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Topology Optimization of Aircraft with Non-Conventional Configurations

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1. Abstract
The optimal structural layouts of new aircraft configurations such as the flying wing and blended wing body (BWB) are not yet understood. These new configurations may require quite different design methods from those used conventionally and one promising alternative that is attracting increasing levels of interest is topology optimization, an approach which is significantly different from conventional approaches and valuable in applications where there is little or no collective knowledge on what an optimal structure may be. This paper proposes a new approach for using topology optimization for developing conceptual designs of an aircraft's structural layout. Its aim is to overcome some of the problems associated with the inclusion of local displacement and buckling constraints. The approach is applied to the design of a BWB UAV's wing and is shown to offer significant advantages over a baseline design.

2. Keywords: Topology Optimization, Aircraft Wing, Blended Wing Body

3. Introduction
Almost all aircraft sice WWII have used the conventional 'tube with wings' configuration. However because of financial and environmental factors new aircraft configurations such as the blended wing body (BWB) are becoming increasingly attractive. These low drag aircraft offer potential reductions in running costs and CO_2 emmisions due to increased fuel economy. The drawback of using these configurations is that their structures are not well understood and there are still many possibilities to explore in order to find an optimal structural layout.
The layout of wings with conventional configurations has been extensively investigated and is well understood. There is very little variation in the layouts of high aspect ratio wings found on the commercial transport jets from major airframe manufacturers since WWII [1]. These wings usually consist of two primary spars positioned at approximately 25% and 75% of the chord width. In some cases a third spar is found between these two in the wing section closest to the fuselage. Ribs usually have a uniform spacing of approximately 2 feet [1].
The use of optimization in exploring the structural layouts of these new configurations has predominantly concentrated on the established approaches of parameterizing the aircrafts' geometry and performing size and shape optimizations [2]. These approaches require a good first design point, however what this initial design should be is not yet known. An alternative to these conventional optimization approaches is topology optimization, a valuable tool when there is little or no collective knowledge on what the optimal structure may be. Topology optimization is used to determine the optimal distribution of material within a desgn space. It is widely used in the aerospace industry. However, at the present time its use has mostly been confined to the design of individual aircraft components such as wing ribs [3,4]. Its use in determining optimal structural configurations of wings has been minimal. It has been used with some success to determine the optimum position of primary spars [5] and also the optimum position of spars & ribs so that the wing's aerodynamic shape is maintained [6]. However both of these cases were confined to a conventional wing. It is also still unclear how these approaches should best be incorporated into a complete optimization methodology that considers all the requirements of the wing's design.
Another use of topology optimization that is currently being explored is in the design of mechanisms for morphing wing structures. Its use here is predominantly confined to the selection of structural members and mechanisms to be used in a predefined layout [7]. This approach does not have the same freedom to distribute material as the density method described below, so is therefore a less desirable option for simply optimizing a wing's structural configuration.
This paper discusses a proposed methodology for incorporating topology optimization into the process of designing the structural layout of a BWB aircraft's wing. Its aim is to overcome some of the limitations of the approach by the inclusion of buckling constraints and the consideration of local displacements as discussed below. The design process should generate solutions that consider both global and local deformation of the wing and buckling load factors.

4. Topology Optimization
The density method of topology optimization used in this paper can be described using the following formulation:

$$
\begin{aligned}
&\textit{Minimize} \quad f(\boldsymbol{\rho}) \\
&\textit{Subject to} \quad g_i(\boldsymbol{\rho}) \le g_i^{constraint} \\
&0 \le \rho_j \le 1
\end{aligned}
\tag{1}
$$

Where f($\boldsymbol{\rho}$) is the objective function, $g_j(\boldsymbol{\rho})$ are a series of responses such as static displacements and ρ_j is the relative density of each element in a finite element model. The elemental densities are related to the elastic modulus using the SIMP (solid isotropic material with penalization) approach [8]:

$$E_j = \rho_j^P \tag{2}$$

Where E_j is the relative elastic modulus of each element and P is the penalization factor. Using a value of P greater than 1 penalizes elements with intermediate densities and helps ensure solutions where most elements have densities close to either 0 or 1. A common approach is to define a 'minimize compliance' objective and a constraint on volume fraction of a designable space. Sensitivities are calculated using a finite element solver and material is removed from regions where it is not needed and added to regions where it is.

Topology optimization is usually used at the concept stage of the design process [9] where its main concern is with global compliance or displacements. The results of the topology optimization must then be interpreted to develop a CAD model of the initial design, which can then be used for further analysis and more conventional shape and size optimization, where additional constraints can be considered. Its place in the design process is shown in Figure 1.

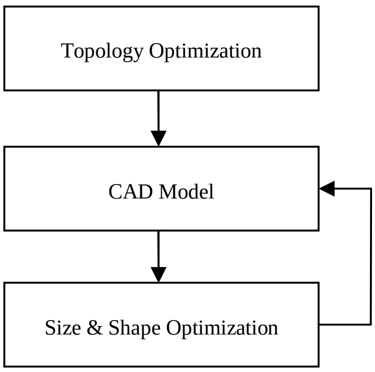

Figure 1: Optimization process

Due to this method of variable densities, topology optimization is not well suited to dealing with the eigenvalue responses required to generate stable designs [10]. Buckling constraints are usually considered later in the design process during size and shape optimization [9]. However, ignoring these responses at the concept stage can result in designs that are incompatible with requirements for structural stability. This highlights the requirement for a methodology that combines the structure needed to improve stiffness with that required to prevent buckling.

5. Methodology & Results

The proposed methodology will be applied to a conceptual UAV design with a BWB configuration provided by QinetiQ Ltd.

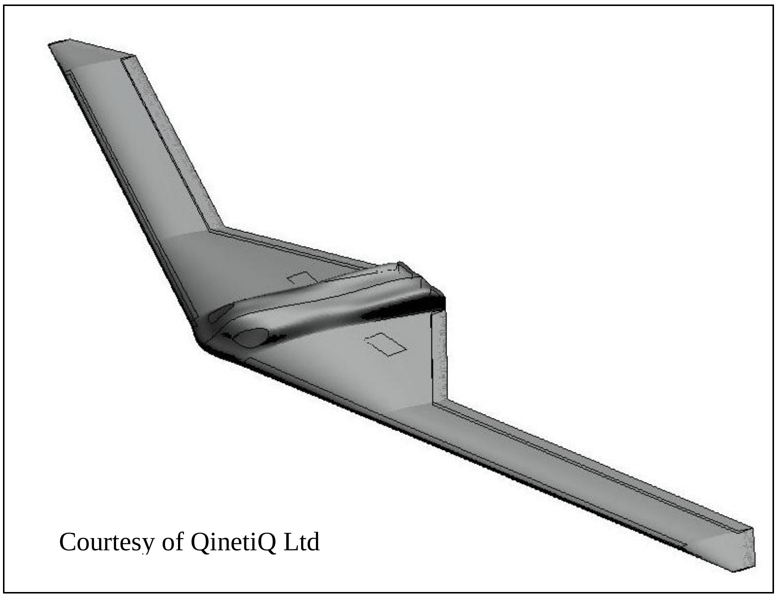

Figure 2: QinetiQ Conceptual UAV design

In the current study the UAV’s centre section will be removed and optimization will be performed on the wing only. This allows more freedom for the topology optimization as structural members are free to connect to the wing root at any location, they are not restricted by the non-designable spaces within the fuselage such as engine, landing gear or load bay locations. A 3.5g ‘pulling out of a dive’ load case will be used in the optimization process. This was chosen as it provides considerable bending and twisting of the wing so that robust designs can be developed. Due to the symmetrical nature of the wing a negative load case will not be necessary. Aerodynamic loadings are calculated using the CFD software, Fluent [11].
A finite element model of the UAV's wing is constructed using a designable space made of 3D solid elements covered in a non-designable skin made of 2D shell elements. The skin is necessary to allow pressures to be applied to the model however a thickness of 2mm is used so that its effect in comparison to material in the designable space is negligible. Control surfaces at the leading and trailing edges are made of non-designable shell elements and are attached to the wing's upper and lower surfaces at discrete points using rigid elements. Aluminium is used for all structural components. Pressures from the 3.5g load case described above are applied to the skin and the wing is constrained in all degrees of freedom at the root. Initially, a simple minimum compliance problem formulation is used with a constraint of 0.3 on maximum volume fraction and 0.25° constraint on the wing’s twist at the tip. An extrusion manufacturing constraint is included which forces all structure to remain uniform through the thickness of the wing. This is to prevent all material being used to thicken the wing's skin and improve bending stiffness, and instead, be used to indicate the optimum position of structural members. Optimization is carried out using Altair's Optistruct [12] and the results are illustrated in Figure 3.

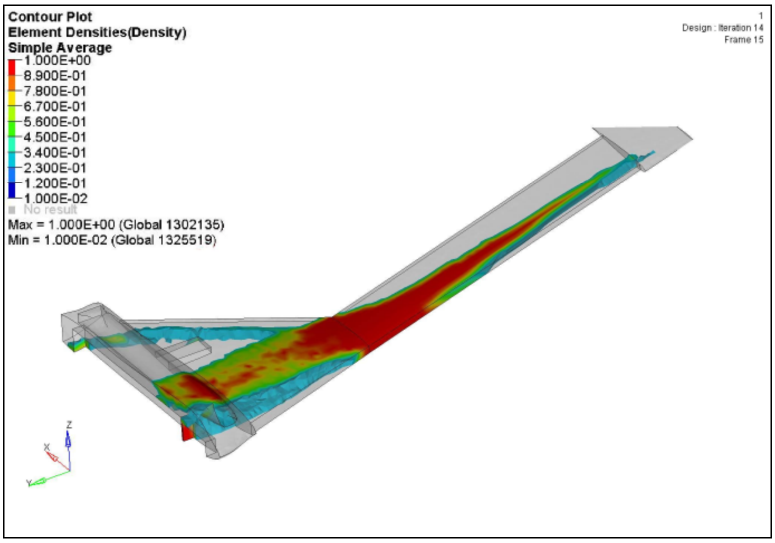

Figure 3: Material distribution after initial topology optimization

The topology optimization process for this minimum compliance formulation is dominated by the global bending and twisting of the wing, making it a useful tool in determining primary spar positions, however it neglects the smaller local deformation of the wing's skin. Due to the importance of the wing maintaining its aerodynamic shape, these local displacements cannot be overlooked. Also, because of the difficulties associated with buckling analysis within topology optimization, methods for including local buckling constraints into the optimization process must be explored.

5.1. Local Deformation of Wing Skins

To allow the wing's design to be driven by both local and global displacements, the following problem formulation is proposed for topology optimization. In addition to the 3.5g load case, a second load case in which pressures on the upper and lower surfaces of the wing are identical is included, therefore there is no bending or twisting of the wing. Constraints of 150mm maximum tip displacement and 0.25° maximum twist are applied to the 3.5g load case with an objective of minimizing compliance for the symmetrical load case. The volume fraction of the designable space is again constrained to 0.3. The aim of this formulation is to ensure just enough material is used to keep the wing's global deformation within some predetermined limits, and allow the rest of it to be used to minimize the local deformation of the wing (Figure 4). The constraints on the wing's global deflection and twist are made artificially strict. This is necessary because, due to limitations on mesh density, unrealistically large, solid aluminium structural members are being distributed in the design space. Note that it is possible to use more realistic values later in the design process.

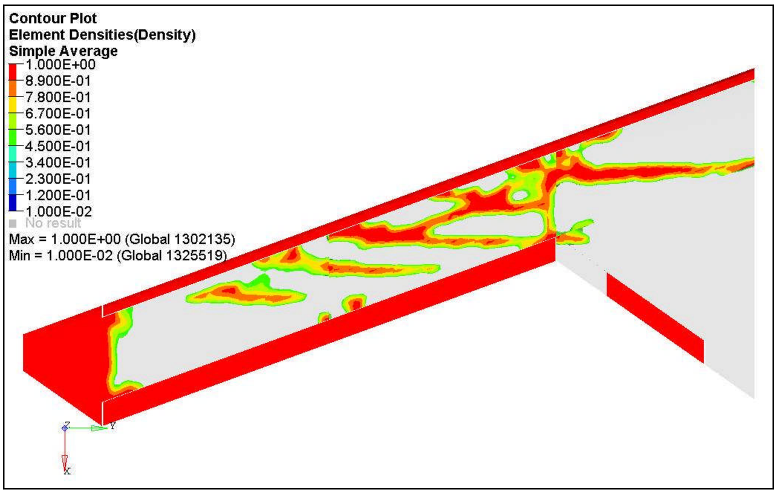

Figure 4: Material distribution after topology optimization

5.2. Wing Skin Buckling
Two methods are proposed to deal with buckling in the topology optimization process. Both methods include the topology optimization step described earlier and a separate shape optimization step using buckling constraints to determine rib positions. Both methods also assume an average rib spacing of approximately 2 feet as indicated in the literature [1].

5.2.1. Approach 1
Firstly the topology optimization described above is carried out and then a shape optimization is performed to determine rib pitch. The shape optimization process starts with an estimate of the average rib pitch. A finite element model of the aircraft with ribs is then created using 2D shell elements. The maximum range of movement for the ribs is set by morphing the finite element mesh using Altair's HyperMorph tool. In this case a range of ±1/3 of the average rib pitch is used, allowing maximum movement of the ribs without creating very high aspect ratio elements. The junctions of the ribs with the front and rear spars are allowed to move independently so that rib orientation can also be optimized. A shape optimization is then performed to maximize the buckling load factor. The repositioning of ribs (Figure 5) results in the buckling load factor being increased by 18% as well as being more uniformly spread over the section of the wing closest to the root (Figure 6). All ribs remain parallel to the centerline of the aircraft.

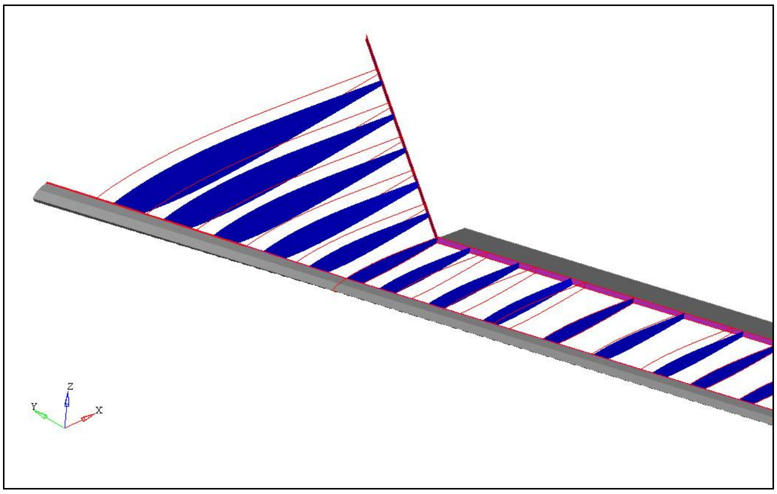

Figure 5: Optimized (blue) and original (red) rib positions

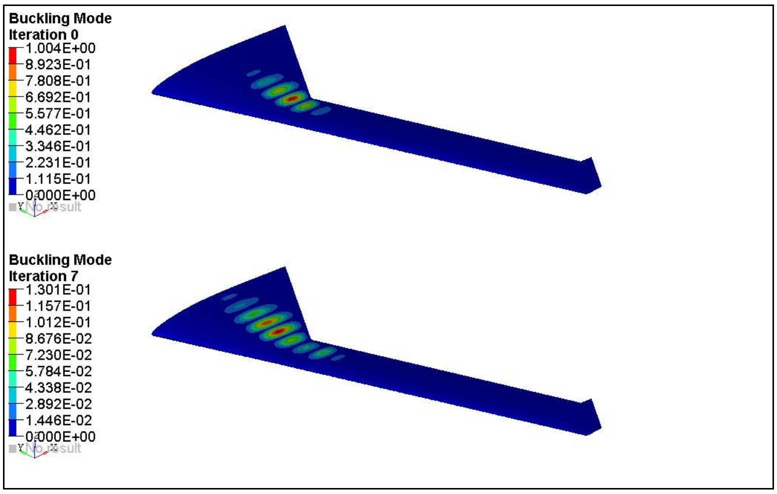

Figure 6: Buckling load factor before (top) and after (bottom) shape optimization

The results from the topology optimization are then interpreted as spars made of 2D shell elements. These are combined with the rib positions from the shape optimization step to provide a final finite element model to be used for further analysis and optimization (Figure 7).

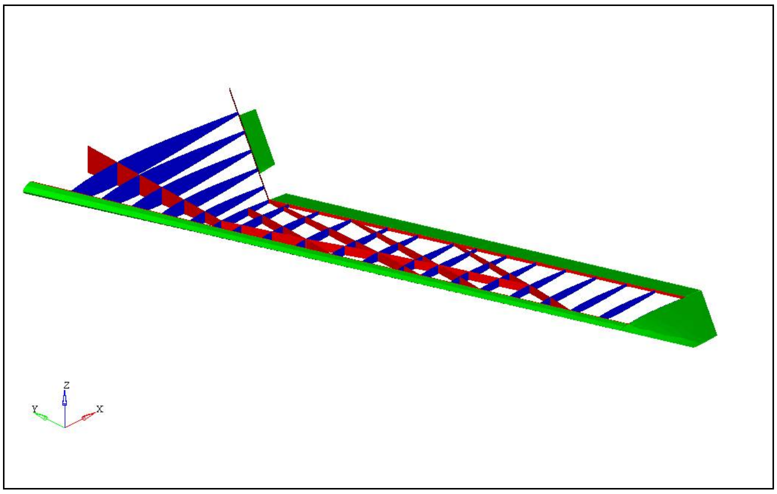

Figure 7: Interpretation of topology and shape optimization (approach 1)

5.2.2. Approach 2

The second method differs from conventional approaches using topology optimization as discussed so far. Rather than topology optimization being the first step in the design procedure, a shape optimization is initially conducted to determine the optimum rib pitch for maximum buckling load factor. The ribs are then included in the finite element model as non-designable 2D shell elements, separating a series of 3D designable spaces. A rib thickness equal to the average element size is used so that the ribs do not become negligible when compared to the material distributed within the designable space. Topology optimization is performed (Figure 8) and the results are interpreted as 2D shell elements and, along with the optimized rib positions, give a final finite element model (Figure 9) to be compared to the one from the first method.

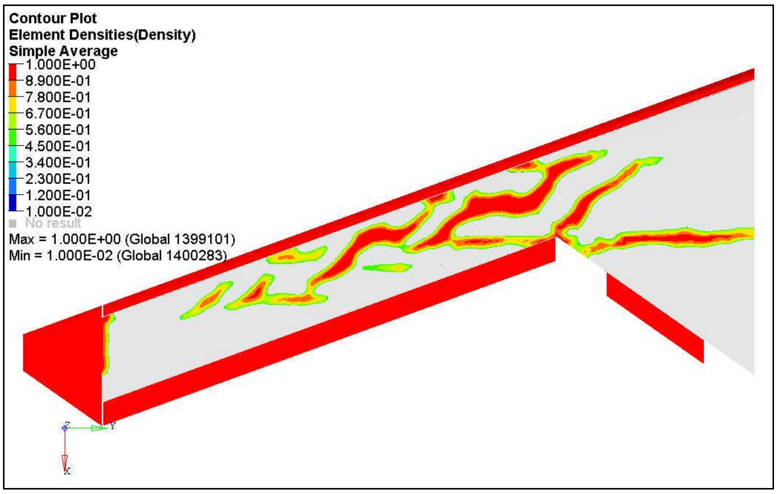

Figure 8: Material distribution after topology optimization (approach 2)

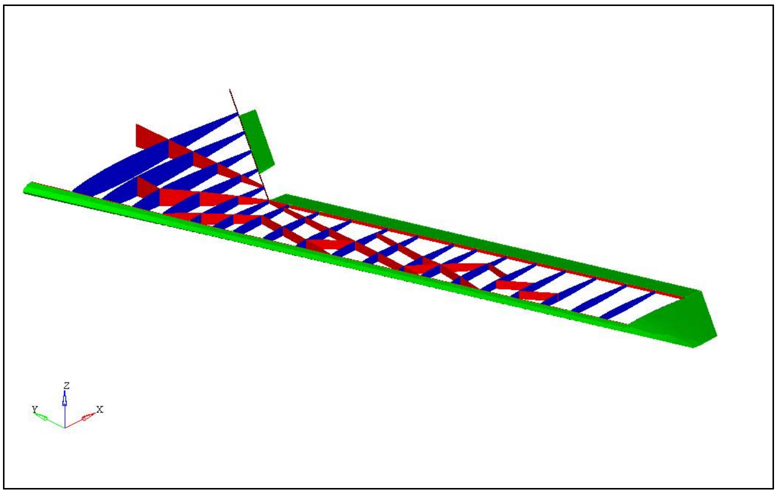

Figure 9: Interpretation of topology optimization (approach 2)

5.3 Discussion of Approaches Applied

Approach 1 allows complete freedom at the topology optimization stage, so that material can be distributed in the best way to reduce skin deformation while keeping global displacements at a desired level. However, the solver has no knowledge of the rib positions and therefore may use material that is later made obsolete by the presence of ribs. Also, because the optimum position and orientation of structural members to reduce local deformations differs from that required to prevent buckling, it may prove difficult to satisfy both criteria and provide a minimum mass configuration. Approach 2 is a little more restrictive at the topology optimization stage because of the pre-imposed rib positions. The method's primary concern is with buckling, other design considerations are then incorporated around this. However all the material used in the designable spaces is working with the ribs to reduce local deformations and will not be made obsolete later in the design process.
To compare the two methodologies, a sizing optimization is performed on both finite element models. The skin is separated, by the ribs, into 20 sections. The spars are also split into sections. The thicknesses of each of these along with the thicknesses of each rib are the design variables (table 1) and the following problem formulation is used (table 2).

Table 1: Design variables

Component	Design variables	Start value	Min. value	Max. value
Skin thickness/mm	20	10	2	25
Spar thickness/mm	18	10	5	50
Rib thickness/mm	20	10	5	50

Table 2: Problem formulation

3.5g Load case	Symmetrical load case
Objective = minimize mass	
Twist angle < 1°	
Von Misses stress < 50MPa	
Buckling load factor > 1	
	Compliance < 80

At this point, the constraint on the wing twist angle is relaxed, a stress constraint is introduced and no constraint is applied to the wing tip deflection. To assess the methodologies the same optimization is also performed on a baseline design, without the additional spars derived from topology optimization, having only the front and rear spars where the control surfaces are attached. A uniform spacing of 2 feet is used for the ribs. The constraint on compliance for the symmetrical loading case is determined from initial analysis of both models (Figures 9 & 10). The value used is achievable by both layouts and offers an improvement over the baseline deign.

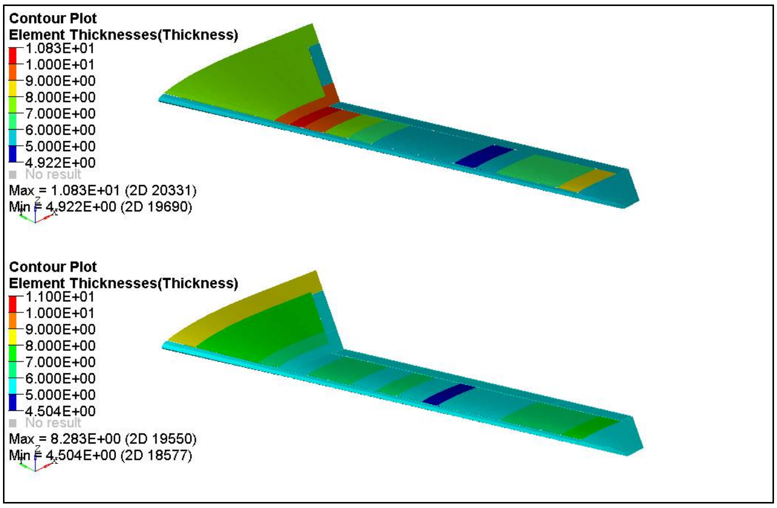

Figure 10: Skin thickness after size optimization for approach 1 (top) and approach 2 (bottom)

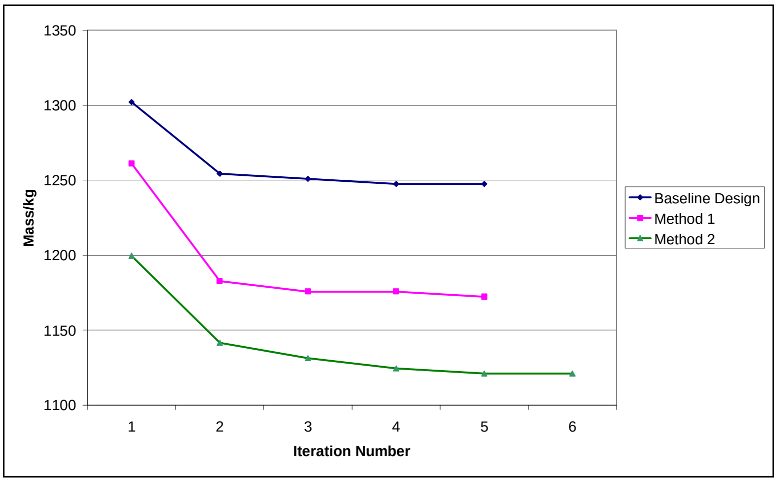

Figure 11: Reduction of mass during size optimization for both methodologies and baseline model

Both topology optimization methods offer a reduction in mass compared to the baseline design, 6% and 10% for methods 1 and 2 respectively. However, as predicted some of the structural members included in method 1 are under-utilized due to the presence of the ribs. Their thicknesses are reduced to the lowest value possible without buckling. It should be noted that for the baseline design buckling is not a driving factor, the buckling load factor remained at 1.2. This is because for this design the only method for improving compliance for the symmetrical load case is to increase skin thickness. The skin thicknesses required to satisfy the compliance constraint are greater than those required to prevent buckling.

6. Conclusions

A new approach for the use of topology optimization in wing design is introduced where structural stability and local displacements are considered at the concept stage. The methodology combines the use of topology, size and shape optimization. This approach is applied to the structural optimization of a BWB aircraft wing in two ways. Both methods show significant improvement in the form of a mass reduction when compared to a baseline design. The addition of buckling responses at the topology optimization stage remains a problem, however the importance of considering buckling at early stage in the design process is shown. The proposed approach requires selection of a compliance constraint at the size optimization stage. The value used is important as it can determine whether the design is driven by constraints on buckling or local deformation of the wing. A study of the effect of a symmetrically loaded wing's compliance on the aerodynamic performance will be conducted so that suitable values can extracted for future work.

7. Acknowledgments

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