Application of Topology, Sizing and Shape Optimization Methods to Optimal Design of Aircraft Components

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Abstract

Topology optimisation has for a considerable time been applied successfully in the automotive industry, but still has not become a mainstream technology for the design of aircraft components. The explanation for this is partly to be sought in the larger problem sizes and in the often quite complicated support and loading conditions for aircraft components. Also, aircraft components are often stability designs and the compliance based topology optimisation method still lacks the ability to deal with any buckling criteria. The present paper considers the use of the compliance formulated topology optimisation method and detailed sizing/shape optimisation methods to the design of aircraft components but also discusses the difficulties in obtaining correct loading and boundary conditions for finite element based analysis/optimisation of components that are integral parts of a larger structure.

Keywords: Leading Edge Ribs, Wing Box Ribs, OptiStruct, Topology, Size and Shape

1.0 Introduction

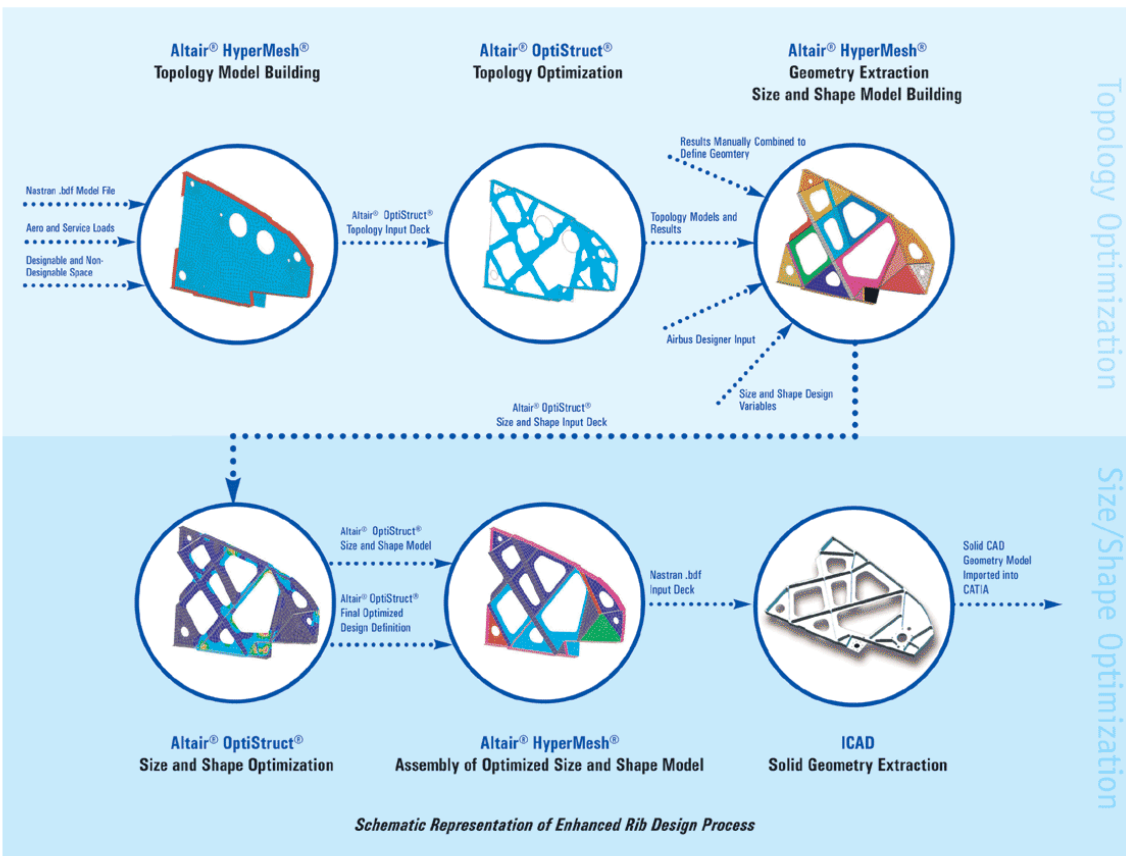
Aggressive weight targets and shortened development time-scales in the civil aircraft industry naturally calls for an integration of advanced computer aided optimisation methods into the overall component design process. Airbus has in a number of recent studies used Altair's topology, sizing and shape optimisation tools in an attempt to achieve lighter and more efficient component designs. Considered components include wing leading edge ribs, main wing box ribs, different types of wing trailing edge brackets as well as fuselage doorstops and fuselage door intercostals. The designs for most of these components are to some extent driven by buckling requirements but also by for example stress and stiffness requirements.

Finite element based topology, sizing and shape optimisation tools are typically used as part of a two-phase design process. Firstly, a topology optimisation is performed to obtain a first view on an optimal configuration for the structure – an initial design with optimal load paths. Next, the suggested configuration is interpreted to form an engineering design and this design is then optimised using detailed sizing and shape optimisation methods with real design requirements. Numerous examples from the automotive industry have demonstrated the ability of such an approach to quickly generate optimum components for stiffness, stress and vibration designs.

The success of the above optimisation scheme relies on a topology optimisation to suggest a good initial design. Numerous examples have shown that the major weight savings are achieved when selecting the type of design and not when doing the detailed design optimisation. The aerospace industry is very aware of this and often spends considerable time studying different design alternatives. Efficient designs have therefore evolved through decades of manual optimisation. However, topology optimisation methods may still have a place as new sizes/types of aircraft are designed and as new materials and manufacturing processes continue to appear.

This paper studies the use of Altair's finite element based topology, sizing and shape optimisation tools for design of aircraft components. Aircraft components are often stability designs and topology optimisation methods still completely lack the ability to deal with buckling criteria. The present work therefore uses the traditional compliance based topology optimisation method to suggest an optimal design configuration, which is engineered to provide the design with some stability. Finally, a detailed sizing/shape optimisation is performed including both stability and stress constraints.

This design process (Figure 1) has been used for optimisation of various aircraft components. The examples included in the following sections shows how topology optimisation may be used to suggest good initial designs for aircraft components, but also demonstrates how a topology optimisation followed by a detailed sizing and shape optimisation may be used to provide efficient aircraft component designs satisfying manufacturing, stability and stress constraints.



Schematic Representation of Enhanced Rib Design Process

Figure 1: Topology, Sizing and Shape Optimisation Process for Design of Aircraft Components

This optimisation process includes the full process from finite element model generation through to the generation of a final design and import of this design back into a CAD system.

2.0 Optimisation of Main Wing Box Ribs

The traditional design of Airbus main wing box ribs incorporates a shear web, stabilised against buckling by adding a rectangular grid of stiffeners. The added grid of stiffeners serves both to increase the buckling load by splitting the shear web into smaller panels and to provide the rib with its post-buckling strength but also serves to resist loads such as the compressive rib brazier loads and lateral fuel pressure loads. The shear web gives a good general design allowing the component to carry loads acting in different directions. A finite element model illustrating this traditional Airbus rib design is shown in Figure 2.

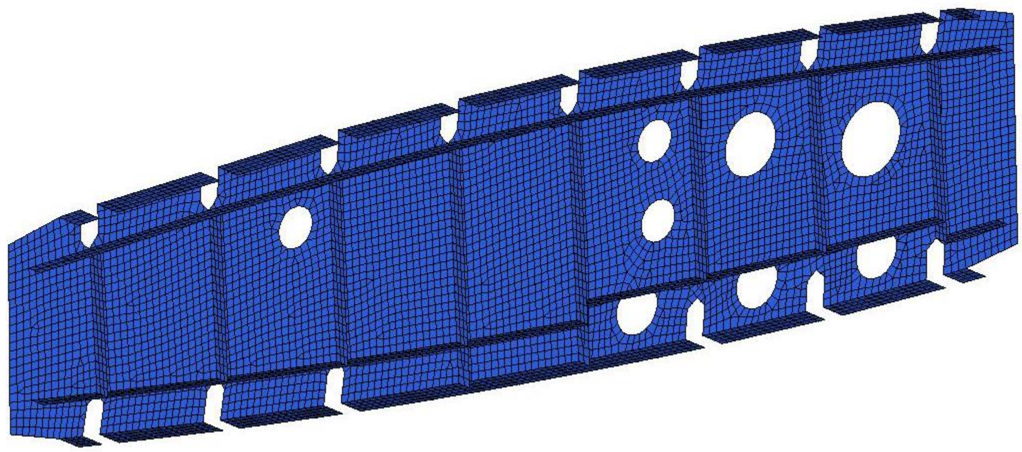


Figure 2: Typical Shear Web Design as Used for Airbus Main Wing Box Ribs

The design depicted in Figure 2 is not too different from the result that could be expected from a compliance based topology optimisation, if obtained using optimally layered microstructures . Examples of topology optimised designs obtained via different formulations of the topology optimisation problem may be found in [1] and [2]. A topology optimisation performed using layered microstructures would typically suggest a design with a stiff exterior edge of solid isotropic material and with an interior web made from a low-density anisotropic material. Such a solution could be realised via a design with a thick external flange and with a thin internal anisotropic shear web. Hence, a design concept somewhat similar to a traditional Airbus rib, only without the stabilising stiffeners.

Topology optimised designs obtained using optimal layered microstructures are often claimed not to be manufacturable, as the stiffness and the orientation of the layered composite are allowed to change from point to point in the structure. The same thing holds for other formulations of the topology optimisation problem allowing formation of areas with intermediate material densities. Topology optimised designs are therefore often forced into isotropic truss-like designs by artificially penalising the formation of regions with anisotropic materials/intermediate material densities. Figure 3 below shows an example of the use of such a penalisation technique to avoid formation of areas with intermediate densities, and clearly demonstrates the topology optimisation methods ability to predict both shear web and truss like designs.

The example in Figure 3 considers topology optimisation of an outboard wing box rib, subject to both local air pressure loads and running wing box loads diffusing into the rib from several wing bending/twist cases. For the example in Figure 3 the upper and lower channel sections with stringer cut-outs and skin attachments have been frozen, in order to allow an easy implementation of a suggested solution. Figure 3 shows the available design space and topology optimisation results without/with penalisation.

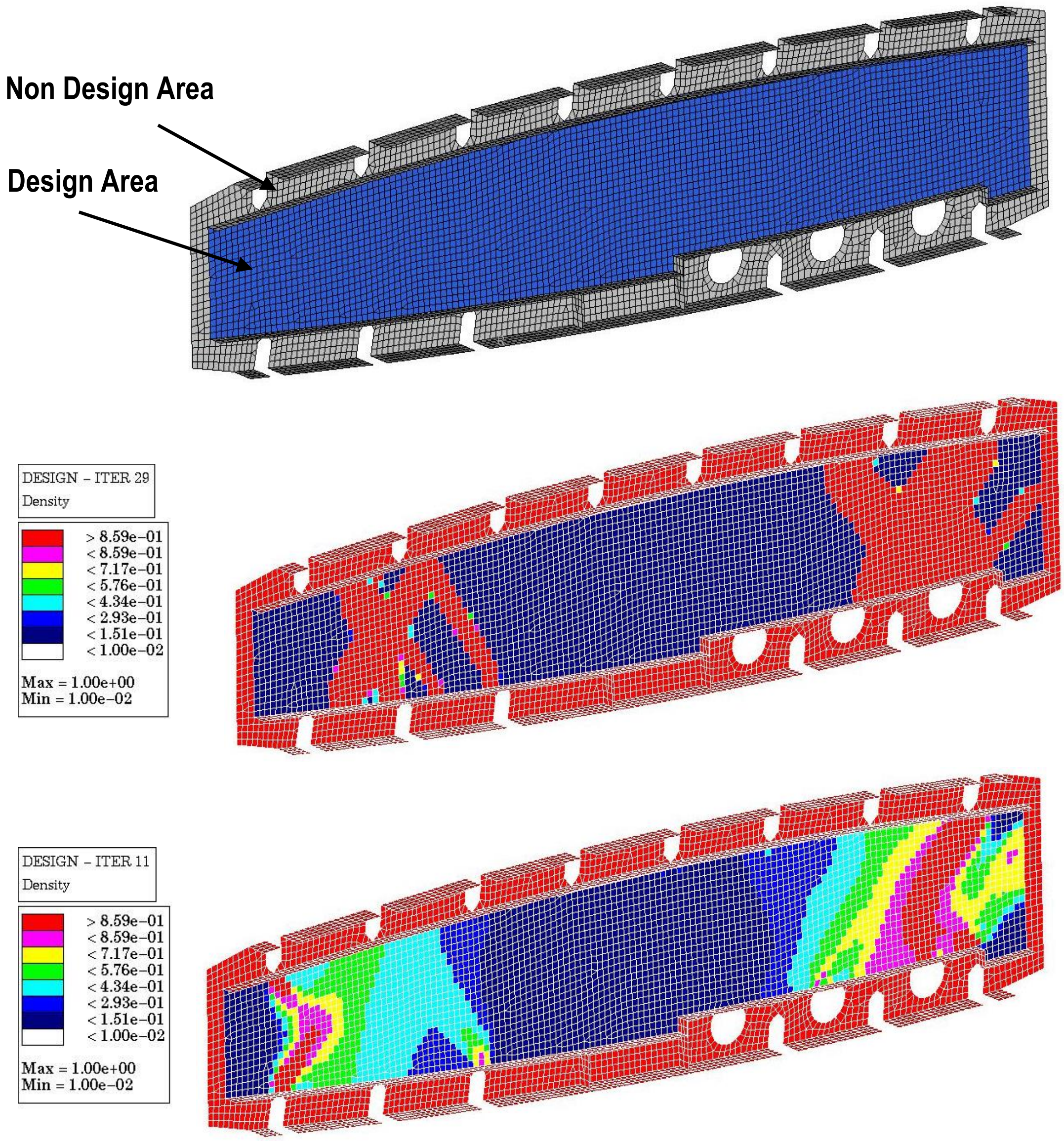


Figure 3: Topology Optimised Main Wing Box Rib

(Top picture shows the designable and non-designable areas of the rib. Middle picture shows a shear web type design obtained by not penalising intermediate material densities. Bottom picture shows a more truss-like design obtained by penalising the formation of areas with intermediate material densities)

Determining a topology optimised design, such as the results shown in Figure 3, may be seen as a problem of finding a structure with optimal load paths to transfer a number of well defined loads to well defined supports. Aircraft components are often part of a larger structure and the applied component interface loads cannot be fixed. The stiffness of the component will change how loads diffuse into the component, and the loading is therefore a function of design. The designs shown in Figure 3 were obtained by initially condensing all loads/supports delivered by the surrounding structure into boundary load vectors and a boundary stiffness matrix, and then solving the topology optimisation problem for fixed external loading. The boundary loads could have been updated after each iteration, allowing the loads in the skin to redistribute and thereby allowing the rib loading to change.

Figure 4, below illustrates the importance of the boundary support conditions for the rib design and also the importance of exploring the design space using the topology optimisation tool. The main wing box rib has in this example been optimised, removing the stiff non-designable upper and lower channel sections. This creates a very different and possibly more optimal topology, but also a design that could prove difficult to implement due to final assembly issues around rib/skin bolting.

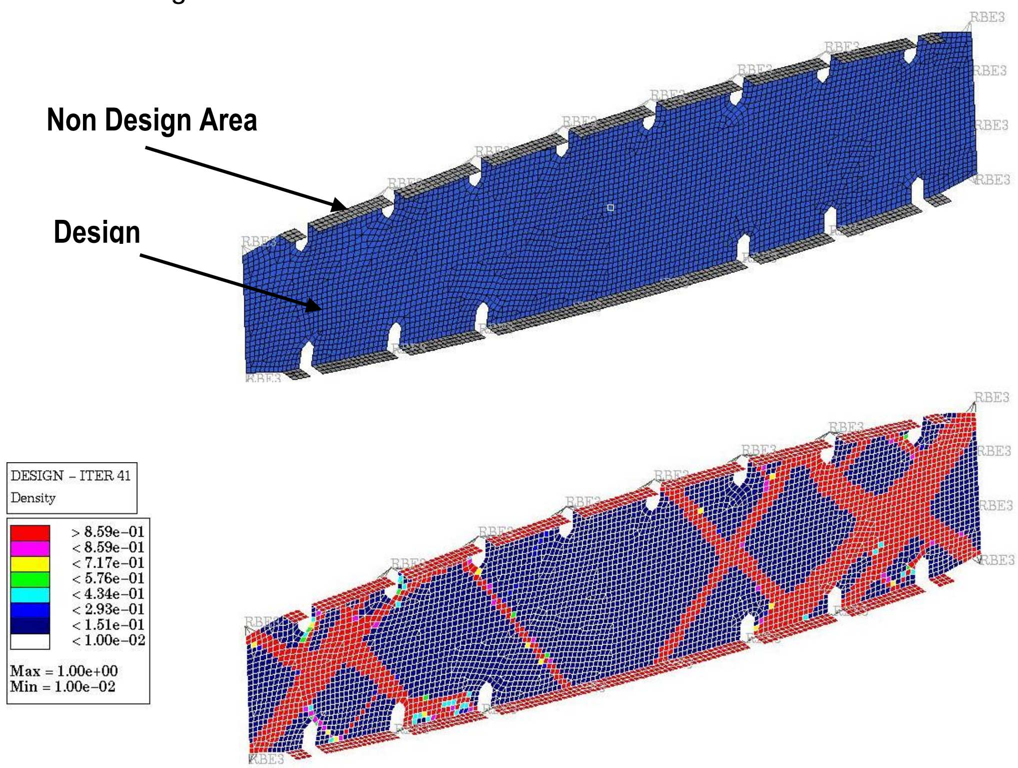


Figure 4: Topology Optimised Main Wing Box ib

(The formation of intermediate material densities have been penalised and a minimum member size constraint has been used to obtain a well-defined design. Load cases include both local air pressure loads and running loads from several wing-bending cases)

The effectiveness of the shear web design and the truss like design in Figure 3, are generally not very different. The optimum configuration for a component like a wing box rib is therefore likely to be determined by the amount of weight that needs to be added to stabilise the design in buckling. This question unfortunately is not addressed by the topology optimisation and can only be answered by a detailed sizing and shape optimisation. Current studies at Airbus UK therefore consider detailed sizing and shape optimisation of both traditional shear web rib designs and of truss like rib designs generated from topology optimisation results. Figure 5 shows how the topology optimisation result in Figure 4 may be used to form an initial design for a sizing and shape optimisation. The interpretation of the topology optimisation result includes adding stiffeners to stabilise the rib against out of plane buckling before a final sizing and shape optimisation is performed including both stress and stability designs. The use of sizing/shape optimisation is discussed in Section 3.

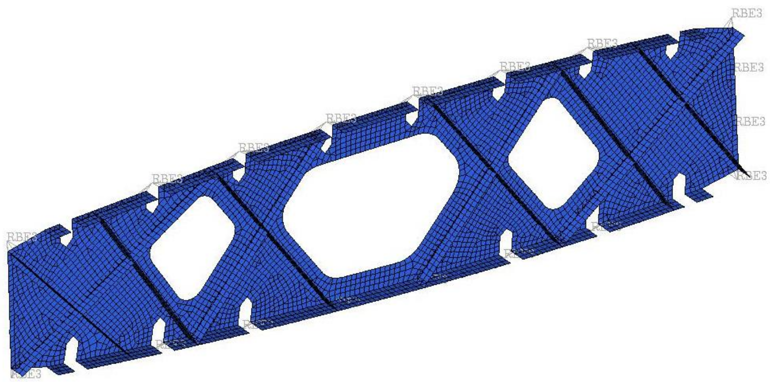


Figure 5: Initial Design for Sizing/Shape Optimisation
Obtained by Engineering the Solution from a Topology Optimisation.

3.0 Optimisation of A380 Leading Edge Droop Nose Ribs

The following describes the first real application of topology optimisation methods at Airbus UK to assist the design of aircraft components. A set of leading edge droop nose ribs for the Airbus A380 aircraft was designed and optimised using Altair's topology, sizing and shape optimisation tools. An initial design study incorporating a stiffened shear web design, had suggested difficulties reaching a very demanding weight target. Discrete force inputs on the droop nose ribs, which are used to hinge and activate two high-lift surfaces, made the set of ribs ideal candidates for topology optimisation. A work program was therefore launched to design and optimise the 13 droop nose ribs using topology optimisation followed by a detailed sizing and shape optimisation. The 13 droop nose ribs were optimised during a very concentrated "five-week" work program involving engineers from Airbus UK's structural optimisation team and A380 inboard outer fixed leading edge team but also engineers from both Altair Engineering and BAE SYSTEMS Aerostructures. The work program resulted in a set of conceptually different ribs, shown in Figure 6, which met the weight target and satisfied all stress and buckling criteria included in the optimisation.

At the start of the droop nose optimisation program Airbus UK and Altair Engineering both had very limited experience applying the topology, sizing and shape optimisation to the design of aircraft components. The very short work program left very little time to investigate how to best represent load/boundary conditions and how to best handle local and global buckling criteria in the detailed sizing/shape optimisation. A lot of problems were encountered during the work, and not all of the problems could be resolved in the short time frame. The work therefore was followed up by a validation of the designs via traditional hand stressing methods, and qualification of the ribs/structure against fatigue and bird strike is still ongoing.

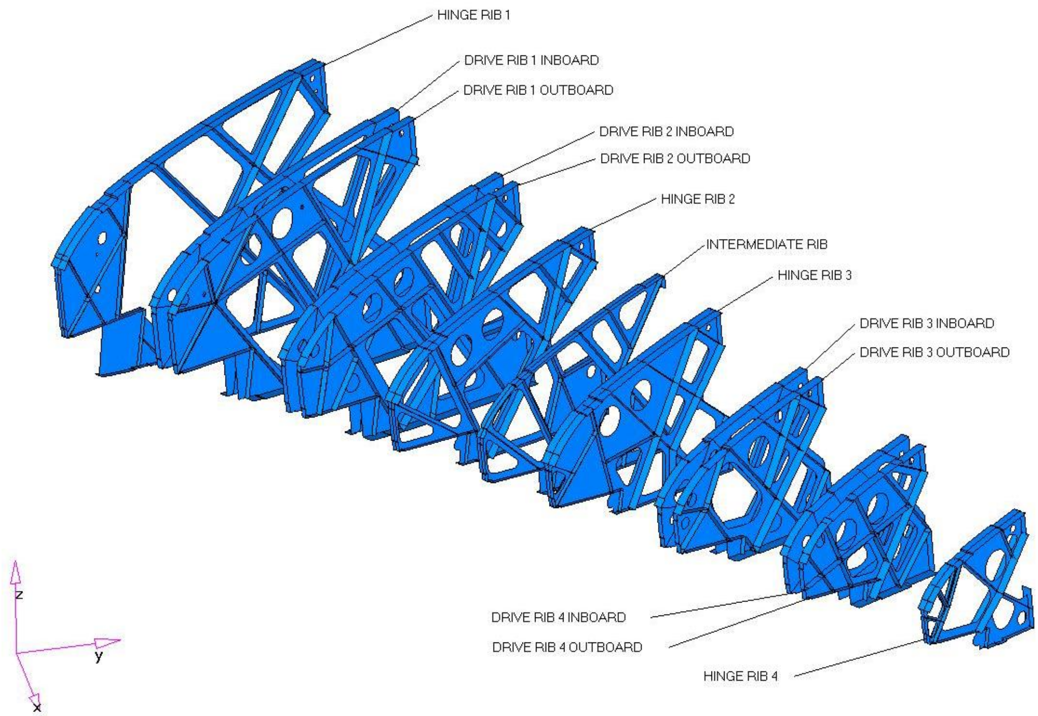


Figure 6: Topology, Sizing and Shape Optimised A380 Droop Nose Ribs

3.1 Topology Optimization of A380 Leading Edge Droop Nose Ribs

The first question that arose when considering topology optimisation of the droop nose ribs was how to best represent the attachment of the ribs to their surrounding leading edge structure (droop nose skin, main wing box front spar and skin overhang) and also how best to model the diffusion of air pressure loads into the droop nose ribs. In the section on optimisation of main wing box ribs, this was done applying super element techniques. However, for the optimisation of the A380 droop nose ribs we had not investigated such modelling techniques and therefore had no experience on how they would work with topology optimisation.

Some preliminary studies had been undertaken at Airbus UK, studying issues with boundary conditions. Leading edge droop nose ribs had been topology optimised considering the ribs in isolation and considering the ribs as part of the leading edge droop nose structure. The global compliance formulation used in the traditional formulation of the topology optimisation method had shown difficulties giving any structure, when optimising ribs as an integral part of the leading edge droop nose structure.

This problem was put down to the global compliance objective function, which included the total elastic energy in both the droop nose rib being designed but also in all of the surrounding structure. Better results had been obtained optimising ribs in isolation, but again the topology optimisation was shown to be very sensitive to stiffness of the rib/droop nose skin attachment flange. This problem was put down to the global compliance objective function used in the traditional topology optimisation method. The objective function now included both the energy in the designable area of the rib but also the energy in the rib flange that was generally considered to be non-designable.

From the very start of the new droop nose optimisation program, the decision was taken not to attempt to model the surrounding structure, as this would result in several detailed modelling issues and also increase the optimisation run times. Instead simplifying assumptions were made and all attachments to the surrounding structure were modelled using single point constraints. All lateral translations around the edge of the ribs were for example restrained to represent the very stiff span wise support from the main wing box front spar, sub spar and the droop nose skin. Constrained degrees of freedom in the plane of the ribs were also used to represent the attachments to the main wing box front spar and skin overhang.

The topology optimisation was again seen to be quite sensitive to the constrained degrees of freedom, and several studies was performed to accurately model the load transfer between the rib and the main wing box front spar and skin overhang. These boundary condition modelling issues have since been resolved using super element techniques. An example of a result of a topology optimisation is shown in Figure 7.

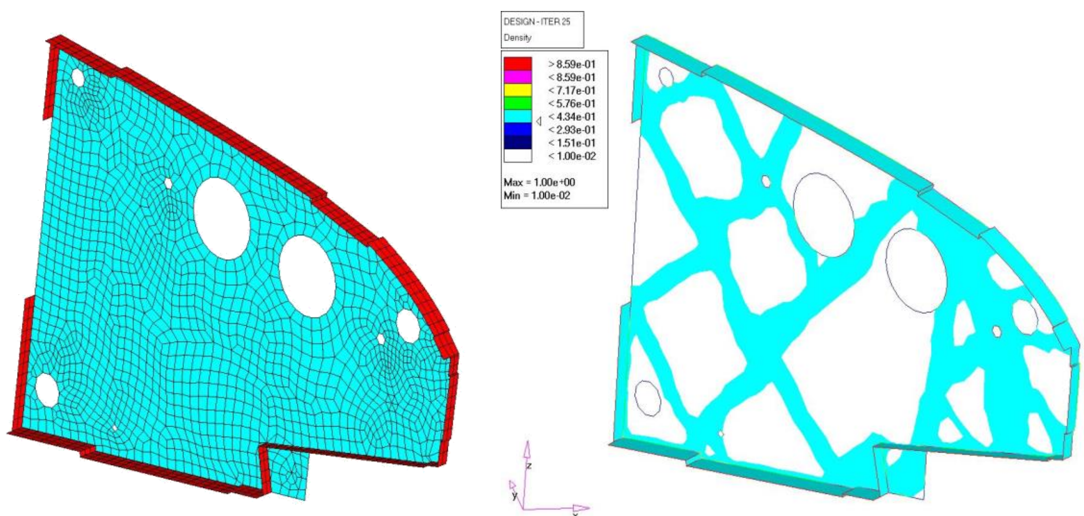


Figure 7: Topology Optimisation of Leading Edge Rib.

(The left picture shows the designable and non-designable areas for the rib while the right picture shows the design suggested by topology optimisation. A total of between 6-12 load cases were used for the topology optimisation of the leading edge ribs)

3.2 Sizing and Shape Optimization of A380 Leading Edge Droop Nose

Based on the topology optimisation results, which are used to determine a design with optimal load paths, engineering solutions were created. Interpreting regions with high density of material as structure and regions with low density of material as holes, the topology optimised designs could be interpreted as truss-like structures.

Engineering designs incorporating a mixture of truss-design and shear-web design were now formed in collaboration with the A380 designers. The ribs were also given some out of plane stability by adding vertical stiffeners at the centre of the truss members, resulting in T-sections for single-sided machined ribs and cruciform shaped sections for double-sided machined ribs (Figure 8). The engineering designs were initially built as finite element models (Figure 9) which served as initial designs for a detailed sizing and shape optimisation, incorporating both stress and buckling constraints.

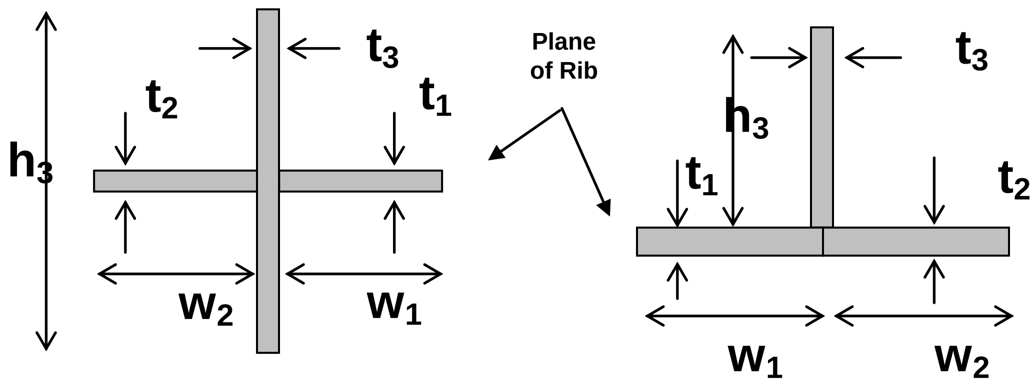


Figure 8: Design Variables for Cruciform-Section and T-Section Truss Members. The Variables w_1 and w_2 were Fixed in the Sizing and Shape Optimisation

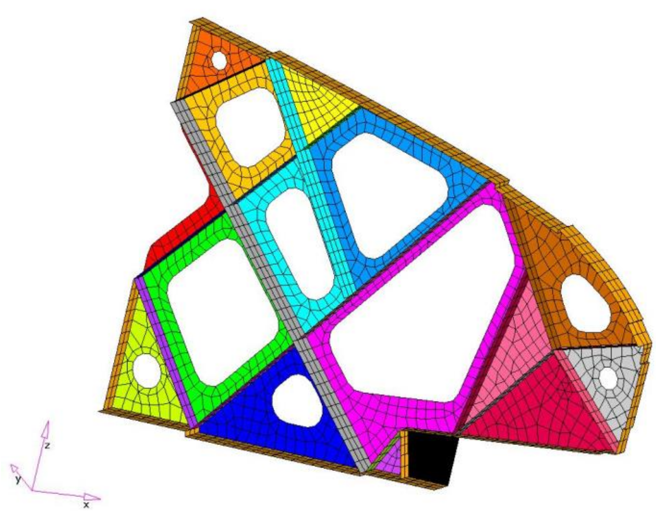


Figure 9: Initial Design for Sizing and Shape Optimisation Created by Interpreting the Topology Optimisation Result

Ideally, all of the dimensions of the truss-member cross-sections as well as the shear web thickness should be allowed to vary as design variables in the optimisation, allowing a detailed optimisation of the in-plane and out-of-plane stability of the ribs. In practice the height/thickness of the vertical stiffeners were allowed to vary, but only the thickness of the horizontal segments. Allowing the width of the horizontal segments (w1 and w2) to vary would involve changing the shape of the cut-outs in the ribs, and design variables would have to be linked to ensure for example that the vertical stiffeners remained along the centreline of the truss-members. With the current shape optimisation pre-processing tools for OptiStruct this would have been time consuming to set up, and with the short time scales of the project this complexity was not implemented.

Having constructed finite element models for detailed sizing and shape optimisation, optimisation was now performed designing for minimum mass with both manufacturing requirements and stress and buckling allowables as design criteria in the optimisation process. For stress, a Von Mises stress allowable was used with a reduction factor for fatigue. For buckling, the design philosophy was not to allow buckling of the structure below ultimate loads. The buckling constraints for the optimisation were defined requiring the buckling load factor in linear eigenvalue buckling to be greater than unity for all ultimate loads. To avoid optimisation convergence problems, due to buckling mode switching, buckling constraints were formulated for the five lowest buckling eigenvalues in each load case.

The optimisation as it stood converged to a feasible design for all thirteen ribs, with the final masses summing to a total close to the weight target specified for the work package. Subsequent to the optimisation, the new rib designs have had to be analysed / tested for several other criteria including local flange buckling, fatigue and birdstrike. Both fatigue tests and machining trials are currently ongoing. Figure 10 shows a prototype rib for the A380 droop nose rib.

Figure 10: Topology, Sizing and Shape Optimised A380 Prototype Leading Edge Droop Nose Rib Machined from High Strength Aluminium Alloy

4.0 Conclusions

The present work illustrates how topology, sizing and shape optimisation tools may be used in the design of aircraft components. The technology has been successfully used in an industrial environment with short industrial time scales and has on a single application proved to be able to provide efficient stress and stability component designs.

Initial studies have shown that care should be taken in the modelling of the load and boundary conditions of the components. For aircraft component design it is also important to be aware of the impact of changing loading situations. The truss type designs obtained using the topology optimisation are highly specialised designs optimised for certain loading situations.

Load definitions generally change as the design of an aircraft mature, and this could seriously affect the optimality of the structure. It could therefore prove important to carefully select applications for topology optimisation and only use the technology on structures with well defined loading conditions.

5.0 References

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