Influence of Fuselage Bulkhead Stiffness on Composite Wing Weight of a Civil Aircraft

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Abstract

Weight estimation of aircraft components is extremely important in the initial phase of aircraft design process as it will be a crucial input to estimate aircraft performance parameters. Generally, the sizing of aircraft components has to be performed individually by simulating the stiffness of the adjoining structure. Thus a conceptual design of how the components are integrated is of paramount importance. In the case of wing design, having done a conceptual design of integration of wing to fuselage, for weight estimation of the wing structure, it is appropriate to include the fuselage bulkheads in the wing model to simulate close to real boundary conditions though not actual. However, it is important to provide proper stiffness to the bulkheads as it will have a major impact on the outcome of the results. Hence numerical optimization studies are carried out on the composite wing structure of a civil aircraft along with the fuselage bulkheads of varied stiffness using NASTRAN solver. The optimization problem is formulated with minimum mass as the objective with strength and buckling constraints. The stiffness of the bulkhead is varied by varying the thickness with a constant cross section. Only the inter-spar box of the wing is considered for the study as it is the main load carrying portion of the wing. It is observed that the bulkhead stiffness plays a major role on the final results.

1.0 INTRODUCTION

Accurate weight estimation of aircraft structure in the initial phases of aircraft design process is required for aircraft performance parameter evaluation. This requirement basically demands accurate and quick methods of weight estimation of the aircraft structure under consideration rather than forecasting the weight with respect to other existing aircraft of similar category which are error prone due to lack of sufficient data. FEM Optimization can be considered as an effective tool in achieving this objective, provided a design is available for the structure and also its integration scheme to the adjoining structure which basically helps in simulating appropriate boundary conditions. For the wing structure of a civil aircraft, the integration scheme to fuselage is crucial in simulating proper boundary conditions. Therefore in the present work, a brief description of integration of wing to fuselage is presented there by explaining how the boundary conditions are chosen for the optimization problem formulation. The influence of fuselage bulkhead stiffness on the wing weight is discussed thereon. NATRAN is used as the solver for the parametric studies. Only the inter-spar box of the wing is considered for the study, as it is the main load carrying section of the wing.

2.0 WING/FUSELAGE INTEGRATION SCHEME

The typical wing/fuselage integration scheme in a transport aircraft is as shown in Figure 1. In most of the civil aircraft, the wing structure is basically made of three segments viz. one center segment called the Center Wing Box (CWB) and two outboard segments, an LH and a RH wing. The CWB is integrated to the fuselage through two bulkheads connecting to front spar and rear spar webs. The outboard wings are then connected to CWB through cruciforms and triforms as shown in Figure 1. The bending moment of the outboard wings is basically carried through the constant bending moment segment CWB. Only the shear load is transferred through the front and rear spars to the fuselage bulkheads.

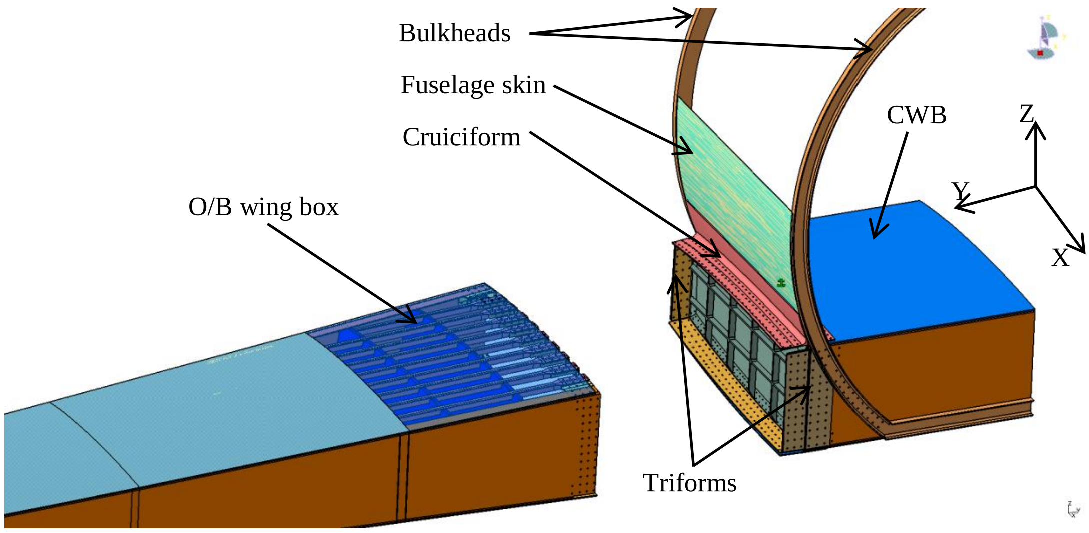

Fig. 1: Wing/Fuselage integration scheme

3.0 LOADING AND BOUNDARY CONDITIONS

The ‘pull-out from dive’ load case (2.5g case), which is the critical load case for the wing structural design is considered. The engine load is applied as the inertia load as shown in Figure 2 a). Total load on the wing is 34550 kg, whereas the inertia load due to engine is 3800kg. The boundary conditions are selected based on the integration scheme of the wing to fuselage. Symmetry boundary conditions are given at the a/c centre line (y=0) at bulkheads and wing centre. Z is constrained all along the spar web where bulkheads are connected. X is constrained along the wing top skin at the fuselage intersection line as shown in Figure 2 b).

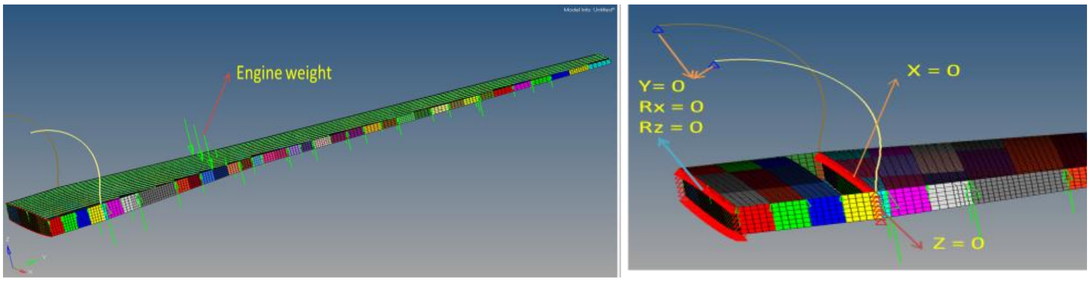

Fig. 2: a) Loading b) Boundary conditions

5.0 MATERIAL PROPERTIES

T800 class carbon composite material is considered for all the components of the wing box viz. skins, spars, ribs and stringers. Material for bulkhead is taken as Aluminum with properties E=70GPa, Ultimate strength=430MPa and poisson's ratio=0.33. The properties of composite material are shown in Table 1.

Table 1: Composite material properties

S. No	Property	Value	Unit
1	Longitudinal Modulus	150×10^{3}	N/mm^{2}
2	Transverse Modulus	9×10^{3}	N/mm^{2}
3	Poisson's ratio	0.35	
4	Ply thickness	0.15	mm
5	Shear modulus	4×10^{3}	N/mm^{2}
6	Mass density	1.6×10^{-6}	kg/mm^{3}
7	Tensile strength	1200	N/mm^{2}
8	Compressive strength	625	N/mm^{2}
9	Shear strength	36	N/mm^{2}

6.0 FINITE ELEMENT MODELLING AND OPTIMIZATION PROBLEM FORMULATION

Hypermesh and Patran are used as pre- and post-processors respectively. The inter-spar box of the wing is modelled with two-dimensional shell elements (CQUAD4, CTRIA3) with the property of PCOMP for all composite parts except stringers and bulkheads. C-section bulkheads and HAT cross-section stringers are modelled with one dimensional element (CBAR) with the property of PBAR. The dimensions of bulkhead are taken as H=100mm, w=50mm and that of stringers as Dim1=30mm, Dim2=3mm, Dim3=10mm and Dim4=15mm as shown in Figure 3. Orthotropic material zero direction was aligned with the front spar of the wing. NASTRAN is used as the solver for optimization. Optimization problem is formulated as below.

- **Design variables**: The components of wing box viz. skins, spars and ribs are divided into many design zones as shown in Figure 4. More design zones are provided near the root region where much of the activity will be happening. In each of the design zones, each super-ply in the 0º, +45^0,-45^0 & 90º direction is made as the design variable.

- **Optimization constraints:** Failure-index (Tsai-Wu criteria) is restricted to an upper limit of 1.0 and Buckling Eigen value to a lower limit of 1**.**
- **Objective:** Minimize the mass of the structure.

- Minimum thickness for each ply is defined as 0.15mm (manufacturable ply thickness) which defines the minimum laminate thickness of 1.2mm for eight plies.

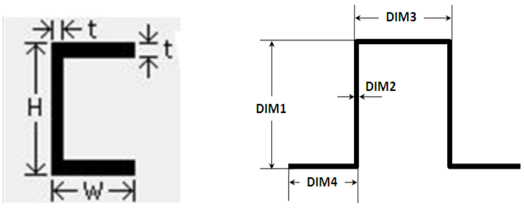

Fig. 3: a)Bulkhead b)Stringer

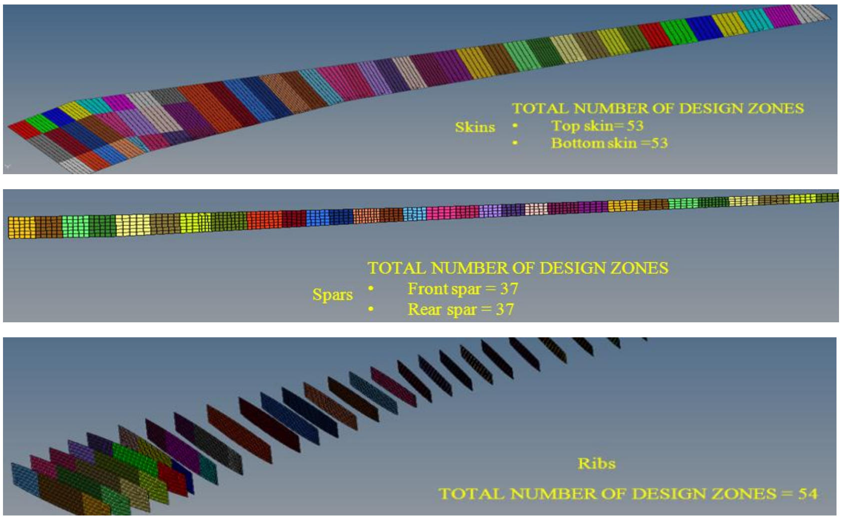

Fig. 4: Design zones

7.0 RESULTS AND DISCUSSIONS

In order to understand the stiffness effect of the bulkhead on the wing box weight, parametric studies are carried out with different bulkhead stiffness. The bulkhead stiffness is varied by varying the thickness of the bulkhead with a constant cross section. The bulkhead thickness is varied as 4mm, 6mm, 10mm and 14 mm. The optimization problem in all the cases converged to a feasible solution with the first buckling mode happening at a buckling factor close to 1 and composite failure index varying from 0.2 to 0.9. The huge variation in failure index can be attributed to the reasons that the thickness in most of the top skin is governed by buckling considerations and in the outboard regions of the box by the minimum thickness of the laminate defined in the problem (1.2mm) owing to less loads. The plots of buckling modes, failure indices, deflections and thickness are shown in Figures 5 through 8. The variation of wing inter-spar box weight for different bulkhead thickness is shown in Figure 9 and variation of individual component weights are shown in Figure 10.

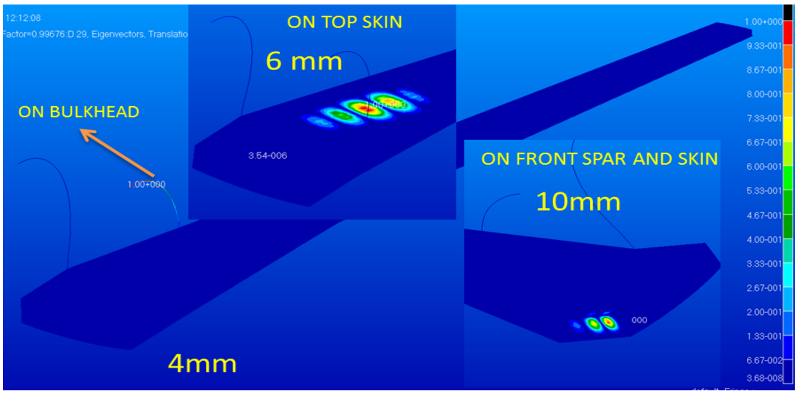

Fig. 5: First buckling mode for different bulkhead stiffness models

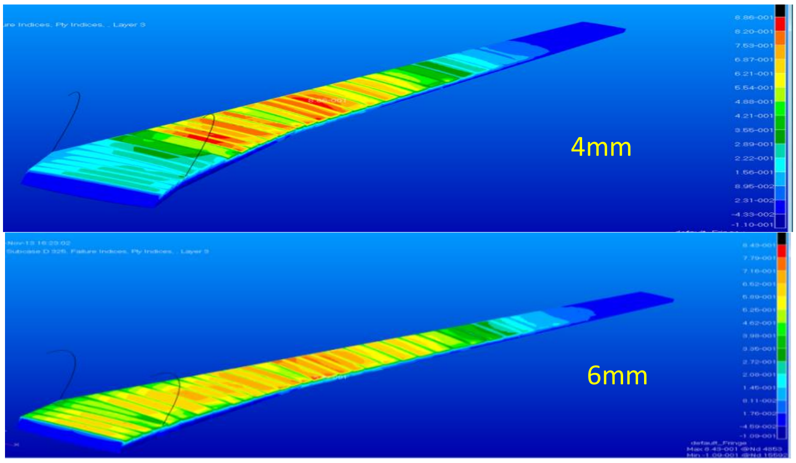

Fig. 6: Composite failure index plot for different bulkhead thickness

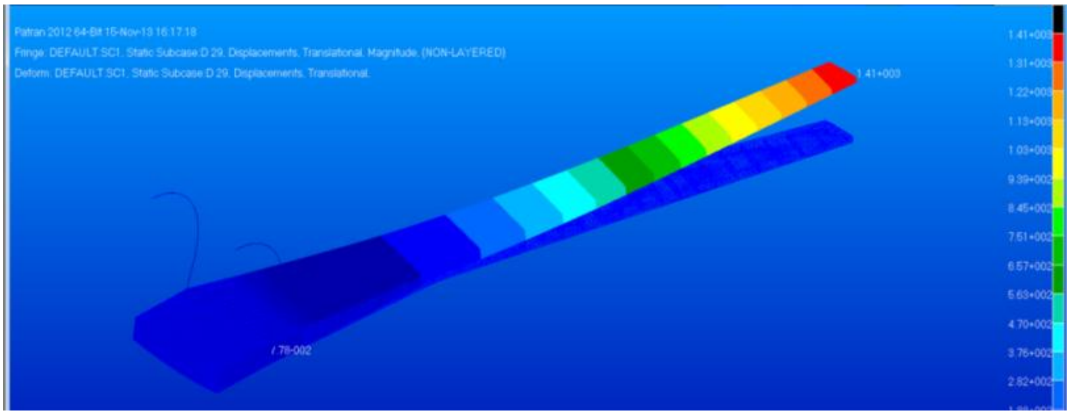

Fig. 7: Wing inter-spar box deflection contour

As can be seen from Figure 5, for bulkhead thickness of 4mm, the buckling is happening at the bulkhead unlike in other cases of 6mm and 10mm, where the buckling is in top skin and spars. For 4mm thickness bulkhead case, in order to avoid the bulkhead buckling or in other words any load being transferred to the bulkhead, the wing box component thicknesses near the root region are increased to as high as 18mm in top and bottom skins, as can be seen from Figure 8. The thicknesses in spars and ribs in the root region are around 16mm. Also it can be observed from Figure 6 that the composite failure index is only about 0.2 to 0.3 in the root region of the wing, owing to the same reason that the large thickness in these regions is not because of strength or buckling considerations of the respective components. Whereas in other cases of bulkhead thickness equal to 6mm and 10mm, the wing top skin and bottom skin thicknesses near the root regions are very nominal which are in the range of 5 to 7mm. The spar and rib thicknesses are ranging from 2 to 7 mm. The failure indices values are also reasonably good ranging from 0.5 to 0.9.

The individual component weights and tip displacement of the wing box with different bulkhead thicknesses are tabulated in Table 2. A plot of total wing box weight with bulkhead thickness is shown in Figure 9. As can be seen from Figure 9 and Table 2, the total weight of the box is exorbitantly high in the case of 4mm bulkhead thickness owing to very high thicknesses in the root region of the wing box. The same is the case with individual component weights also as seen in Figure 10. For all the other cases, the weight figures are very much consistent. The tip displacement of the wing is of the order of 1500mm in all the cases indicating fairly constant wing box stiffness.

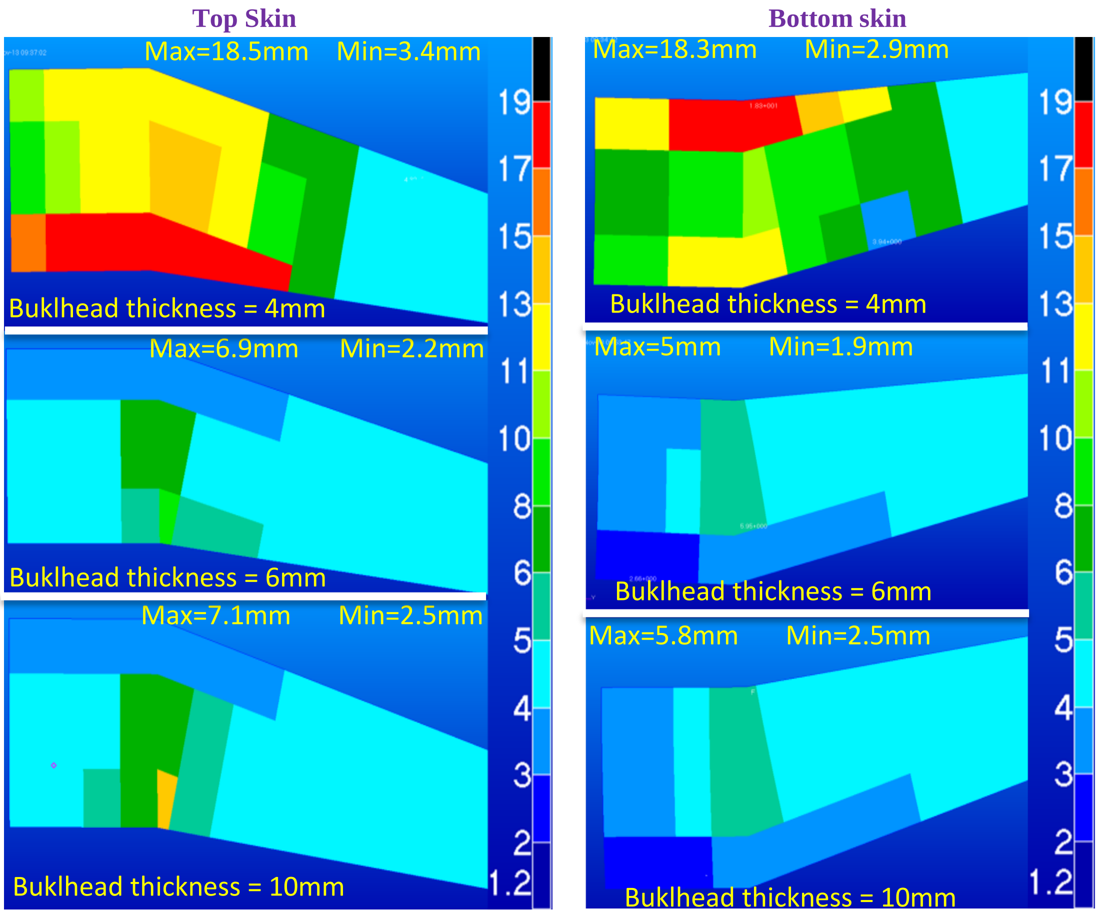

Fig. 8: Thickness plot of top and bottom skins for different bulkhead thickness

Table 2: Individual component weights for different bulkhead thickness

	WEIGHT (Kg)								Tip Displ-ment (mm)
Bulkhead thickness t (mm)	Top skin	Bottom skin	Spar	Rib	Stringer (Top+ Bottom)	Bulk-head	Total weight with bulkhead	Total weight without bulkhead	
4	172.2	148.1	72.7	174.3	105.9	9.7	682.9	673.2	1410
6	103.9	89.7	31.6	69.9	105.9	9.2	410.1	400.9	1410
10	96.6	89.4	33.9	74.9	105.9	22.8	423.5	400.7	1540
14	97.3	89.9	34.3	72.4	105.9	30.6	430.3	399.7	1500

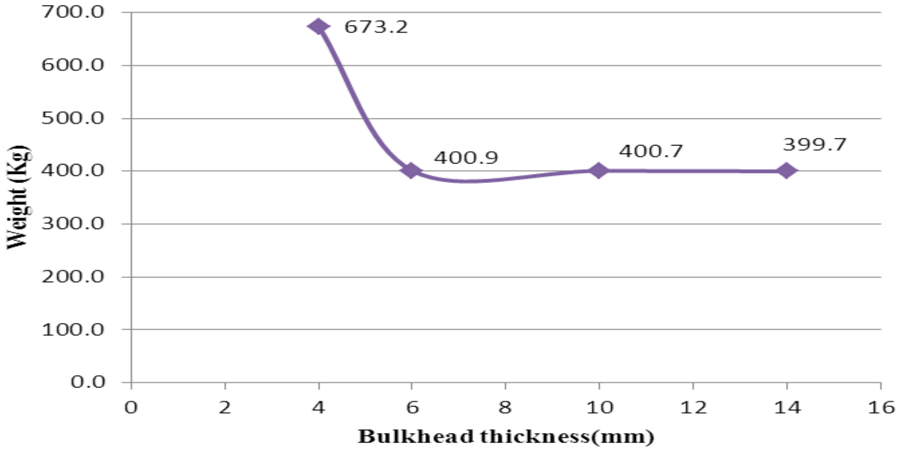

Fig. 9: Wing weight variation with respect to bulkhead thickness

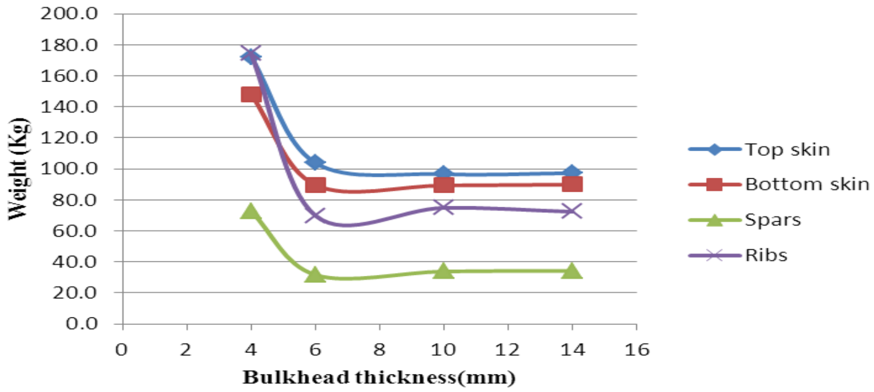

Fig. 10: Individual component weight variation with respect to bulkhead thickness

8.0 SUMMARY AND CONCLUSION

Wing to fuselage integration scheme is discussed, which basically helped in choosing appropriate boundary conditions for the optimization problem. Parametric studies are carried out in order to assess the effect of bulkhead stiffness on the weight of composite wing box, by varying the thickness of the bulkhead. It is observed that a sufficiently stiff bulkhead yielded consistent results with respect to total wing box weight and also the individual component weights with reasonable thicknesses of the components which otherwise resulted inordinate figures both in terms of weight and thicknesses.

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