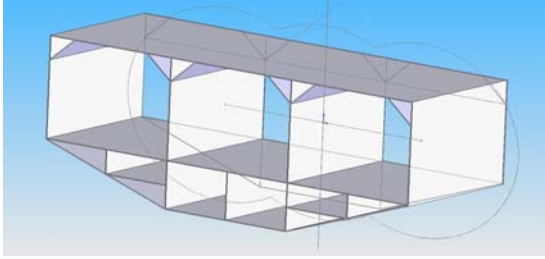


Figure 14. Box fuselage scheme with Y-brace for 480 passenger version BWB vehicle.

A schematic view of this 3 bay Y braced fuselage concept is shown in Figure 14. An initial finite element analysis of the fuselage indicated excessive stress at the joint where the pressurized section ends and non-pressurized section begins. To alleviate this stress, additional Y brace were added as shown in Figure 15a and 15b.

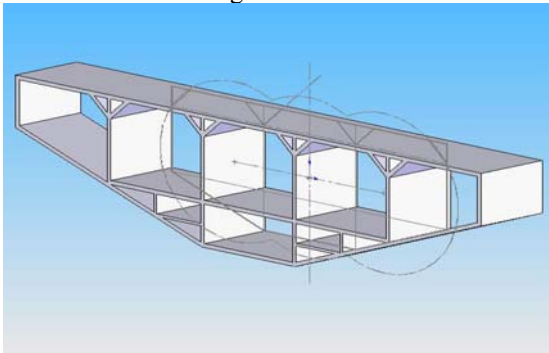


Figure 15a. Modified fuselage design with additional Y brace at wing-fuselage junction.

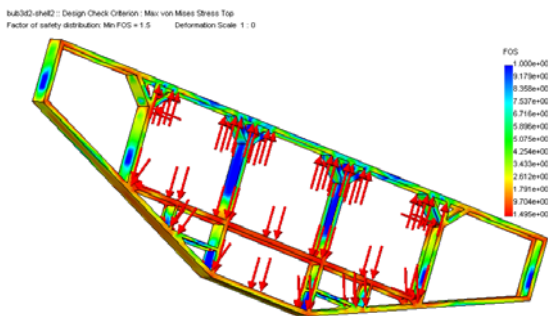


Figure 15b. Factor of safety distribution of fuselage slice with AL6061 material, 24 inch (0.61 m) frame spacing, 0.25 inch (0.0063m) thick skin, at 9.3 psi (62760 Pascal) internal pressure and 1 psi (6896 Pascal) floor load.

Figures 16a and 16b show the modified fuselage designed with the Y brace replaced by

vaulted shell. A large number of rapid FEM analyses were done with solid and ribbed shell finite element model for different configuration for stress, deflection and safety margin check using SolidWorks and Cosmos/DesignStar FEM software. Each FEM model represent a slice of fuselage with 24 inch (0.61 meter) frame spacing, 0.25 inch (0.0063m) skin and frame with AL6061 material, with about 26,000 degrees of freedom. The fuselage is subjected to 9.2 psi (62760 Pascal) internal pressure load and 1 psi (6896 Pascal) floor load. The FEM model is inertia balanced to satisfy free body boundary condition.

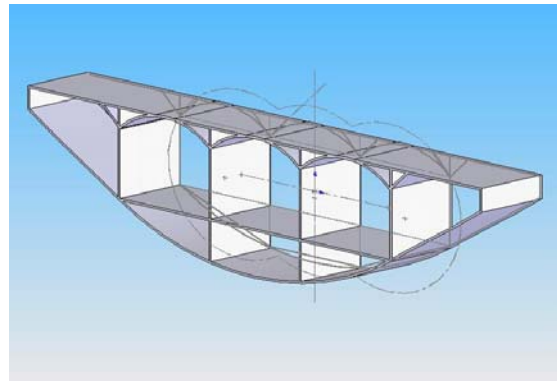


Figure 16a Modified fuselage designed with Y brace replaced by vaulted shell.

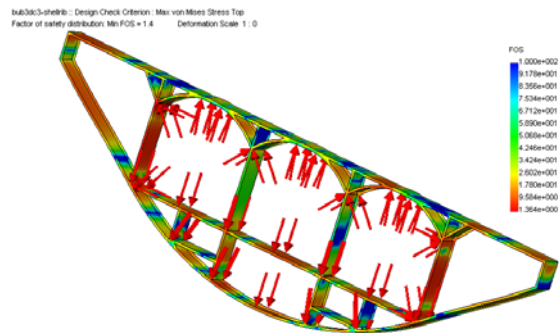


Figure 16b Factor of safety distribution on modified fuselage designed with Y brace replaced by vaulted shell, AL6061 material, 24 inch (0.61 m) frame spacing, 0.25 inch (0.0063m) thick skin, at 9.3 psi (62760 Pascal) internal pressure and 1 psi (6896 Pascal) floor load.

Modeling of sub-structure with stitched composite skin and foam core is necessary for future detailed analysis, as an alternative to multi-bubble aluminum skin-stringer construction. Detailed full vehicle finite element analysis is presently being conducted at Boeing. The Boeing design report also proposed, for phase-II, fabrication of a series of test components and tests in order to determine the elastic properties of test



coupons for future finite element analysis and to establish the failure modes of stitched RFI composite construction of vehicle components.

### **Conclusions**

Design and analysis of efficient structural concepts for pressurized fuselage design of blended-wing-body type flight vehicles were presented. Vaulted shell and special multi-bubble geometric configuration are efficient in distributing the stress due to internal pressure load for these non-conventional flight vehicles. Due to manufacturing concern, Y braced box type fuselage design using special composite material construction is a possible practical alternative. It is shown that this configuration can be improved to a modified vaulted shell partial multi-bubble type fuselage which has better stress distribution, for same material and dimension. Efficient design of non-cylindrical pressurized structure is vital for non-conventional Aeronautics and Exploration Mission vehicles. Advanced Geometric configuration for stress balancing and Composite Material fabrication techniques are essential. Structural weight penalty can be severe. For a successful design, it is necessary to develop efficient rapid geometric and structural layout, FEM analysis and optimization tools.

### **Acknowledgement**

The author wishes to thank Dr. Robert Liebeck, Daniel Hansen and Alexander Velicki of Boeing Company and Kenneth Bradley of US Air Force for their contribution and insight. The work was funded by Efficient Aerodynamics and Shape Integration (EASI) project, Conceptual Design Shop (CDS) sub-project. The finding support by EASI Project manager Jim Pittman and EASI/CDS sub-project Manager Craig Nickol are gratefully acknowledged.

### **References**

<sup>1</sup>Liebeck, R. H. "Configuration Control Document CCD-3: Blended Wing Body:" Final report Under Contract NAS1-20275 NASA Langley Research Center, Oct. 1, 1997.

<sup>2</sup>Liebeck, R. H., Page, M. A., and Rawdon, B. K. "Blended-Wing-Body Subsonic Commercial Transport." AIAA Paper 98-0438, Jan. 1998.

<sup>3</sup>Liebeck, R. H. "Design of the Blended Wing Body Subsonic Transport," *Journal of Aircraft*, Vol. 41, No. 1, Jan-Feb. 2004, pp. 10-25.

<sup>4</sup>Mukhopadhyay, V., 'Structural Concepts Study of Non-circular Fuselage Configurations,' Paper No. AIAA SAE WAC-67, World Aviation Congress, Los Angeles, Calif. Oct. 22-24, 1996.

<sup>5</sup> Mukhopadhyay, V., Sobieszczanski-Sobieski, J., Kosaka, I., Quinn, G., and Vanderplaats, G., "Analysis, Design and Optimization of Non-cylindrical Fuselage for Blended-Wing-Body Vehicle," *Journal of Aircraft*, Vol. 41, No: 4, July-August, 2004, pp. 925-930.

<sup>6</sup>Bradley, K. R., "A Sizing Methodology for the Conceptual Design of Blended-Wing-Body Transports, *MS Thesis, Joint Institute for Advancement of Flight Sciences, George Washington University, Sep. 2003.*

<sup>7</sup>Velicki, A., and Hansen, D. A., "Novel Blended Wing Body Structural Concepts," NASA TCAT NRA Phase-I Final Report, Boeing Co. CA, July 2004.