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BLENDED WING BODYAIRCRAFT

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Abstract: In recent years there has emerged a significant increase of interest in the design of Blended Wing Body (BWB) aircraft, specifically applied to a large commercial transport aircraft. The BWB design has been proven to have significant improvements in aerodynamic efficiency, as compared to the conventional wing fuselage design. However, due to inability to counteract significant pitching moments, there is difficulty in the design of high lift devices for BWB, especially trailing edge devices. Due to large wing area increased lift-to-drag ratio, it was found that, in terms of longitudinal stability, high lift devices could be successfully applied to the aircraft, which would meet the take-off and landing requirements for a field length comparable to those of current conventional large transport aircraft.

1. Introduction

Begin with the reference to Wright Brother's flyer aircraft, design and flown in 1903, much-advanced research was done to improve the design and performance of an aircraft. Some of them include swept-wing Boeing B-47, who took flight in 1947. A comparison of these two plane shows a remarkable achievement within the period of four decades. Fig.1 shows the evolution of the design of the plane within the period of nine decades.

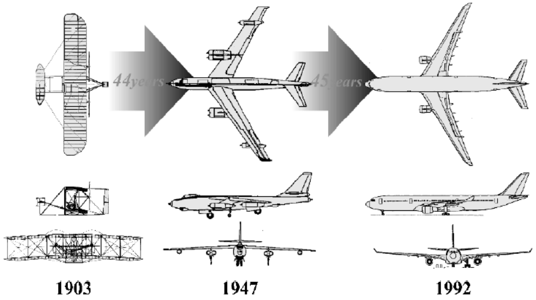


Fig.1: Aircraft design evolution, the first and second 44 years. [1]

In 1988, a brief preliminary design study was conducted by NASA at McDonnell Douglas to create and evaluate alternate design configuration to improve the efficiency [1]. Fig.2 shows a preliminary configuration which is lateral extension of double-concept in which, the pressurized passenger compartment consisted of adjacent parallel tubes. Comparison of blended design with the conventional airplane sized for the same design mission shows that the blended configuration has lower fuel burn and high lift to drag ratio.

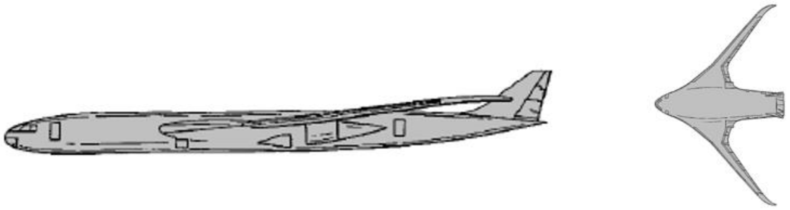


Fig.2: Early blended configuration concept. [1]

The intention of the paper to study the concept and performance characteristic of BWB configuration.

2. BWB Aircraft

Blended Wing Body (BWB) aircraft have a flattened and aerofoil shaped body which form a single entity by merging fuselage with wing and tail [fig.3]. BWB is a hybrid of flying-wing aircraft and the conventional aircraft where the body is designed to have a shape of an aerofoil and carefully streamlined with the wing to have a desired plan-form. In the conventional aircraft, the wing is generating the major part of the lift, whereas in BSW in addition to the wing, the fuselage is also contributing in the generation of lift, thus increasing the lifting surface area. The streamlined shape between fuselage and wing intersections reduces interference drag, reduces the wetted surface area that reduces friction drag. Since there is a slow evolution of fuselage-to-wing thickness which creates the wing root area comparatively thick which can be used for payload and fuel capacity.

Fig.3: A Blended Wing Body Aircraft [2]

The BWB concept aims at combining the advantages of a flying wing with the loading capabilities of a conventional airliner by creating a wide body in the center of the wing to allow space for passengers and cargo. Especially, for very large transport aircraft, the BWB concept is often claimed to be superior compared to conventional configurations in terms of higher lift-to-drag ratio and consequently less fuel consumption.

3. Evolution of BWB concept

NASA Langley Research Centre started a small study to develop and compare a subsonic transport aircraft with advanced technology capable for design mission of 800 passengers with flying Mach number of 0.85 and have 7000 n mile (12964 km) range. Advanced technology turbofan engines are used for propulsion and composites materials are used for structure [1].

For initial consideration three canonical form with enough surface area to hold 800 passengers is chosen. However, sphere required the minimum surface area but it cannot be taken into consideration due to nonstreamlined. Conventional cylinder and disk are a streamlined body and

both of them have nearly equivalent surface area. Now for generation of lift, each of fuselage is placed on a wing that has a total surface area of 15,000ft^2 [fig.4].
By effective installing the wing with disk fuselage, the total aerodynamic wetted area is reduced by 7000ft^2 in comparison to cylindrical fuselage plus wing configuration [fig.5].

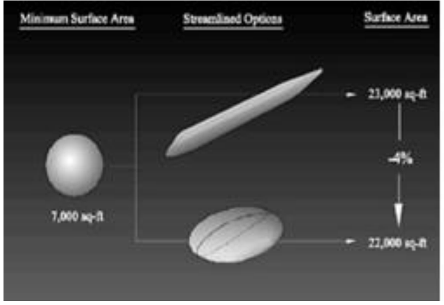


Fig.4: Effect of body type on surface area [1]

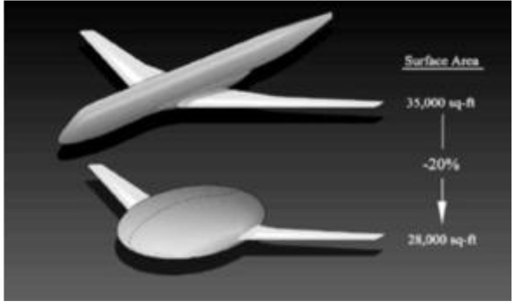


Fig.5: Effect of wing/body type on surface area [1]

By adding engine there is a difference in the total wetted area of 10,200ft^2 [fig.6]. Finally adding the control surface required for to safe flight to each of configuration, there is total wetted area difference of 14,300ft^2 or a reduction of surface area by 33% [fig.7]. As the cruise lift-to-drag ratio is a function of wetted area aspect ratio, b^2/S_{wet} , there is a substantial improvement in aerodynamic efficiency of BWB configuration.

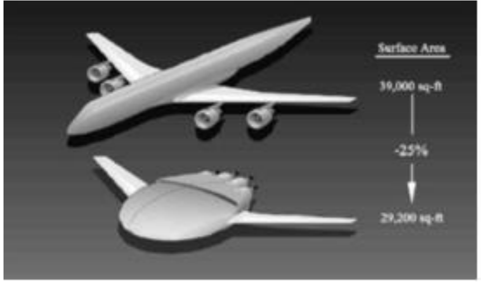


Fig.6: Effect of engine installation on surface area [1]

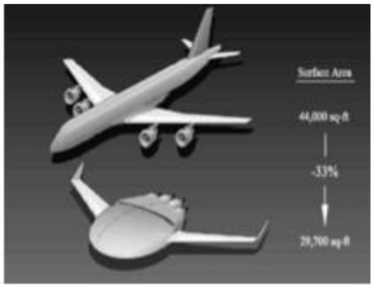


Fig.7: Effect of controls integration on surface [1]

The fuselage of BWB configuration is also using as a wing, engine inlet, and control surface for monitoring the pitching moment. Verticals act as control surface by providing the directional stability and also acts as winglets to reduce induce drag and increase the effective aspect ratio.

4. Comparison Between Conventional Plane & BWB Aircraft

Centre body of BWB structure is used as passenger cabin as well as wing also, so it must carry the pressure load bending as well as wing bending load. A comparison made between aerodynamic and inertial loads acting on BWB with that of a conventional configuration is given in fig.8 [1].

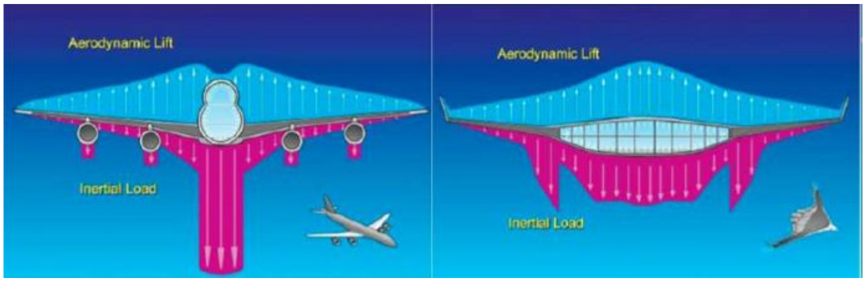


Fig.8: Comparison of aerodynamic and inertial load [1]

In conventional aircraft, the wing is only the main contributor for generation of lift whereas in BWB aircraft fuselage generate lift together with the wing [fig.9].

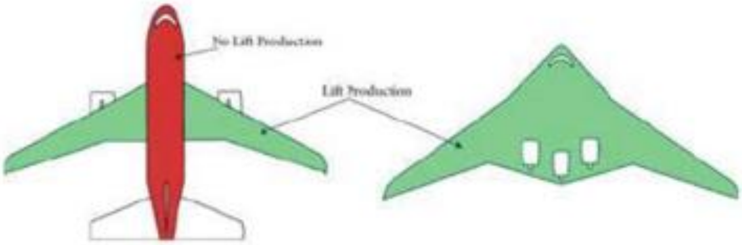


Fig.9: Comparison of lifting surface area [1]

5. Features Of BWB Design

Since the initial design of the BWB wing in 1988, it has been refined to its current state. The principal concept behind the current iteration of the BWB is the blending of single lifting surface. As a result, the BWB fuselage is harder to distinguish from the wing (i.e. it is harder to tell where the wing ends and the fuselage begins).

There are some key concepts to note about the design of the BWB:

a) The BWB is a tailless aircraft:

Because of the disc-shaped nature of the fuselage, the BWB does not have a tail. As a result, the BWB does not have a rudder.

b) The engine location of the BWB:

Engines of BWB aircraft are located at the aft sections of the plane. Because of the weight and balance considerations of the plane, the engines needed to be placed at the rear of the plane. Additionally, with the engines at the rear of the plane, the fuselage can serve as an inlet for intake of air.

c) Control surfaces:

The control surfaces of the wing are located along the leading and trailing edges of the wing and on the winglets. The number of control surfaces can vary from 14 to 20 depending on the BWB design.

d) The BWB is a windowless aircraft.

6. Baseline BWB model and an assessment of its aerodynamics

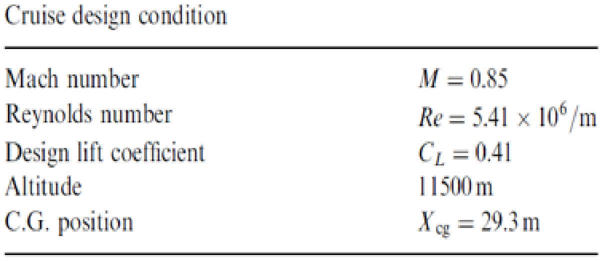
In the late 1990s, through a series of papers, Liebeck et al presented work on the design studies of blended wing body aircraft which can be the potential candidate for large subsonic transport design in future. The project involves NASA, Boeing and universities in The United States

(South California, Stanford, Florida and Clark Atlanta). For the 800 passengers and Mach 0.85 cruise design condition, the configuration evolves from 85m span with a trapezoidal aspect ratio of 10 to 106m span with a trapezoidal aspect ratio of 12 [5].

In this report, the half model geometry of BWB Baseline configuration is considered which is composed of central body, an inner wing and outer wing with attached winglets. All the parts are blended to form the BWB geometry. The total span is approximately of 80m including winglets. For the present study of BWB design, the propulsion system is not included, although its importance is fully appreciated.

The design cruise conditions are considered in table1. Hence to balance the weight of aircraft by considering the trapezoidal reference area of 842m2, the design CL is 0.41. All the aerodynamic coefficient provided in this report are based on this trapezoidal reference area.

Isometric view of CAD model generated by using the aerodynamic surface provided by Delft University [2] (fig10).



Cruise design condition

Mach number	$M = 0.85$
Reynolds number	$Re = 5.41 \times 10^6/\mathrm{m}$
Design lift coefficient	$C_L = 0.41$
Altitude	11500 m
C.G. position	$X_{cg} = 29.3\,\mathrm{m}$

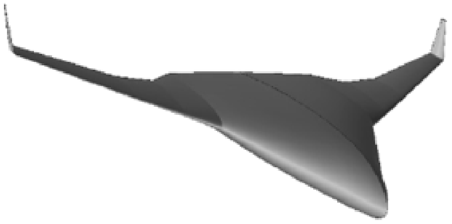


Table.1: BWB cruise design condition [5] **Fig.10: BWB baseline configuration: plan-form [5]**

The model is consist of two lifting bodies, which are blended to configure the BWB geometry [fig11]:

- A thick streamlined body, to accommodate the payload, from 0 to 13m span.
- A pair of inner wings, which carry the fuel tanks, from 13 to 23.5m span.
- An outer wing, to which winglets is attached, from 23.5 to 38.75m.

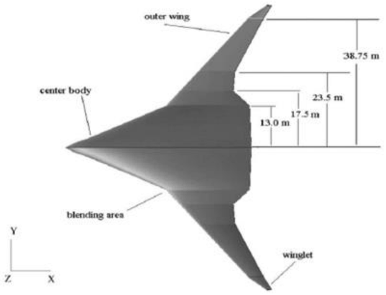


Fig.11: BWB baseline configuration: plan-form [5]

To make the aircraft compatible with existing airport runways, the span of the aircraft is limited to just under 80m. Swap back angle of leading edge is 63.8^0 from the centre body and 38^0 from the outer wing. The aspect ratio of aircraft is maintained to 4.26. For the pitching moment coefficient and the lift per unit of span definition, the mean chord (C_{ref} = 12.3m) is taken as reference and for the aerodynamic coefficient definition, trapezoidal wing area ($842m^2$) is taken as reference. The length of centre chord is 50.8m and wetted area (S_{wet}) is $3079m^2$. The Aspect ratio of reference trapezoidal including the wing is 7.6 [5].

Fig.12 shows the variation of the thickness of aerofoils for centre body at span-wise location y=0 and 13m, respectively. The centre section has a maximum thickness of 0.09 at (x/c) =0.03 and front positive camber of $(z/c)_{max} =$ 0.01 at x/c = 0.21. At 60% of chord camber is reflexed and have $(z/c)_{min}$ = -0.004 at x/c= 0.81. At cruise condition, the reflexed camber design is essential to provide the longitudinal stability [5].

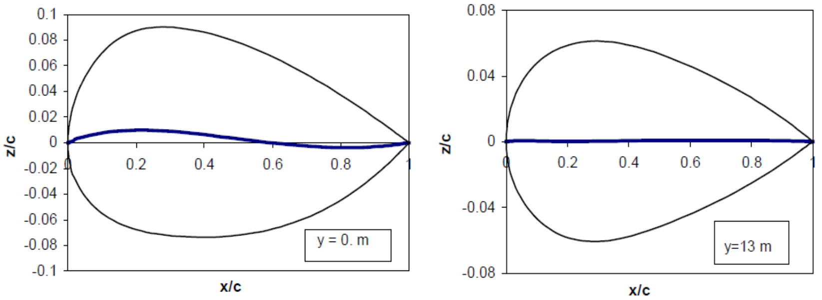


Fig.12: BWB baseline: centre body root and tip section profile. [5]

Moving span-wise from centre section to wing section, both leading edge positive camber and trailing edge reflected camber approaches to aero at y = 10m. At y =10m profile becomes almost symmetrical and remains same to the outer section of centre body (y =13m).

Fig.13 shows the variation of the thickness of aerofoils for an inner and outer wing at span-wise location y=17.5 and 23.5m, respectively. Thickness distribution shows that both the wing sections are composed of aerofoils with aft camber design to improve the performance during transonic region (supercritical).

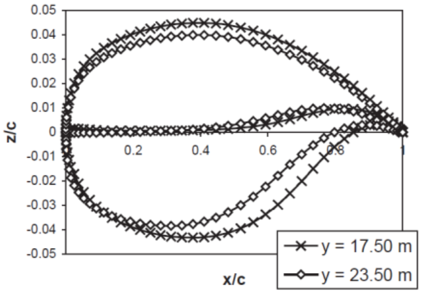
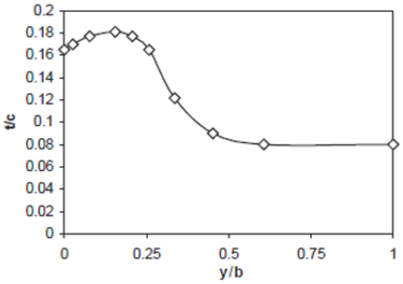


Fig.13: BWB baseline: inner and outer wing section profiles. [5]

Fig.14 shows the variation of span-wise thickness to chord ratio. Thickness distribution shows that centre body has an average thickness of 17% with the maximum thickness of 18% at about 6m span.

Fig.15 shows the twist distribution of the aircraft along the span where upward pitching about the leading edge is considered as positive. Twist distribution shows that as compared to inner wing, the centre body and outer wing are twisted downwards.



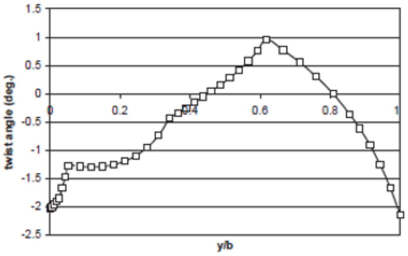


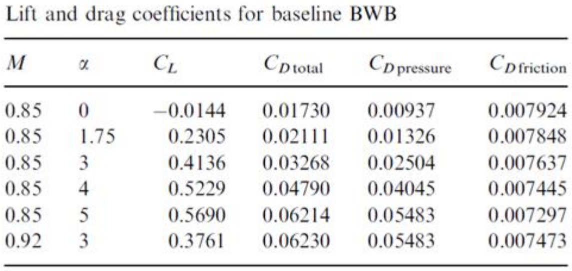
Fig.14:BWB baseline: span-wise thickness distribution.[5] **Fig.15: BWB baseline: twist distribution.[5]**

I. Assessment of aerodynamic performance

To plot the drag polar [fig.16] for baseline BWB configuration, a series of computations at different incidences for M=0.85 were carried out. The different initial condition and corresponding aerodynamic coefficient are presented in Table 2. In order to observe the behaviour of aircraft at a speed nearer to speed of sound (off-design condition) computation at M=0.92 is also performed.

The result shows that for M=0.85 and at an incidence of 3^0, the total drag is composed of 23% skin friction drag and 77% pressure drag. With the increase of incidence, the rate of lift increase reduces while the rate of pressure drag increase goes up.

Fig.17 shows the distribution of the span-wise local lift coefficient for the various lift coefficient. The Distribution shows that outer wing, where chord length is much shorter as compared to centre body and inner wing, is very highly loaded. At design condition, i.e. 3^0, the local lift peaks at about 80% of span. As compared to the outer wing, the local lift for centre body is much lower.



Lift and drag coefficients for baseline BWB

M	α	C_L	$C_{D\,\mathrm{total}}$	$C_{D\,\mathrm{pressure}}$	$C_{D\,\mathrm{friction}}$
0.85	0	−0.0144	0.01730	0.00937	0.007924
0.85	1.75	0.2305	0.02111	0.01326	0.007848
0.85	3	0.4136	0.03268	0.02504	0.007637
0.85	4	0.5229	0.04790	0.04045	0.007445
0.85	5	0.5690	0.06214	0.05483	0.007297
0.92	3	0.3761	0.06230	0.05483	0.007473

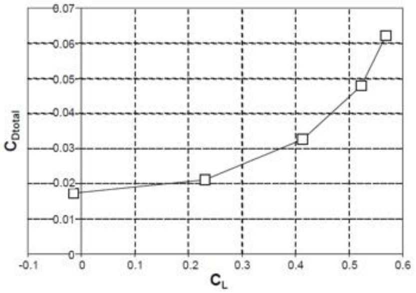
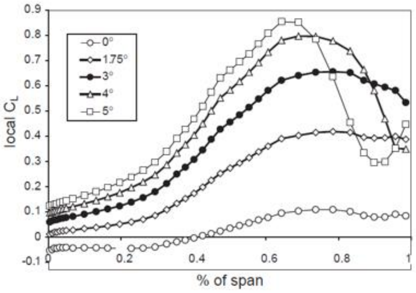


Table.2:Lift and drag coefficients for baseline BWB.[5] **Fig.16:Lift-drag polar for baseline geometry M=0.85.[5]**

At α= 1.75, shock starts to appear on the upper surface of the outer wing. As the incidence increase, this shock gets stronger. At incidence higher than 3^0, the outer portion of wing stalls as this portion of the wing can no longer sustain the high lift [fig.17].



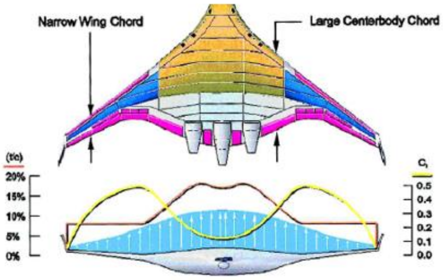


Fig.17:Span-wise local lift for baseline geometry.[5] **Fig.18:Section lift coefficient & t/c ratio variation with span.[1]**

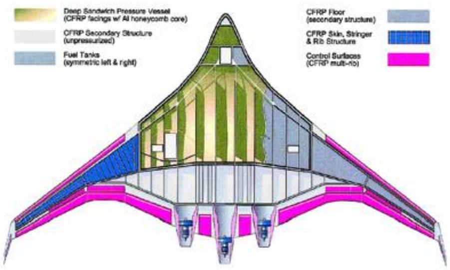
To maintain an elliptical span-load, the centre body, with its very large chord, requires lower lift coefficient which allows the very thick aerofoil for the passenger compartment and trailing edge reflex for pitch trim [fig.18].

II. Propulsion

Installing the engine on aft location for BWB design offers the opportunity for ingestion of boundary layer generated on centre body which is forward of engine inlets. In principle, ram drag is reduced by boundary-layer-ingestion & thus improving the propulsive efficiency. Other advantages of aft engine location include foreign object damage, noise, reverse thrust, emergency egress, ditching, and maintainability.

III. Structure

Centre body of BWB structure is a unique element. As functioning as passenger cabin, it has to carry pressure load in bending, and as it is also acting as lifting body (wing), it must carry the wing bending load. The primary challenge was to develop a structural concept for centre body which can carry the cabin pressure load. The passenger cabin of BWB configuration has to experience its design pressure load on every flight unlike the passenger cabin of conventional aircraft which rarely experiences its design load. Thus considering the fatigue failure as a critical case for passenger cabin, centre body should be built using composite materials due to their comparative immunity to fatigue [fig.19].



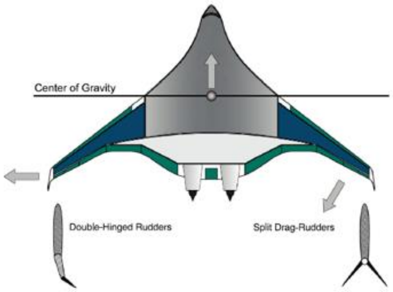


Fig.19: Structural layout of baseline BWB. [1] **Fig.20: Yaw control. [4]**

IV. Stability & Control

The trailing edge control surfaces, which are hinged on the outer wing, functions as elevons. The elevons which are on the outer surface of the wing are primarily pitch and roll control due to largest lever arm about the centre of gravity.

The rudders which is installed on the winglets provide primary directional stability and control. For the engine out condition at low speed, the outboard elevons become split drag rudders [fig.20]. Both rudders would be deflected to opposite sides to cancel out each other's yaw moments and their drag will act as an air brake.

V. Safety and Environmental

Since the pressure vessel of BWB designed to carry both the pressure and wing bending load, the pressure vessel is robust and no impact occurs on the pressure vessel at the time of uncontained engine failure.

As the slotted flap trailing-edge high-lift system is absent, there is a reduction in airframe noise. As fuel requirement for BWB configuration is less, so engine emissions are also reduced.

7. Second Generation BWB

In 1994, to demonstrate the technical and commercial feasibility of BWB concept, NASA/industry/university team was formed. McDonnell Douglas was the Program Manager, and team members include NASA John H. Glenn Research Centre al Lewis Field, NASA Langley Research Centre, the University of Southern California, Stanford University, and Clark-Atlanta University. Design mission of 7000-n mile and 800 passenger capacity was retained.

The study involved the refined sizing of the baseline BWB configuration, where minimum take-off gross weight (TOGW) was the figure of merit. Primary constraint includes a cruise Mach number of 0.85, 11,000ft take-off field length, $C_{L\ max}$ of 1.7 and approach speed of 150-kn. To obtain the minimum TOGW, a variation of Initial cruise altitude (ICA) was allowed, but the requirement that least ICA should be 35,000ft. This yielded a trapezoidal wing of AR of 10, with the corresponding area of 7840ft^2 and span of 280ft. The resulting trapezoidal wing loading was of 100lb/ft^2, which is than that of modern subsonic transport aircraft (150lb/ft^2). An explanation of above statement was that considerable portion of the trapezoidal wing is in effect hidden by centre body, and thus the effect of trapezoidal wing area on drag of an airplane is reduced. This allowed the optimization of airplane with a larger trapezoidal area to increase span with a low cost of weight. Fig. 21 shows the front and isometric view of BWB configuration.

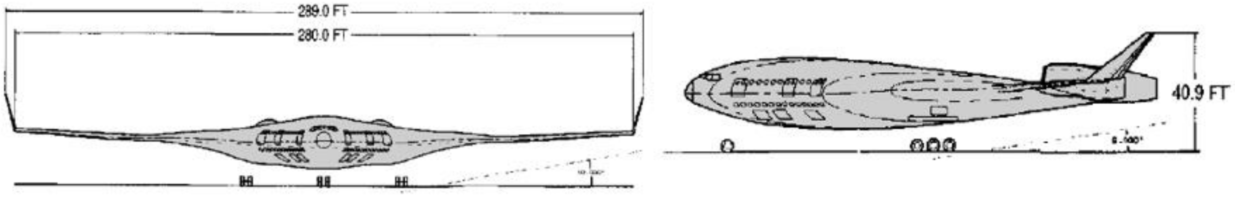


Fig.21: Second Generation BWB. [3]

8. Flight Demonstrator

At Stanford University under NASA sponsorship, a 6 % scale flight control testbed was built to explore the low- speed flight mechanics of BWB configuration [fig.22]. The weight of the airplane is 120lb, a wingspan of 17ft and called as BWB-17. Two 35cm^3 two-stroke engines with propellers are used to power the airplane. To match the flight characteristic of full-scale BWB, the model was dynamically scaled. The Flight test was recorded by an on-board computer which also provides the stability augmentation to the airplane. On 29 July 1997, at El Mirage Dry Lake in California, the first flight of BWB-17 took place. Within the normal flight envelope, the airplane had excellent handling qualities.

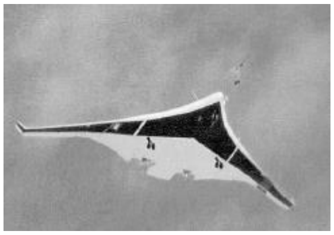


Fig.22: Flight control testbed built by Stanford University. [3]

9. Flight Unique Opportunities and Challenges for BWB Configuration

The motivation behind the concept of the original BWB configuration was to search an airplane that may offer improved efficiency with ease of manufacturing as compared to a conventional wing. Specific fuel consumption and take-off weight were the primary figures of merit, and the BWB configuration has shown a considerable amount of reduction in both the performance parameter. However, the BWB configuration also offers some other unique opportunities which were not envisioned nor planned during its original creation in 1993. Some of these are described below:

I. Manufacturing Parts Count

The BWB design consists of a large wing with an integrated fuselage and no empennage, save the winglets. There are no complex joints of highly loaded structure, wing-fuselage, and fuselage-empennage joint, at 90^0 to one other, and there are no fillets. There are no spoilers and there is no track motion of control surface as they are hinged at trailing edge. This reduces the number of parts as compared to a conventional configuration.

II. Passenger Acceptance, Ride Quality, and Emergency Egress

As the interior configuration of BWB design is unique in itself, it offers both opportunities as well as challenges. Similar to a railroad car, vertical walls of passenger cabins offer a more spacious compartment as compared to curved walls of a conventional airplane. At the same time, passenger capacity of each cabin of BWB configuration is lower when compared with wide-body conventional transports. There is a window for each main cabin door, but there is no provision of the window for cabin walls. As a replacement of a window, the array of digital video cameras are connected to flat screen display to make every seat a window set. Fig.23 shows some example of interior renderings.

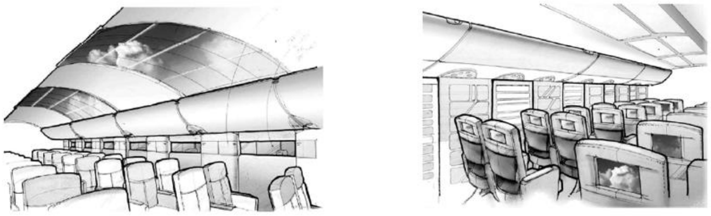


Fig.23: Interior concepts for the BWB. [3]

When passenger capacity exceeds 400, emergency egress becomes a significant challenge as a consequence of the square-cube law. As per square-cube law, passenger capacity varies with the cube of length scale, whereas surface area required for egress varies with the square of length scale. To resolve this problem, there is a main door provided in front of each aisle, and an emergency exit at the back of each aisle through the aft pressure bulkhead [fig.24].

Thus, from any position in a cabin, a passenger will have a direct view of at least one exit. Unlike in conventional aircraft to reach a door from the aisle a 90-deg turn is required.

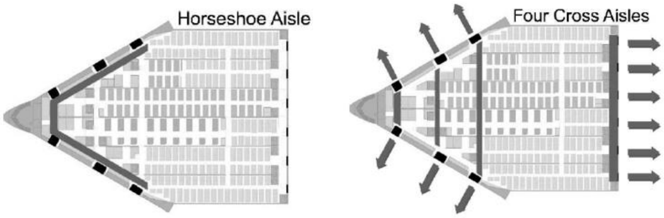


Fig.24: Cabin egress flow patterns. [1]

10. Conclusion

Combining wing and fuselage in BWB configuration is an innovative idea which increases the efficiency of aircraft as compared to the conventional wing. However, BWB design needs creative and continuous revision so that it will be used as commercial transport in the future generation. In this report, the aerodynamic performance of BWB configuration is studied in order to improve the conceptual design. Investigation of aerodynamic performance includes a variation of lift, drag, and pitching moment coefficients. Pressure distribution, longitudinal stability, controllability and drag polar diagram is also studied. In summary, geometry and plan-form of baseline BWB configuration and the conventional airplane is compared, and the BWB configuration is proposed as more efficient as compared to the conventional airplane.

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