BWB MILITARY CARGO TRANSPORT FUSELAGE DESIGN AND ANALYSIS

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Abstract

A Columned Multi-Bubble Fuselage (CMBF) concept is proposed for a Blended Wing Body Ultra Heavy Lift aircraft design. Inner-cabin wall sections of Multi Bubble Fuselage were replaced with columns to provide a large and contiguous area. The configuration allows the membrane stresses of the round wing panels to be balanced with the tensile stresses in the columns. CMBF was analysed and compared with a conventional Multi Bubble Fuselage (MBF) to verify its structural performance regarding weight reduction and stiffness. Initial analysis shows that the CMBF has a significant weight advantage over conventional MBF. The paper introduces the objectives of the project and presents preliminary structural design and analysis results.

1 Introduction

Blended-Wing-Body (BWB) is an innovative aerial transport that allows higher efficiency over conventional aircrafts. However, its unique configuration faces a major technical challenge in its centre body section, where the structure must withstand stresses incurred by both cabin pressurisation and wing bending. Past research has been focused on BWB that has a number of separated cargo bays for passengers. However, the separations can be considered as obstructions for military missions, where a sufficiently wide open compartment is required for large bulk payloads. In this study, Columned Multi-Bubble Fuselage (CMBF) is proposed for the BWB Ultra Heavy Lifter. Inner-cabin separation walls were replaced with columns to provide one large and contiguous area. CMBF is analysed and compared with the conventional Multi Bubble Fuselage (MBF).

2 Fuselage Structure Development and Analysis

Unlike a conventional cylindrical pressurised fuselage, the centre structure of a BWB suffers from both internal cabin pressurisation and spanwise wing bending loads. The combined loading results in non-linear stress behaviour, whose complexity is undesirable for the design process. In addition, the resulting deflection of aerodynamic surfaces can significantly drop the performance of the BWB's otherwise advantageous aerodynamic behaviour. Therefore, efforts were made to develop a fuselage such that it consists of two separate and independent structures to resist each internal pressure and wing bending loads, minimising the aerodynamic surface disturbance. The outline of proposed fuselage is sketched in Figure 1.

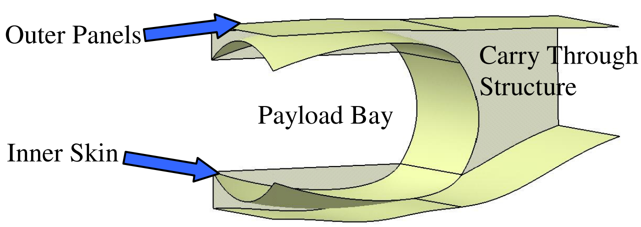

Fig. 1. Conceptual Fuselage Section of a BWB

The internal cabin pressure is resisted by the resulting membrane stress of inner skin, while the high bending load is resisted by the outer structure. The inner membrane structure is connected to the carry-through-structure such that the deformation of the pressure-bearing inner skins is permitted as long as the inner skin does not contact the outer aerodynamic panels. The space in-between the inner and outer skin panels holds an equivalent ambient pressure, thus the outer panels will not suffer from internal cabin pressurisation, and the single-membrane structure will provide sufficient stiffness and function as the conventional cylindrical pressurised fuselage. This membrane approach is also a lighter solution than an integral structure according to a Cranfield study [1].

BWB has a wide non-circular/box-type centre body section, and the accompanying mass of the fuselage structure is widely distributed spanwise, while that of a conventional tubular fuselage is heavily concentrated on its centreline. Figure 2 illustrates this difference. The distributed centre-body mass helps to relieve the wing bending stress in the centre body section, and the maximum bending moment tends to occur at the kink region not at the centre line of BWB. It also provides large cabin bay volume to accommodate various payloads that could not be accommodated in conventional aircraft.

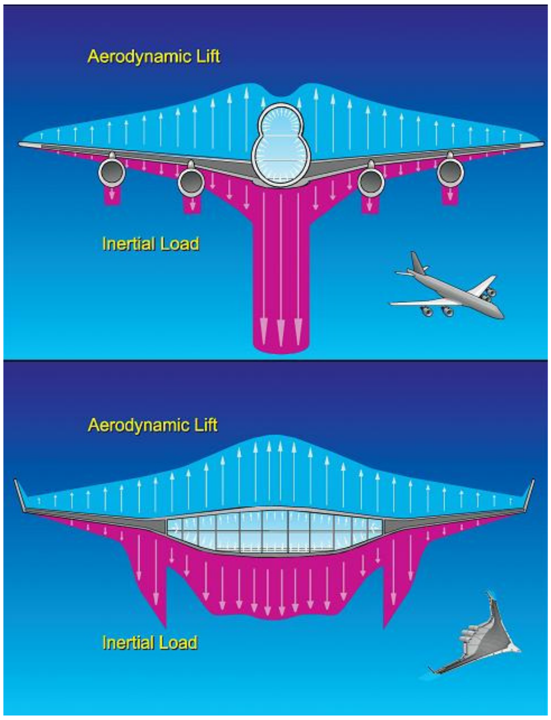

Fig. 2. Aerodynamic Lift and Inertial Load Distributions of Conventional Aircraft and BWB [11]

However, the box-type cabin area holds a major technical challenge under pressurisation. This type tends to resist the internal pressure by the bending stress of flat panels, while the circular fuselage resists it with membrane stress; so the stress level of the box-type fuselage is an order of magnitude higher. Unfortunately, the efficient circular fuselage is not applicable to flat and wide cabin area of BWB. Hence, efforts were made to design a wide pressure resisting fuselage preserving the benefits of conventional circular fuselage.

Figure 3 shows NASA's Multi Bubble Fuselage (MBF). Multiple circular fuselages are merged sharing an inner-cabin wall, which, in ideal case, balances the membrane stress of the fuselage skins with its tensile stress. This configuration preserves the advantage of membrane fuselage structure and, at the same time, fulfils the requirement to cover the wide cabin area along wing span. Figure 3 shows that the inner-cabin walls are highly loaded and indicate that they play a major structural role in the Multi-Bubble Fuselage.

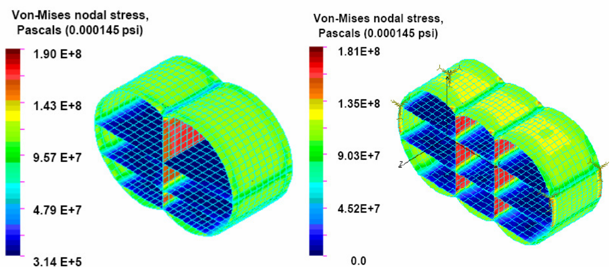

Fig. 3. Multi Bubble Fuselage (MBF); 2-Bubbles & 3-Bubbles Version [2]

MBF configuration is rather ideal for passenger jets or commercial cargo jets that have compact payloads. The inner-cabin walls are undesirable for the military cargo transport, whose Request For Proposal (RFP) states that the payload bay has to be one piece and continuous. An ultra heavy lifting military cargo transport would require being capable of lifting various payloads such as large artilleries, helicopters, tanks, small aircraft etc. MBF would not be particularly suitable for such missions.

4.1 Columned Multi-Bubble Fuselage (CMBF); Pressure Bearing Structure

As an initial design approach, efforts were made to develop an appropriate inner membrane panel structure which resists the major internal cabin pressurisation. Since the MBF preserves the benefits of cylindrical fuselage (a membrane configuration), initial attempt was to modify the efficient MBF to fulfil the requirement of the one and continuous cabin bay. The tensile structure, inner-cabin walls, were removed and replaced with a series of columns and the chordwise ends of the top and bottom membrane panels were modified to have arch structures between each adjacent column. The arch structure relieves the chordwise bending stress and bears the pressure load rather with membrane stress, thus in ideal case, the concentrated stress of the arches and membrane panels at the joint is balanced with the tensile stress of each adjacent columns. Figure 4 illustrates the general configuration of the modified MBF. The top/bottom membrane panels got a circular curvature chordwise as well as spanwise; it has a multi-sphere like configuration. The sphere-like sections of fuselage relieve the chordwise bending stresses by a significant amount. This can be re-applied into a BWB passenger jets as shown in bottom model of the Figure 4. In general, the stress level in a pressurised sphere-vessel is an order of magnitude lower than that of cylinders, however, in this configuration, there were no full-sphere utilised, thus the maximum structural benefits could not be expected.

To minimise the mission interruptions inside the payload bay, the number of rows of columns were minimised to one; such that a single row of columns resist the pressure load in the middle of 2-Bubbled CMBF. Initially, CMBF were comparative-analysed against MBF for its pressure resisting performance and bending load stability. Finite element models of both fuselage configurations were constructed with simple shell elements around a section of the required volume and ran on a finite element solver. Under the load case 1, when exposed only under the pressure load of 18.6 *psi*, CMBF indicated 50% less von Mises stress level than MBF, confirming its improved pressure resistance. However, on the second load case where equivalent compressive and tensile load were applied to the models to simulate the wing bending load, the CMBF showed unstable structural behaviours, once again confirming the separate membrane approach.

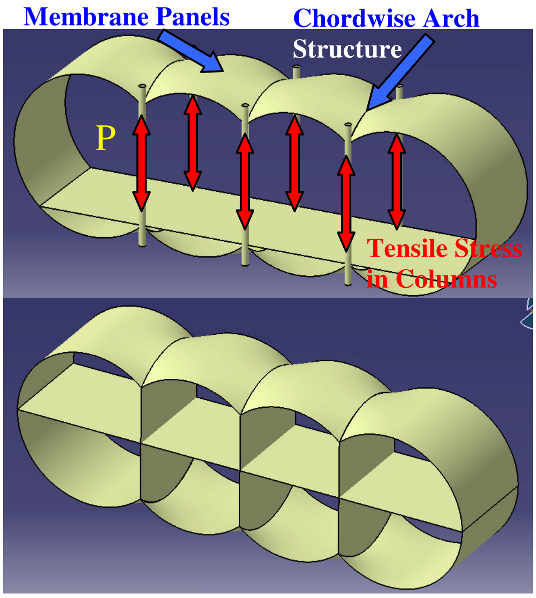

Fig. 4. Columned Multi Bubble Fuselage (CMBF) under Pressure (P) & Its Application for Passenger BWB (Below); 4-Bubbles Versions

In the conceptual development phase of the CMBF, two different design constraints were considered. The first one was the maximum allowable stress of a material used, and the second constraint was the maximum deformation of 4 *in* [5]. The first constraint allows the deflection of the CMBF as long as it does not contact the outer structures, while the second constraint was based on the case of an integral structure without membrane approach, so the deformation of the inner panels directly disturbs the outer aerodynamic surface. The understanding is that the deformation of more than 4 *in* can drop the aerodynamic performance significantly. The impact of the design constraints on the sectional weight was studied along with the outer radii of the CMBF curvature.

Figure 5 summarises the results of the analysis. The graph indicates that approximately 20% of the weight reduction has been achieved using the first constraint, the maximum allowable stress, rather than using the second option. The membrane structure reaches the allowable deformation of 4 *in* far before the material reaches its maximum allowable stress. The maximum deformation at the point where the structure reached the maximum allowable stress was 9.45 *in*. The CMBF design and analysis is in its conceptual development phase and does not involve any stiffening elements yet, so the deformation value can be unrealistically large, however this kind of comparative analysis can be reliable in the early design stage.

Due to the fixed chord thickness of outer aero-surface and internal cabin volume, the amount of panel curvature of the inner membrane is fairly limited. Within the range, the radii of the outboard curvature have been varied along two constraints as shown in Figure 5 and been optimised for the best weight reduction. Top features of Figure 5 illustrate the finalised CMBF and its moderate distribution of von Mises stress. The equivalent flat plate thickness equals to 2.2 *in*, but again, with appropriate stiffening elements, the panel thickness can be reduced to a manufacturable level.

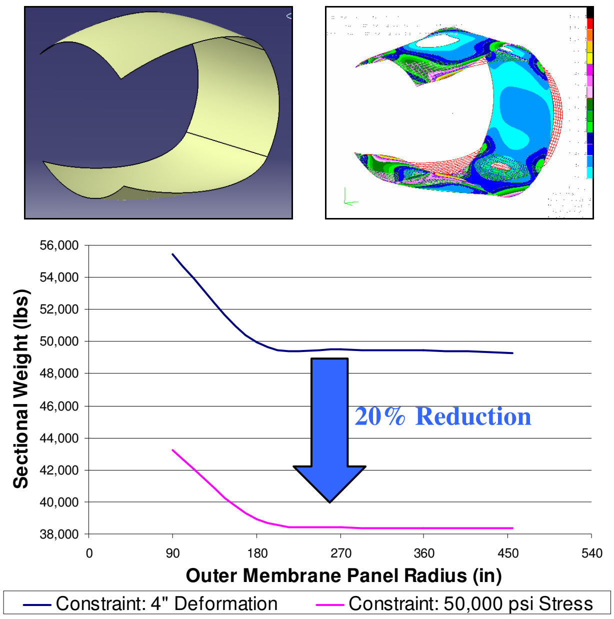

Fig. 5. Shape Optimised double-Bubbled CMBF

4.2 Carry Through Structures (CTS); Bending Load Bearing Structure

Conventional military cargo transports, such as A400M or C-17 Globemsater, have a high wing configuration which has no structural interruption issues inside the payload bay and it provides a low cargo bay floor for easy loading and unloading on the ground for a fast deployment of troops and payloads. In addition, the so-called ‘wing centre box’ structure bears the maximum wing bending load and transfer the wing loads into fuselage. However, the BWB has a fuselage compartment embedded inside the blended wing, thus the BWB can be considered to have a mid-wing configuration. Where the BWB military cargo transport cannot afford any further structural interruptions in the CMBF, carry through structures to transfer the wing bending loads around the CMBF were investigated. Figure 6 shows the carry through structures of a fighter jet and the BWB J-UCAS X-45; the load bearing spars and accompanying frames are shown. This kind of structure is ideal to apply around CMBF, where multi-spar configurations distribute the loads into several paths and support the bending load with better stability. The multi-spar structure generally suffers from weight penalties; however it is an inevitable issue to provide an uninterrupted cabin bay.

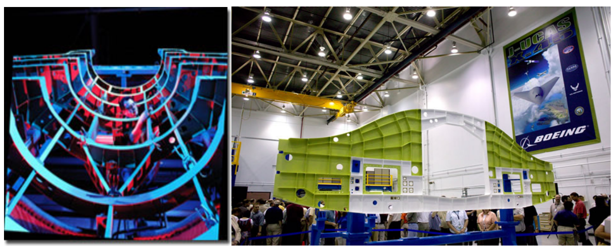

Fig. 6. Carry Through Structure (CTS) of a Fighter Jet & BWB J-UCAS Boeing X-45

Figure 7 illustrates the initial structural outlines of the centre body section of the BWB military cargo transport. It is designed to transmit the structural loads into five main spars and to not interrupt the CMBF, each main spars diverges into upper and lower spars around the membrane structures. The equally spaced internal columns function as internal wing ribs as the columns are attached to the upper and lower spars providing torsion and bending resistance as well as balancing the membrane stresses from internal cabin pressure loads. A BWB passenger jet has an advantage of placing internal wing ribs inside the cabin area to efficiently resist the structural loads, whereas the requirements of the military cargo specify an unrestricted cargo area; ribless cabin structure. Thus, the ribs outside the cargo bay must be as close to the bay as possible and substantially thicker than conventional configurations. In addition, the spars and ribs of the centre body are very deep, being more than 200 *in* at its maximum. Therefore the spar and frame webs are considered to be truss structures. The buckling characteristics of the truss elements can be another design task of this project.

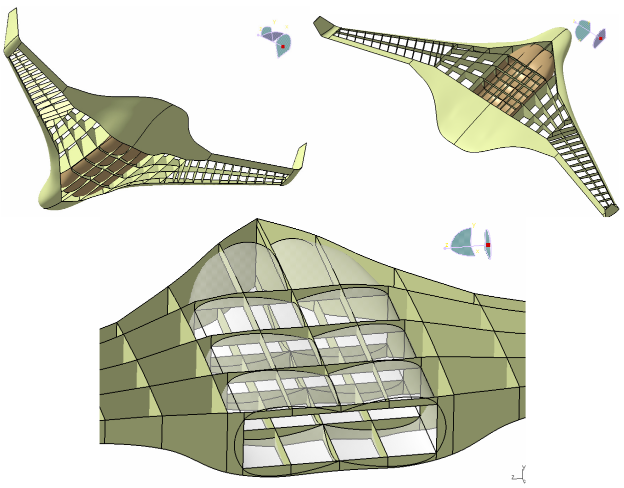

Fig. 7. General Outlines of the Centre Body Structures

4.2.1 Topology Optimisation

As a design effort for the truss structure of the spanwise carry through structure, the spanwise frame around the CMBF was topology optimised. Figure 8 shows the 3D topology model and the design suggested by the optimisation. The outer boundary surfaces were modelled with 2D shell elements as non-designable domain, whereas the inner 3D-tetrahedral elements were modelled as designable domain. As an initial approach, the model was optimised under the wing bending load only to minimise the frame volume in order to eventually achieve the maximum weight reduction. The 4 *in* maximum deformation of top/bottom aero-surfaces were the design constraints and buckling analysis were yet to be considered.

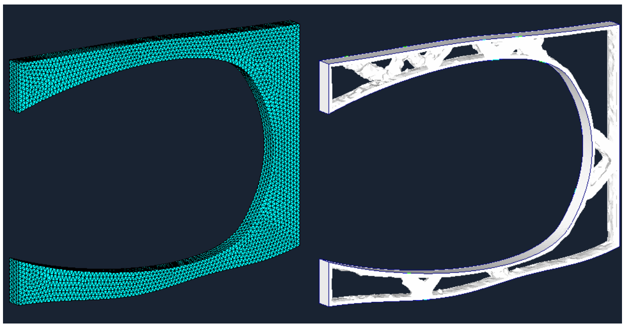

Fig. 8. Topology Model and Topology Optimisation

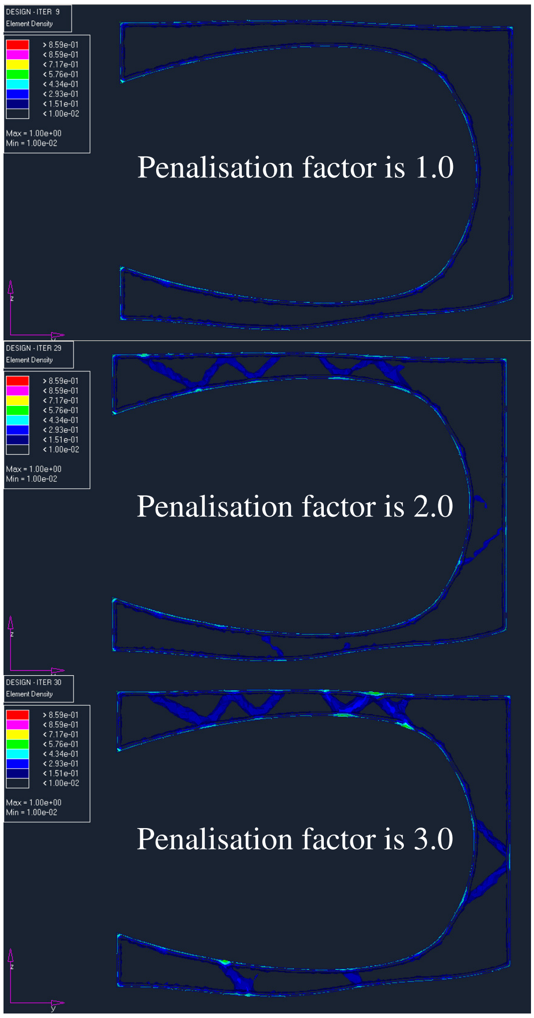

Fig. 9. Topology Optimisation Results with varying Penalisation Factors.

The topology optimisation process involved a large grey area of intermediate densities in the designable domain, hence a penalisation method was adopted to remove the intermediate densities and to force the design to be represented by densities of either 0 or 1. Figure 9 indicates the suggested final design from the topology optimisation with 3 different steps of penalisation factor. It can be clearly seen that as the penalisation factor increases, the density being used to resist the bending load becomes clearer; void and solid.

Figure 10 shows the final topologically optimised design of the spanwise frame. A significant weight reduction is achieved through this optimisation process and the general outlook of the truss structure is suggested by the optimiser. Since in this loading condition, only a wing bending load has been considered, further optimisation process would be conducted to assess other critical load cases.

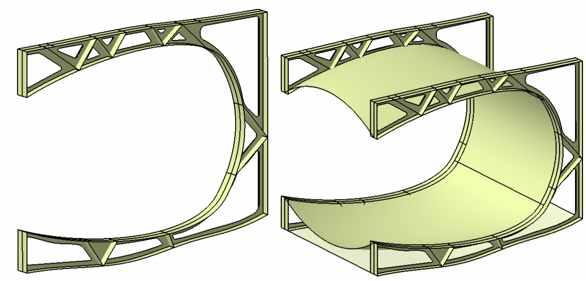

Fig. 10. Topology Optimised Spanwise Frame

5 Conclusion

The conceptual design of a BWB military cargo transport fuselage, and its efficient structural configurations were presented. (See Figure 11) Under pressure loads, a CMBF was more efficient than a conventional MBF for the extensive wide-flat cabin area of the BWB, but it was not suitable for resisting bending loads as much larger deformation was indicated. Thus, two separated independent pressurised cabin sections and wing structures were adopted, and a pressure resisting inner shell was optimised for a double-bubble fuselage. The CMBF demonstrated significant improvement on sectional weight over a blended MBF configuration, but further studies are necessary for acceptable optimisation.

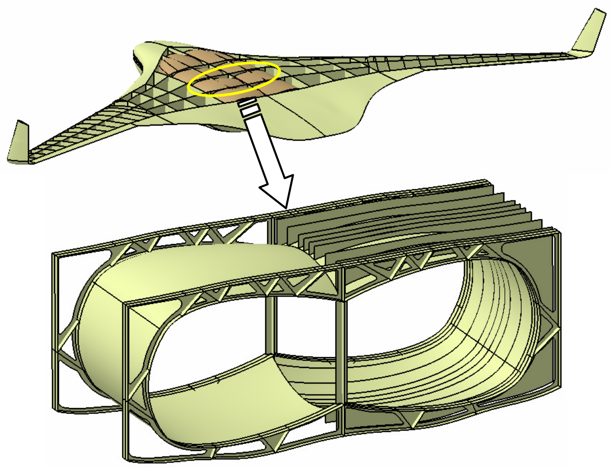

Fig. 11. Cutaway View of the BWB Military Cargo Transport Centre Body Structure

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