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AIRCRAFT WING RIB TOPOLOGY OPTIMIZED DESIGN

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Abstract. *Modern jet transporters have achieved a level of structural complexity and the search of weight reduction is a big concern in aircraft design. In order to achieve weight reduction goals, structural optimization can be used as a design tool. In this work, an aircraft wing was designed and a wing rib finite element model was extracted from the wing model. A minimum compliance topology optimization using MSC Software Analysis Solver NASTRAN was carried out using the wing rib model. Based in the SIMP (Solid Isotopic Material with Penalization) topology optimization method, the material density functions of each element were assumed as the design variables and design constraints for mass reduction to 50% and buckling were imposed. The influence of penalty factors on results was also studied.*

Keywords*: Topology Optimization, Wing Rib, Finite Elements*

1. INTRODUCTION

Modern jet transporters have achieved a level of structural complexity and the search of weight reduction is a big concern in aircraft design. Aircraft airframes design must save as much weight as possible, meeting the required safety level, but looking for future lower operational costs.

In this scenario, structural optimization is called upon and can be used as a way to have optimized structural components that satisfy the required margin of safety with no undesired material accumulation.

An initial optimized design of a regional jet wing rib is accomplished based on topology optimization techniques, utilizing the finite elements solver MSC.Nastran.

2. TOPOLOGY OPTIMIZATION

The search for the best result using the available resources is an usual objective. Different optimization methods can be used to achieve the design goal, as experimental, analytical and numerical methods.

The optimization process may be defined as the process of finding the minimum or maximum of some characteristic, which may be called the objective function. The parameters that could be changed in the system while searching for the determined objective are the design variables. For the design to be acceptable it must also satisfy some requirements, which are the design constraints.

Structural optimization basically comprehends Size, Shape and Topology Optimization

Sizing and Shape structural optimization problems are usually stated in terms of a minimum weight approach with constraints that limit the maximum allowable stresses and displacements.

Topology structural optimization problems have been usually stated in terms of a minimum compliance approach, which means maximum stiffness. The aim is to distribute a given amount of material in a certain domain, so that the stiffness of the resulting structure is maximized (the compliance, or strain energy, is minimized) for a given load case. Thus, the material mass is restricted to a predefined percentage of the maximum possible mass.

The optimal thickness distribution minimizes or maximizes a physical quantity such as the mean of compliance, peak stress, deflection, etc., while equilibrium and other constraints on the state and design variables are satisfied (Bendsoe and Sigmund, 2003).

2.1. Topology Optimization Method: Solid Isotropic Material with Penalization (SIMP)

Among the Topology Optimization methods, homogenization based methods have became the main approach to structural optimization, especially, the Solid Isotropic Material with Penalization (SIMP) method due to its implementation simplicity has been widely accepted and applied.

Topology optimization problems for continuum structures are generally formulated and solved as material distribution problems, using predefined design space model. Using finite elements modeling techniques, a loaded and supported grid topology optimization design space is initially built and the topology optimization material distribution problem is formulated by associating an artificial material with a continuously variable material density and material stiffness to each of the finite elements within the fine grid design space model. The construction of the topology optimization design space model may include modeling of both non-design features, such as predefined holes and fixed parts of a structure (Krog *et all*, 2004).

In the design of the topology of a structure the determination of the optimal placement of a given isotropic material in space is the interest focus, i.e., it should be determined which points of space should be solid material points or void points.

The intermediate value of the material density function can be penalized by using the relation below, where p is the penalty factor, $\rho(x)$ is the material normalized density (design variable) and E_0 is Young's modulus

$$E(x) = \rho(x)^p E_0,\ p \geq 1 \qquad \begin{array}{l} E(\rho = 0) = 0 \\ E(\rho = 1) = E_0 \end{array} \tag{1}$$

3. METHODOLOGY

A wing rib model was extracted from an aircraft wing model and the wing resulting deflections due to the flight and ground loads application were applied to the perimeter of the rib model (local model) as enforced displacements, see Figure 1 below as reference. This simulates the loads transferred across a free-body section of the global model where the local model is embedded in.

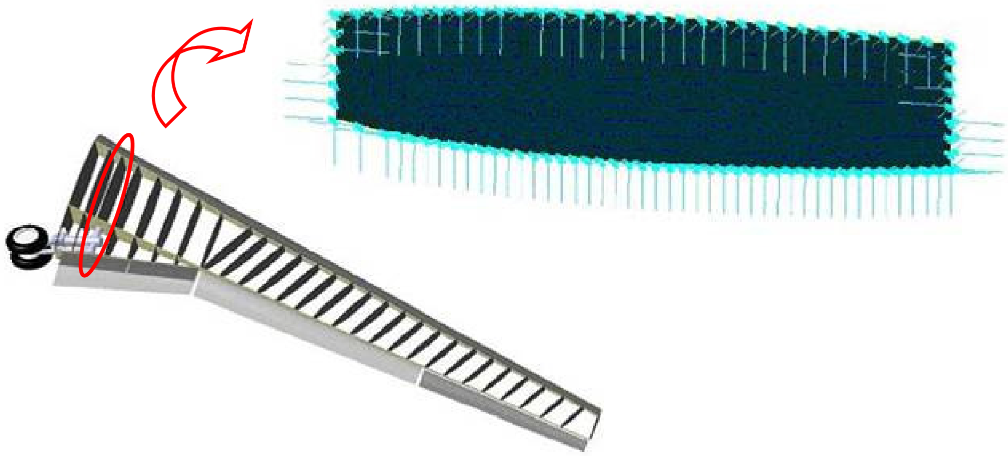

Figure 1. Rib Finite Elements Model extraction from a aircraft wing.

Topology optimization using MSC Software Analysis Solver NASTRAN was carried out using the wing rib model. Compliance minimization is the objective. The material density function $\rho(x)$, i.e., the material normalized density, was the design variable related to each element and design constraints for mass reduction to 50% and buckling constraint were applied. Buckling constraint was applied indirectly, using the rib structure eigenvalue. Firstly, it was analyzed a non-optimal rib model for buckling. The smallest positive eigenvalue obtained in this first analysis was considered as acceptable to the optimized rib model, since wing deflections were acceptable. Then, a design constraint was imposed to the rib eigenvalue, aiming to keep it as closest as possible to the original one.

A checkerboard free algorithm was used as a means to prevent the "checkerboard effect" on the optimization results.

Regarding the penalty factor, p, initially a penalty factor 3 was used in the topology optimization. Additionally, using the same optimization parameters and rib model, the topology optimization was also performed using penalty factors 2 and 4, in order to study the influence of this parameter on the final results and optimized configurations.

4. RESULTS

Figure 2 shows the critical von Misses stress distribution in the rib finite elements model pre and post-optimization, design cycle 0 and 29, respectively.

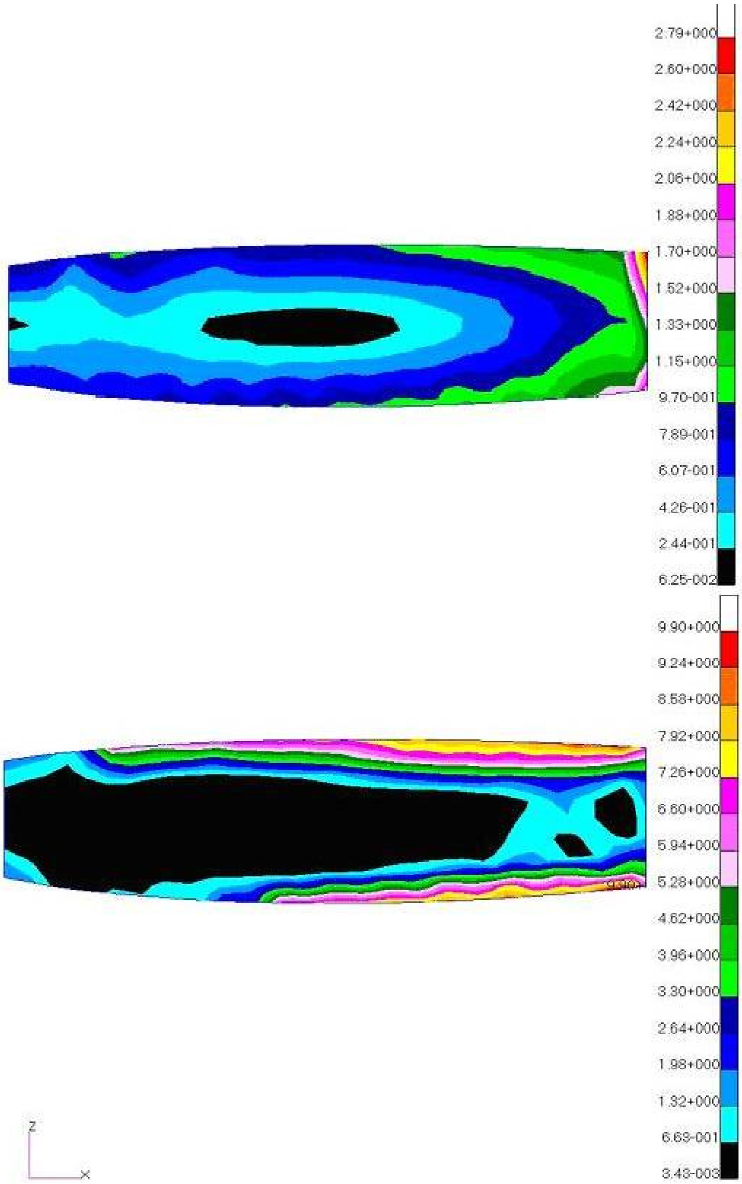

Figure 2. Stress distribution: Pre-optimization: Design cycle 0 (upper) and Post-optimization: Design cycle 29 (lower)

Comparing the stress results before and after optimization, it can be noticed that the gain in terms of material stress distributions is very significant. For the optimized rib finite elements model the stress tensor increased approximately 250%, meaning that the material stiffness distribution was better used.

Linear buckling analysis was performed in order to obtain the eigenvalues (buckling loads).

Figure 3 shows first buckling mode. The corresponding eigenvalue is $\lambda = 0.1147$.

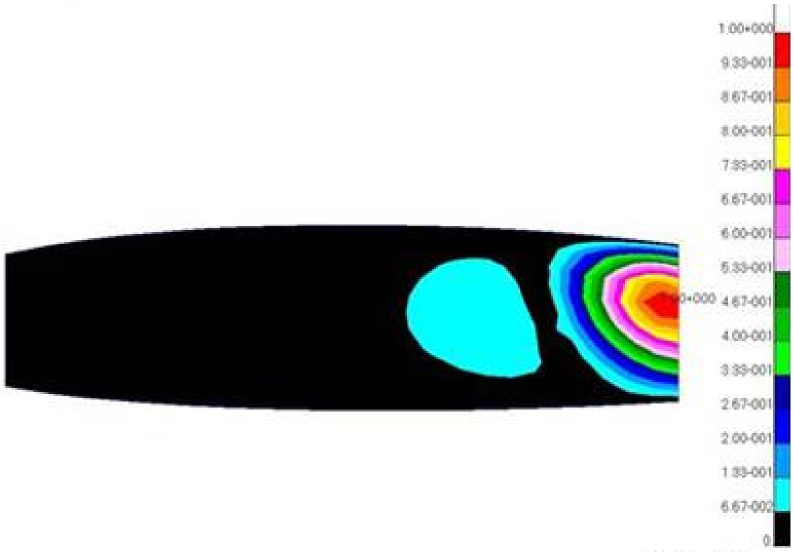

Figure 3. Rib Finite Elements Model Buckling Analysis Result

The smallest positive eigenvalue obtained in this initial analysis was considered acceptable to the optimized rib model. A design constrain was imposed to the rib eigenvalue, aiming to reproduce on the optimized rib the same bucking analysis results and stability characteristics of the original rib.

Optimal element normalized density distributions are also obtained as result of the topology optimization. Figure 4 shows the optimal normalized density distribution results for the wing rib finite elements model. The color distribution indicates the normalized density scale. The white regions indicate that, as a result of topology optimization, the rib material should not be placed on those regions, since they are useless for a maximum stiffness design.

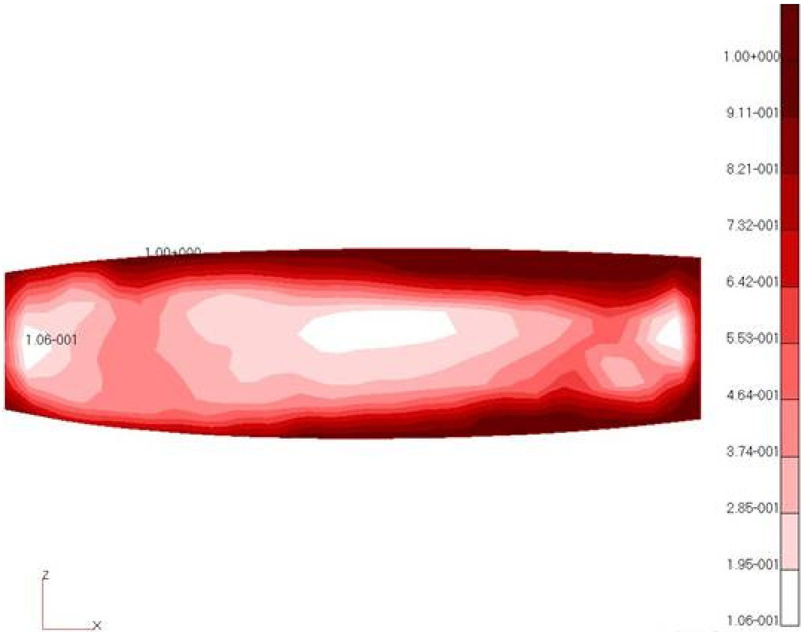

Figure 4. Optimal density distribution

Another way to present the density distribution results is the use of threshold values, which allow exclusively the visualization of elements that have normalized density values beyond the density value limit determined by the threshold value.

In order to evaluate the influence of the penalty factor, two additional optimization models were obtained. Figure 5 to Figure 7 show the optimal element density distribution for a density threshold of 0.50 using penalty factor $p = 2$, $p = 3$ and $p = 4$, respectively.

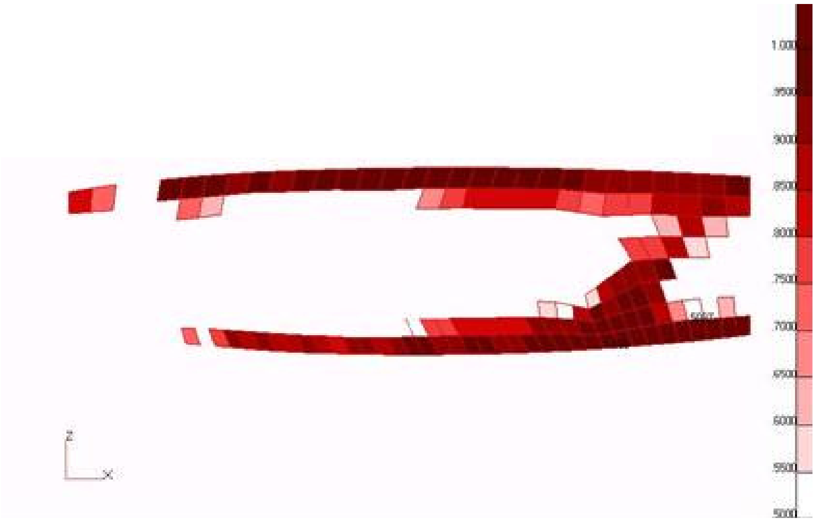

Figure 5. Optimal Element Density Distribution – Density Threshold = 0.5, Penalty Factor = 2

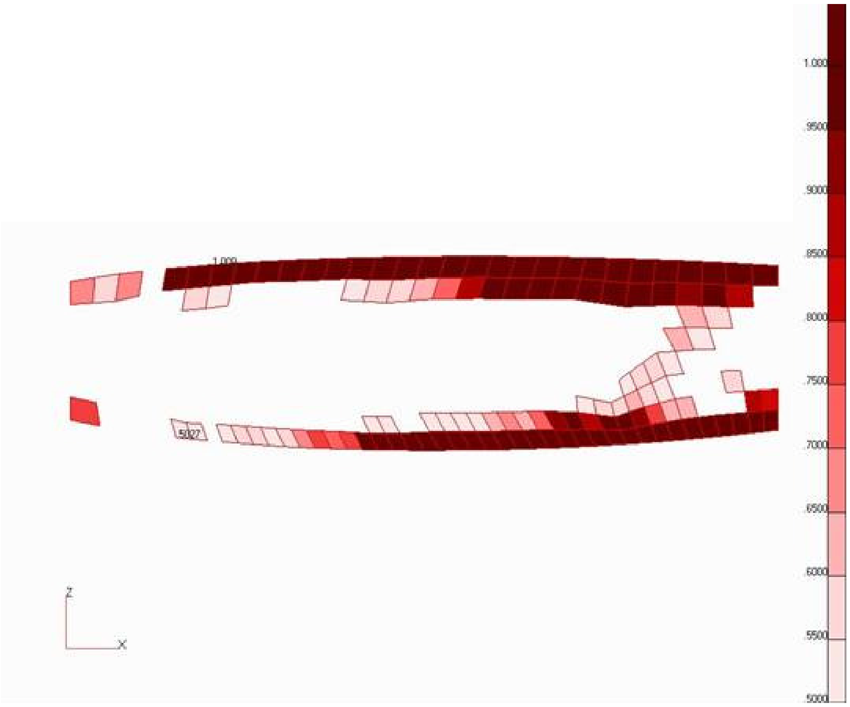

Figure 6. Optimal Element Density Distribution – Density Threshold= 0.5. Penalty Factor =3

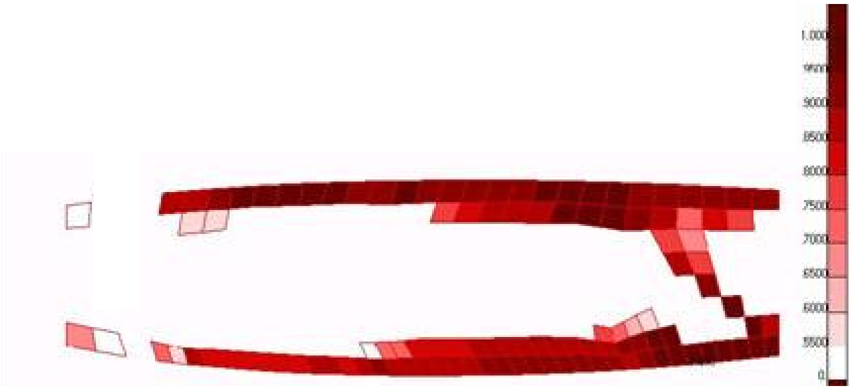

Figure 7. Optimal Element Density Distribution – Density Threshold = 0.5, Penalty Factor = 4

Regarding the penalty factor influence, a larger penalty factor suppresses intermediate thickness values. Comparing the optimal element density distribution results presented before for the three values of penalty factor, p = 2, p = 3 and p = 4, it can be seen that the greater the penalty factor is, the fewer are the intermediate thickness optimized elements. The penalty factor also has a large influence on the solution of topology optimization problems. A lower penalty factor often produces a solution that contains large “grey” areas, with intermediate densities, and a higher value produces more distinct solid and void elements.

5. CONCLUSION

The use of topology optimization to determine an optimal design concept results in novel designs, producing significant weight savings.

Solid Isotropic Material with Penalization (SIMP) approach demonstrated to be efficient in structural design improvements and due to its implementation simplicity can be widely accepted and applied.

Regarding the buckling constraints, although the energy based minimum compliance topology optimization method do not allow to perform optimization with respect to stress and buckling constrains, the eigenvalue constraint imposed on this study showed to be efficient to guarantee a satisfactory buckling performance of the rib when analyzed as a stiffener of the global wing.

Observing the optimal density distribution presented before it is possible to verify that the optimized rib configuration has solid material around its contour and distributed vertically on two intermediate regions (Figure 4), which configures rib reinforcements. Also, observing the first buckling mode in Figure 4 and the optimal density distribution results, it can be noticed that the rib right side “reinforcement” coincides with the first mode buckling deformed region.

The study of penalty factor influence on the solution of topology optimization problems showed that the greater penalty factor is, fewer are the intermediate thickness optimized elements and also its influence on the optimized thickness distribution.

In a general view, it can be concluded that the topology optimization should be performed in the context of a complete study, together with sizing and shape optimization. Topology optimization should be used to provide stiffness optimal design concepts and sizing and shape optimization should be used to provide detailed sizing against stiffness, stress, fatigue and buckling.

6. REFERENCES

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7. RESPONSIBILITY NOTICE

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