Blended wing body structural concept development

A. Velicki and P. Thrash
The Boeing Company
Huntington Beach, California
USA

ABSTRACT

A lightweight robust airframe design is one of the key technological advancements necessary for the successful launch of a blended wing body aircraft. The non-circular pressure cabin dictates that substantial improvements beyond current state-of-the-art aluminium and composite structures is needed, and that improvements of this magnitude will require radically new airframe design and manufacturing practices. Such an approach is described in this paper. It is a highly integrated structural concept that is tailored and optimised to fully exploit the orthotropic nature and unique processing advantages inherent in dry carbon fibres, while also employing stitching to enable a unique damage-arrest design approach.

NOMENCLATURE

2·5g	2·5 times gravity pull-up flight manoeuver load case
2P	2·0 times internal cabin operating pressure load case
AST	Advanced subsonic technology
BWB	blended wing body
CNC	Computer numerically controlled
IML	Inner mouldline
Nx	*X* component of the internal running load acting in the streamwise direction
N_y	*Y* component of the internal running load acting in the spanwise direction
N_z	*Z* component of load acting out-of-plane caused by internal pressure
OML	Outer mouldline
PRSEUS	Pultruded rod stitched efficient unitised structure
Sta	Station value, longitudinal distance from origin of aircraft reference system

1.0 INTRODUCTION

Although advanced flying wing configurations like the blended wing body (BWB) have long been known to offer superior payload-range performance, such benefits will be difficult to take advantage of until the pressurisation and producibility aspects of the airframe design are resolved. The non-circular pressure cabin presents two fundamental problems for the airframe designer: 1. pressurisation causes large secondary-bending effects in the near-flat regions of the shell — substantially increasing structural weight; and 2. the compound-curvature shape exacerbates manufacturing costs — especially if conventional multi-piece aircraft construction techniques are employed. Until these two basic design issues are resolved, the dream of transporting large payload volumes in efficient flying-wing aircraft will not be realised.

To address these challenges, researchers at The Boeing Company in Huntington Beach, California, have developed a highly-integrated stitched-composite airframe solution that is tailored and optimised for the BWB airframe by exploiting the orthotropic nature and unique processing advantages inherent in dry carbon fibre materials. This new design and manufacturing approach is called the Pultruded rod stitched efficient unitised structure (PRSEUS) concept. It is a disruptive technology that is a conscious progression away from

Paper No. 3392. Manuscript received 1 December 2008, revised 15 May 2009, accepted 21 May 2009.
This paper was first presented at the 2008 RAeS Aircraft Structural Design Conference, Liverpool.

https://doi.org/10.1017/S0001924000004000 Published online by Cambridge University Press

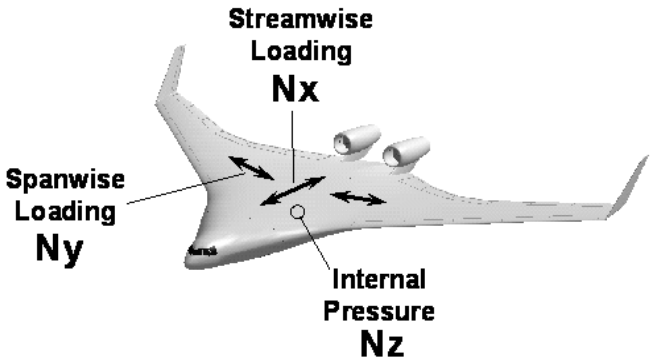


Figure 1. Primary BWB load paths.

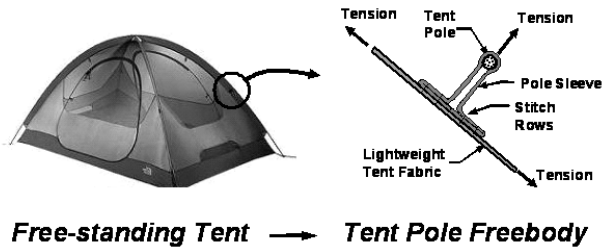


Figure 2. Free-standing fabric structure.

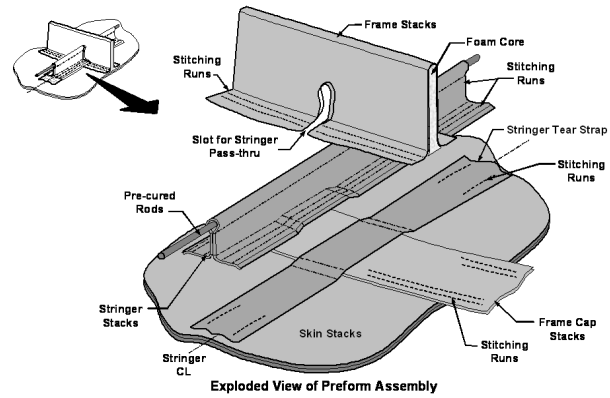


Figure 3. PRSEUS structural concept.

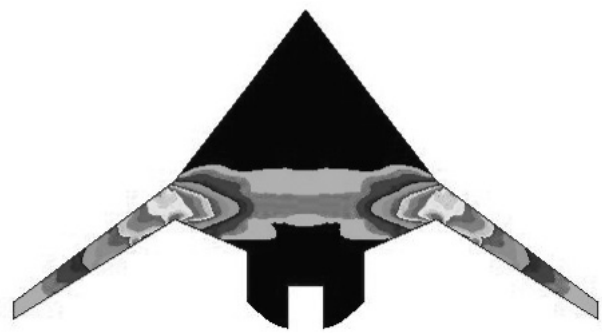


Figure 4. 2·5g manoeuvre spanwise (N_y) running load intensity.

conventional laminated composite design practices that was developed to achieve breakthrough levels of structural performance while simultaneously reducing manufacturing costs for the complex curvatures found on the BWB airframe.

2.0 BWB STRUCTURAL DESIGN CHALLENGE

It is well understood that developing an airframe that is not only lightweight, but also economical to produce is the primary impediment toward moving the elusive BWB airplane configuration forward[1]. The non-circular pressure cabin precludes the use of metallic materials that are fatigue prone, while the high pull-off loads (N_z) makes the use of conventional prepreg composite materials that are susceptible to resin-dominated interlaminar failures unfeasible. In addition, the BWB also experiences an unusual bi-axial loading pattern (N_x, N_y) in the shell that is more nearly equal in magnitude than what is found on conventional tube-and-wing fuselage structures; where the N_x loading direction along the stringer is more highly loaded than the N_y direction along the frame. This unusual loading distribution further complicates the structural concept selection because the optimum panel geometry should have continuous load paths in both directions (N_x, N_y) while also efficiently transmitting pressure loads (N_z) (Fig. 1).

Creating clean load paths in two directions is difficult to achieve with conventional continuous-stringer and shear-clip-to-frame structural arrangements because the shear clip is typically made discontinuous to allow the stringer to pass through uninterrupted. This is done to maintain load continuity in the more highly loaded direction of the panel. Such an approach would carry a higher weight penalty for the BWB because the axial load magnitudes are more equal in each direction. For this reason researchers have tended to focus on sandwich panel skin designs that can be efficiently loaded in both directions. The problem with this approach is that sandwich skins are not damage tolerant and must also be padded-up, or ramped down, at the frame interfaces for joining. In each case, substantial weight is added to the airframe to meet these constraints.

Beyond the difficulties of creating effective load paths, is the challenge of economically producing such a large acreage of compound-curvature structure. The variable loft shape makes the cost of tooling each individual substructure element (stringers, frames, bulkheads, etc.) prohibitively expensive. This would be especially true using a conventional composite manufacturing approach where numerous detail and subassembly tools are needed to lay-up each detail part and then subsequently bond them together into panel assemblies. Clearly a structural solution with less tooling is appealing for the BWB airframe, and in all probability, may be the enabling feature for meeting the producibility constraints.

Bound by these beliefs, our development activity focused on finding a new damage-tolerant design with clean loads paths in three directions that could also be fabricated with a minimum number of tool sets. It was also desirable that fabrication take place outside the autoclave, so that larger integral panel designs could be made to improve structural efficiency and reduce manufacturing costs.

Prior BWB trade studies suggested that sandwich panel concepts would be neither lightweight (when damage arrest features were added) nor practical to fabricate using low-cost out-of-autoclave processing methods[2]. Recognition of these short-comings provided the impetus for finding a monolithic skin design that could more easily be made to arrest damage propagation and ultimately meet fail-safe design criterion. To achieve this for composite structures, through-the-thickness stitching would be needed, which in turn dictated that a dry-fabric fabrication scheme be employed. Fortunately, such an approach also lent itself to unitised construction methods that could be processed outside the autoclave with a reduced number of tool sets using low-cost resin-infusion techniques.

With the recognition that stitching would form the basis of this new integral design approach, the next challenge was to invent a

https://doi.org/10.1017/S0001924000004000 Published online by Cambridge University Press

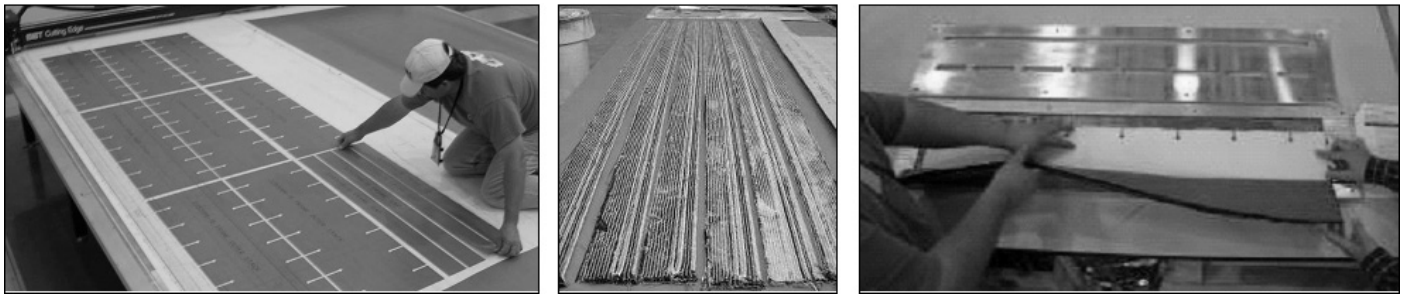


Figure 5. Detail part fabrication: flat pattern trim, stitched stringers, and frame assembly.

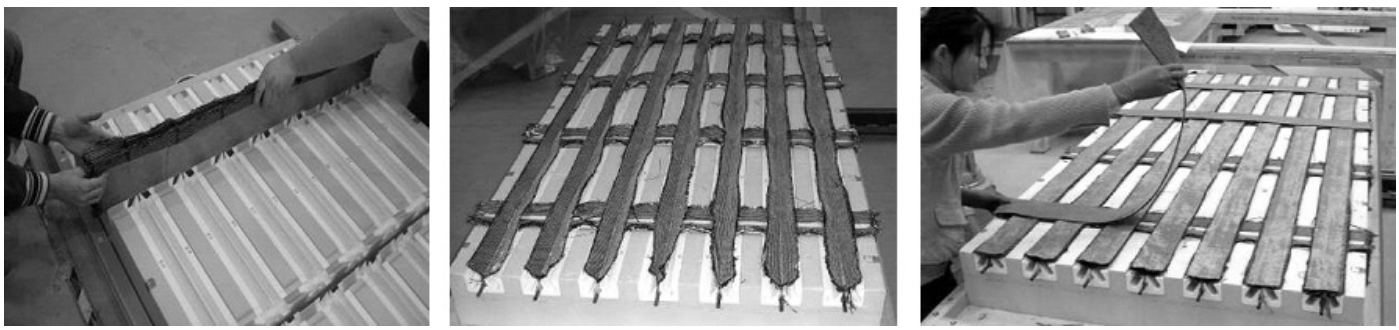


Figure 6. Preform assembly sequence: frames, stringers, tear straps, and skins (not shown).

method (Fig. 2) by which stitched dry carbon fabrics could be held in place, infused with resin, and then cured without expensive or complex inner mouldline tooling. The inspiration for this new fabrication scheme came from an unlikely source, a tent structure. Here was a simple means of supporting dry fabric in a complex geometry without tooling. By adapting these basic principles of a self-supporting fabric structure, the Pultruded rod stitched efficient unitised structure (PRSEUS) concept was created.

Using this approach, complex stitched preform assemblies could be built without exacting tolerances, and then accurately net-moulded in a single oven-cure operation using high-precision outer mouldline (OML) tooling[3]. Since all the materials in the stitched assembly were dry, there would be no out-time, or autoclave limitations as in prepreg systems, which can restrict the size of an assembly because it must be cured within a limited processing envelope. Resin infusion would be accomplished using a soft-tooled fabrication method where the bagging film conforms to the inner mouldline (IML) surface of the preform geometry and seals against a rigid OML tool, thus eliminating costly internal tooling that would normally be required to form net-moulded details.

The highly integrated nature of PRSEUS is evident in the strategic placement of the carbon fibres (Fig. 3). The dry warp-knit fabric, pre-cured rods, and foam-core materials are assembled and then stitched together to create the optimal structural geometry for the BWB fuselage loading. Load path continuity at the stringer-frame intersection is maintained in both directions. The 0-degree-fibre dominated pultruded rod increases local strength/stability of the stringer section while simultaneously shifting the neutral axis away from the skin to further enhance the overall panel bending capability. Frame elements are placed directly on the IML skin surface and are designed to take advantage of carbon fibre tailoring by placing bending and shear-conducive lay-ups where they are most effective. The stitching is used to suppress out-of-plane failure modes, which enables a higher degree of tailoring than would be possible using conventional laminated materials.

The resulting integral structure is ideal for the BWB pressure cabin because it is a highly efficient stiffened-panel geometry in three directions (N_x, N_y, and N_z) that is damage tolerant, stitched to react pull-off loads, and also capable of operating well into the post-buckled design regime, which enables thin-gauge skin-stringer designs to be lighter than non-buckled sandwich designs.

Another important feature is the effectiveness for a minimum-gauge solution. This is readily apparent from the 2·5g manoeuvre running load plot (Fig. 4). Here, the dark regions of the plot show the small effect that manoeuvre loads have on the forward region of the pressure cabin, where the design is primarily driven by the static proof-load condition (2P internal pressure). Here again, the advantages of a skin-stringer design meant that PRSEUS was well suited in the minimum gauge design space, where the optimal panel geometry includes thin skins sized by pressure loading (N_z) where axial loads are carried by the stringers or frames, which are then designed to operate as post-buckled panels in each direction (N_x or N_y).

3.0 PRODUCIBILITY DEMONSTRATION

Manufacture of the dry fibre preform for the PRSEUS panel starts with the cutting and kitting of the plies of dry material that make up the skin, stringer, and frame components (Fig. 5). The 50in wide warp-knit multi-axial carbon fibre fabric were cut into individual details and placed into kits. The precut stringer pieces were folded in half length-wise and stitched in two locations. One seam defines the bulb feature at the top of the stringer while the other establishes the fold line for the stringer flange. Frame details are constructed using dry warp-knit fabric and closed-cell foam materials. The foam core was CNC machined with all the detailed features required to support the frame plies, carbon fibre rods and resin infusion processing. Assembly of the frame preform began with wrapping the dry fabric plies around the machined foam core by hand and then stapling the fabric in place. The individual details are then located in a preform assembly fixture prior to the stitching operation (Fig. 6).

https://doi.org/10.1017/S0001924000004000 Published online by Cambridge University Press



Figure 7. Preform stitching of the stringers and frames to the skin.

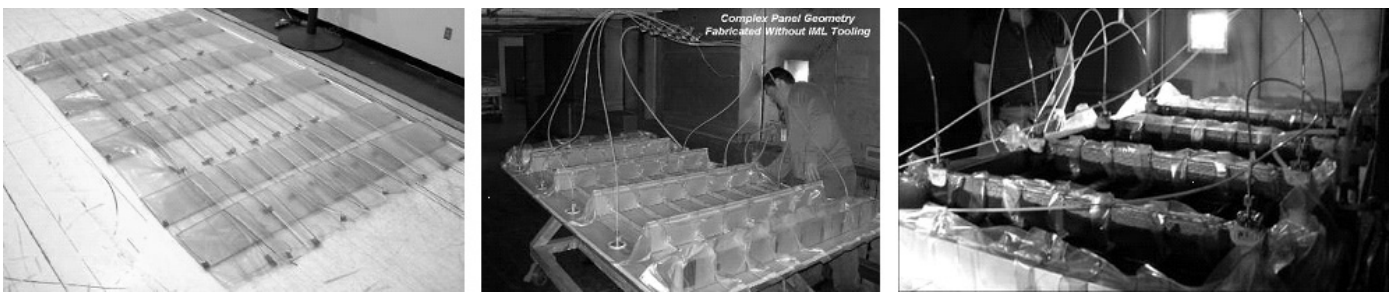


Figure 8. Vacuum bagging and resin infusion.

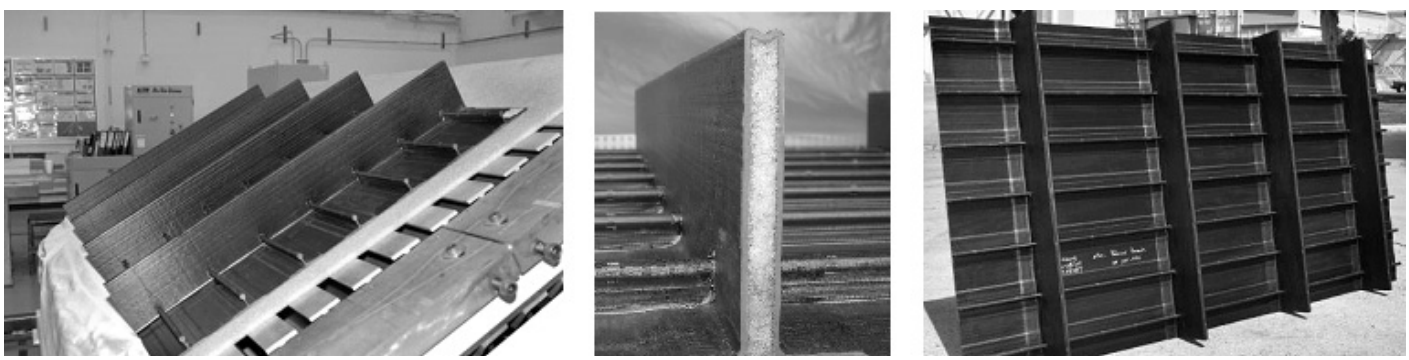


Figure 9. Cured and edge trimmed PRSEUS panel.

The frames are installed into the assembly tool first by simply dropping the stapled foam core preform into the corresponding slot for each frame station, and then the stringers are installed next in between the matching sets of plastic mandrels working from one end of the panel to the other. Full size carbon rods were then pulled through the stringer bulbs. The stringer and frame flanges were folded down next to form the web plies. Strips of fabric making up the stringer and frame tear straps were then placed over the flattened flanges. Finally, the skin ply stacks were positioned over the entire assembly (not shown in the photos).

Stitching is accomplished by using a one-sided robotic stitching system where seams of stitching are inserted into the preform assembly along the stringer and frame flanges (Fig. 7). The self-supporting preform is then transferred to an outer mould line cure tool for resin infusion processing.

The IML tooling is comprised of a pleated nylon vacuum bag that was placed over the preform and sealed down against the OML tool (Fig. 8). Vacuum outlet ports were located at the edges of each frame. The preform was infused with a two-component resin system where the resin and hardener, are automatically degassed, metered, mixed, and delivered on demand to the mould at the predefined temperature and pressure. The cure tool consisted of a machined flat aluminum OML plate and an aluminum perimeter frame that is used to locate the frame and stringer ends.

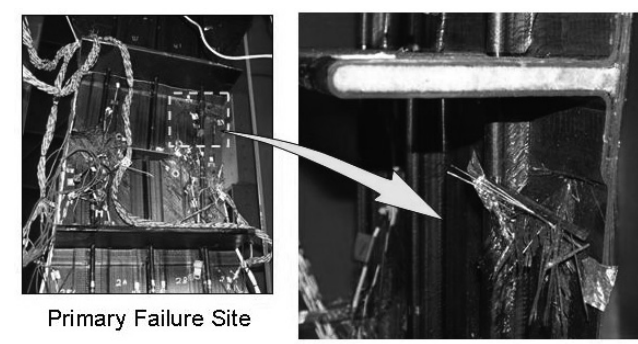


Figure 10. Discrete source damage testing.

The manufacture of multiple PRSEUS panels[3] showed that the essential feature of this concept — the self-supporting preform that eliminates interior mould tooling — was feasible for the near-flat

https://doi.org/10.1017/S0001924000004000 Published online by Cambridge University Press



Figure 11. Post-test element pull-off specimens: stringer, frame, and stringer-frame intersection.

geometry of the BWB airframe (Fig. 9). This accomplishment represented a fundamental breakthrough in addressing the producibility concerns for the BWB airframe.

4.0 STRUCTURAL PERFORMANCE

The use of stitching to arrest damage propagation is one of the key attributes of the PRSEUS structural concept[3]. It enables a PRSEUS structural assembly to utilise a multi-load path design philosophy with numerous fail-safe structural members, including stitched interfaces that allow the structure to sustain large-area damage up to specified load levels. For composite materials, and especially for thin-gauge applications like the BWB fuselage, these damage scenarios typically govern the maximum allowable operating stresses that can be safely attained to avoid fast fractures. By using stitching to arrest damage, the PRSEUS concept is able to maintain higher residual load-carrying capabilities under a variety of damage scenarios. This leads to higher operating stresses than would otherwise be possible using conventional no-growth design practices and ultimately reduces the weight penalty associated with the non-circular pressure cabin of the BWB.

A key aspect of this new approach is the ability to turn cracks, similar to metal structures, thereby redistributing internal loads to reduce the crack-tip stress intensity. This characteristic was demonstrated on a representative fuselage test panel (Fig. 10). The three-stringer dog-bone tension panel with a two-bay crack (slot across central stringer) was statically tested to failure. This specimen was able to arrest propagating damage in both the horizontal and vertical directions as it emanated from the slot edge. Because damage was arrested at the stitched interfaces and fully contained within the two-bay damage zone bordered by the adjacent stringers and frames, the panel was able to continue bearing load beyond the design limit load requirement. The specimen ultimately failed at the frame flange at a load level 30% higher than the design requirement, and 60% higher than the onset of damage propagation at the slot edge. This test clearly demonstrated that substantially higher loads are possible (60% higher) when stitched interfaces are used to turn cracks and arrest damage, thereby enabling a fail-safe design methodology to be employed[4].

Additional load path screening tests were also conducted to assess the out-of-plane load-carrying capability of the PRSEUS concept. In each case, when stringers, frames, or the stringer-frame intersection specimens were tested, the resulting failure loads far exceeded the design loads for the 2P internal pressure condition on the BWB aircraft. As can be seen in the series of photographs (Fig. 11), the integral stitched interfaces were able to suppress resin failure modes, and in most cases, resulted in fibre failures in the individual structural details rather than the first-ply failure modes that are common in conventional unstitched composite constructions. These results validated the out-of-plane structural integrity of the PRSEUS structural concept and opened the way for further BWB airframe development activities.

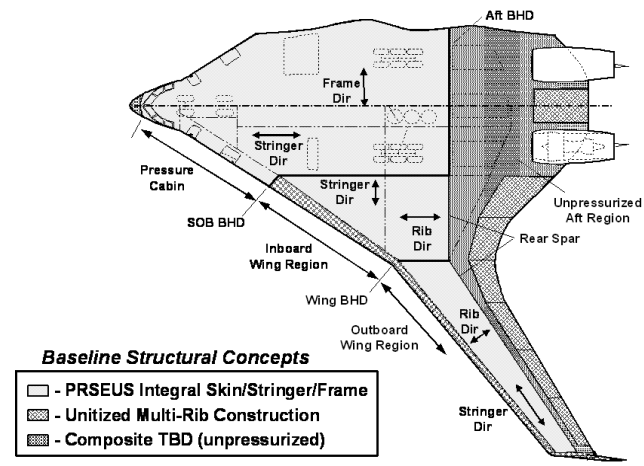


Figure 12. BWB baseline material/structural breakdown.

5.0 BWB AIRFRAME DEVELOPMENT

The PRSEUS BWB airframe features large unitised wing and fuselage components that offer efficient continuous load paths, higher notched design properties, larger allowable damage levels, and enhanced levels of survivability beyond those currently possible using conventional structural concepts. The principle structural assemblies are PRSEUS-based designs (lightly shaded region) and the non-pressurised areas (dark region) are baselined as a combination of metallic and composite components (Fig. 12). Large control surfaces are unitised multi-rib stitched-composite concepts like those pioneered on the C-17 landing gear doors[5], and lightly loaded elements like fairings, doors, and engine nacelles would be fabricated using conventional techniques. The floor structure would also be conventional in nature, but improved with advanced composite materials and aluminum alloys where possible to reduce weight and cost. The pressure cabin has two decks which are divided longitudinally by bulkheads (Fig. 13). Diagonal bracing or gusset members are used to support the frames in the corners to reduce bending moments. In the lower cargo region, the frames extend the entire depth between the skin and the cargo floor.

Deeper frames or support bracing would be used in regions of the lower shell not housing cargo containers, and where landing gear and systems geometries permit. The upper deck floor carries normal vertical loads, as well as reacts side wall pressure loads. To keep the space in the under-floor cargo bays as clear as possible, there will be no intermediate struts for the floor beams between the ribs. The floor beams run continuously across (and through) the ribs, and are attached to the end pressure bulkheads with some degree of fixity. These end attachments will assist the bulkheads in carrying the lateral pressure loads, and in doing so, the beams themselves are subjected to a tension load from the spanwise pressure loads.

https://doi.org/10.1017/S0001924000004000 Published online by Cambridge University Press

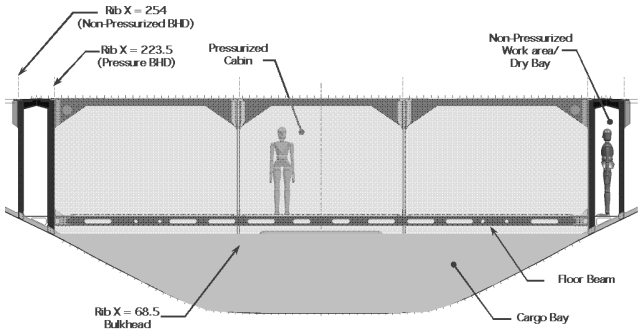


Figure 13. Typical fuselage cross-section.

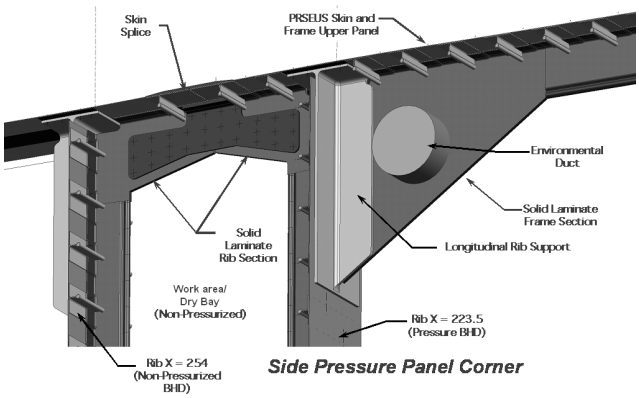


Figure 14. Cabin corner detail.

There are a number of regions for landing gear or systems under the passenger floor that must be unpressurised. The floor above these regions becomes the boundary of the pressure shell and has to carry the full transverse pressure loads. The corner regions of the pressure cabin will maintain bending moment continuity using the pressure panel arrangement depicted in Fig. 14.

6.0 STRUCTURAL SIZING

To assess the benefits of a PRSEUS airframe, a preliminary design trade study was performed with the reference baseline using an FEM-based global-local sizing approach that constrains the overall vehicle-level stiffness and internal load distributions in order to satisfy airplane-level design requirements (Fig. 15). The local panel-level constraints, such as panel stability and strength, were checked by local sizing codes. Updated panel stiffness and mass properties were then passed between the global and local analyses until a converged solution was reached. Once the analytical models converged, the final structurally-sized results were then multiplied by non-optimum factors to generate the final 'as-fabricated' weight distributions for the airplane.

In prior trade studies many different fuselage structural concepts have been assessed for the BWB airframe, and most results pointed to a sandwich panel design approach as the optimum solution. These results were primarily driven by the effectiveness of sandwich panels under bi-directional and pressure loading conditions. The primary problem with this result was that the design allowables used to size the sandwich concepts were based on the assumption that further research would lead to an advanced sandwich panel design that could be made to 'fail-in-a-safe-manner'. Until the failure mode for the core-to-face-sheet interface can be improved, the resulting

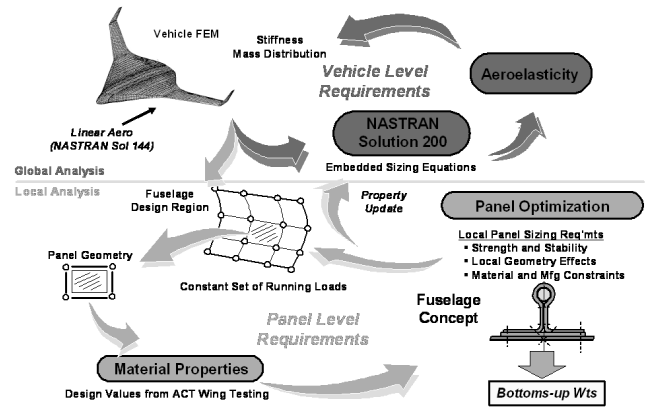


Figure 15. Global-local optimisation approach.

notched compression design values will remain unacceptably low for sandwich panel applications on primary airframe structures.

When the results from the PRSEUS BWB trade study were compared with prior studies, the benefits of structural integration were readily apparent. The pressurised shell elements (skin panels and frames added together) were 28% lighter for the PRSEUS concept than comparable sandwich panels. This was due mainly to the advantages of the skin-stringer design with respect to damage arrestment (results in higher strength allowables), post-buckling of the skins (permits thinner gauges), and an integral frame design (more efficient in spanwise compression loading). The large disparity was particularly evident for the frame members. Here, the padded regions and ramped cores in the sandwich design were not nearly as effective as the PRSEUS integral frame design. In this case, the pad-up regions required at each frame station to transfer loads between the sandwich skin panel and frame elements contributed very little to the overall bending stiffness of the frame and resulted in a large weight penalty.

Frame bending is a key discriminator within the BWB design space, where the combined loading of internal pressure (out-of-plane) and axial compression (along the frame direction) produce large secondary-bending effects in the flat skin panels. Such loads are most efficiently reacted by tall continuous frame members. Structural concepts without an effective frame element straddling the spanwise region of the pressure cabin (between rib bulkheads), as well as lacking an efficient means of transferring out-of-plane pressure loading between the skin and frame elements, will be less effective than integral design solutions like PRSEUS that integrate the skin and frame into a single element (without a shear clip) that is highly proficient in bending.

When the remaining internal structural elements (bulkheads, floors, etc.) that were not changed in the structural sizing exercise and the non-optimum were added to the weights statement, the final overall weight savings attributed to the PRSEUS shell concept was reduced to 10·3% as compared to the sandwich design results (Fig. 16). The resulting normalised plot provides a direct comparison of the prior study results[2] and shows the relative improvement that can be attained using a PRSEUS design approach.

7.0 CONCLUSIONS

The BWB aircraft design represents the type of step-function productivity improvement that is possible by radically reshaping the airframe to achieve first-order aerodynamic benefits rather than just accepting the indirect benefits of weight reduction. By utilising advanced materials and structures to enable a lift-generating centerbody, higher levels of payload-range performance become possible[6].

https://doi.org/10.1017/S0001924000004000 Published online by Cambridge University Press

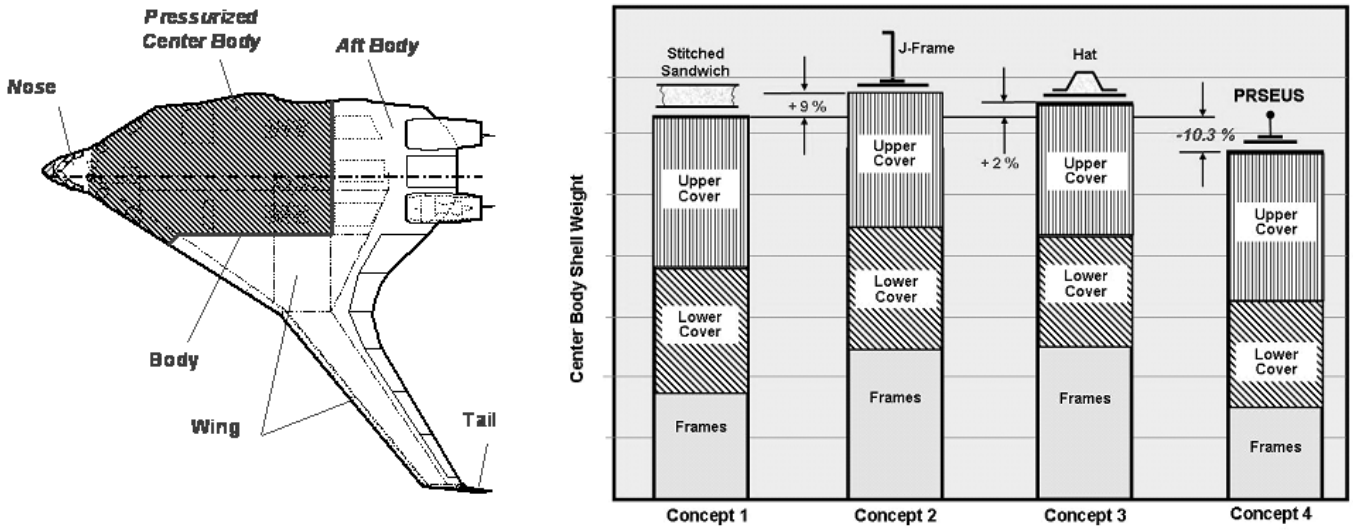


Figure 16. Centre body — normalised weight comparison.

Meeting the performance and producibility challenges of the BWB airframe forms the basis on which the PRSEUS design and manufacturing philosophy was postulated. The PRSEUS concept described in this paper is a highly engineered solution that moves beyond traditional composite design practices to offer an orthogonally-tailored skin-stringer-frame design that can be operated beyond conventional no-growth design constraints. The result is a very efficient BWB airframe structure that combines the skin, stringers, and frame elements into a highly effective structural combination for reacting the complex loading of the BWB airframe. In addition to improved structural performance, this unique embodiment of dry carbon fabric, pultruded rods, foam core, and stitching thread, also serves as an important facet in its innovative manufacturing method to address the producibility challenge. Through the creation of a self-supporting stitched preform that eliminates the need for IML tooling, a new out-of-autoclave fabrication method was developed that promises substantially lower building costs than the 20% improvement (relative to conventional built-up aluminium structures) demonstrated in the NASA AST Composite Wing Study[7], or what would otherwise be possible using traditional composite design and manufacturing practices.

The PRSEUS design approach represents a bold vision in composite design theory and manufacturing methods. It is a conscious progression away from conventional laminated and bonded assemblies toward larger one-piece cocured panel designs with seamless transitions and damage-arrest interfaces created by stitching. The result is an enhanced level of structural performance and producibility that represents the early stages of a feasible BWB airframe design. What remains however, is the systematic engineering development work needed to validate that this new approach is capable of meeting all of the unique structural aspects of the BWB airframe, such as the combined axial-plus-pressure spanwise loading across the shell, impact damage to the leading edge, and pressure-pillowing of the near-flat skins between the stringers and frames.

ACKNOWLEDGMENTS

The authors wish to extend a special thanks to the aerodynamic community, and in particular Dr Liebeck, for their/his tireless efforts in promoting the BWB airplane design and challenging the structures community to develop suitable next-generation composite design and fabrication technologies, as well as Dawn Jegley of NASA-LaRC, and Steve Clay and Dick Holzwarth of the Air Force Research Laboratory for their continued technical support of this novel structural concept.

REFERENCES

1. LIEBECK, R.H. Design of the blended wing-body subsonic transport, August 2002, 2002 Wright Brothers Lecture, AIAA Paper 2002-0002.
2. VELICKI, A. NASA TCAT Phase I Study (Novel Blended Wing Body Structural Concepts), July 2004, Contract NNL04AA36C CLIN 0001.
3. HOFFMAN, K. Air vehicle technology integration program (AVTIP), Delivery Order 0059: Multi-role Bomber Structural Analysis, AFRL-VA-WP-TR-2006-3067, May 2006, Final Report for 14 December 2004-08 May 2006, AFRL-VA-WP-TR-2006-3067.
4. VELICKI, A. and THRASH, P.J. Advanced structural concept development using stitched composites, 2008, 49th AIAA/ASME/ASCE/SHS/ASC Structures, Structural Dynamics, and Materials Conference, 7-10 April 2008, Schaumburg, IL, AIAA Paper 2008-2329.
5. VELICKI, A., THRASH, P.J., BURGESS, R.A. and STANDISH, C. US Patent Application for a Molding Process and Apparatus for Producing Unified Composite Structures, The Boeing Company, Huntington Beach, CA, Patent No 6,896,841 B2, granted 24 May 2005.
6. RENTON, J. W., OLCOTT, D., ROESELER B., BATZER, R., BARON, B. and VELICKI, A. Future of flight vehicle structures (2002-2023), *AIAA J*, 2004, **41**, (51), pp 995-998.
7. KARAL, M. AST composite wing study — executive summary, March 2001, NASA/CR-2001-210650, Prepared for NASA, Langley Research Center under Contract NAS1-20546.

https://doi.org/10.1017/S0001924000004000 Published online by Cambridge University Press