Abstract

The paper demonstrates the application of a modified Evolutionary Structural Optimisation (ESO) algorithm for optimal design of topology for an aerospace component. The capabilities of ESO for producing an optimal design against a specified strength constraint are illustrated using an aerospace design problem of optimisation of the topology of a bulkhead used in an aircraft structure. It has been shown that topology optimisation using ESO can result in considerable reduction in the weight of a structure and an optimum material utilisation by generating a uniformly stressed structure. The paper evaluates and establishes the ESO method as a practical tool for optimum topology design problems for complex industrial structures.

Keywords: Structural optimisation; Topology optimisation; Evolutionary algorithm; Finite element analysis; Structural analysis.

1. Introduction

Topology optimisation focuses on determining an optimum distribution of material within a prescribed region satisfying specified design constraints. Topology optimisation determines the general layout of a structure for given design specifications.

Evolutionary Structural Optimisation (ESO) is a gradient-less, heuristic optimisation method that mimics the Darwinian principles of evolution in naturally occurring structures. This method was proposed by Xie and Steven [1, 2]. ESO works by imitating biological structures in nature. It has been observed that naturally occurring species tend to achieve shapes that are close to ‘fully stressed’ configurations, as
this leads to an optimal material utilisation. In this paper, we apply the traditional ESO algorithm to topology optimisation of a realistic large scale structure. The basic principle of ESO can be expressed as: if a portion of material in a structure does not contribute effectively to the functioning of the structure with respect to its design objective(s), then it can be removed from that region. This gradual removal process leads to a structure that meets the design objective(s) subject to constraints [2].

2. Bulkheads in an aircraft

A primary strength of ESO is that it is a versatile tool that can be used for redesigning an existing structure. The need to lighten structural components without compromising their functionalities was first recognised in the aircraft industry. ESO is particularly suitable for accomplishing weight reduction under a given set of loads and constraints. Here we will demonstrate this by applying ESO to obtain an improved topology for an F/A-18 aircraft bulkhead. The aim here is to produce a lighter bulkhead structure satisfying the prescribed geometric, functional, and strength requirements.

The bulkhead under consideration forms a key component of the F/A-18 aircraft. This aircraft is well-known for its manoeuvrability and high performance. Weight reduction and life extension programs are two important areas of active research. In the context of topology optimisation we will focus on the former aspect. The aircraft as a whole is an extremely complex structure. There are many components that can be potentially optimised to reduce their weights. One specific region of the F/A-18 aircraft that has potential for further weight reduction is the structural components associated with the centre barrel. The F/A-18 centre barrel section and its associated bulkheads can be seen in Fig. 1a.

![A set of full F/A-18 bulkheads](Fig. 1a) A set of full F/A-18 bulkheads (courtesy: DSTO, Melbourne [3]); (b) Half solid model (3D) of the initial bulkhead

![Half solid model (3D) of the initial bulkhead](Fig. 1b)

A 3D solid model of the bulkhead was analysed (Fig. 1b) in which some of the complicated features of the actual structure were simplified provided their effects on the main analysis results of interest were negligible. The major portion of the bulkhead was made of an aluminium alloy (Al7050-T7451). The Young’s modulus ($E$), Shear modulus ($G$), and Poisson’s ratio ($\nu$) were taken as 71,015.7 MPa, 26,889.4 MPa, and 0.33 respectively. Beryllium-copper alloy was used in a small portion of the wing attachment lug with material properties: $E = 127,552$ MPa, $G = 50,193.6$ MPa, and $\nu = 0.27$. A linear-elastic finite element analysis was performed throughout.
3. Finite element modelling

A half-symmetric 3D solid model of the bulkhead, shown in Fig. 1b, was analysed here. The solid model was meshed with 34,306 (21 node) hexahedral (brick) elements and it had 169,333 nodes. The finite element mesh of the initial bulkhead along with the von Mises stress distribution is shown in Fig. 1b. Depending on the state of the aircraft such as take-off, landing, and various flight conditions, the bulkheads are subjected to a range of load cases. In typical structural tests (e.g. those conducted at DSTO, Australia [3]), the loads on the bulkhead were applied through attachment forks using an actuator system. In the analysis, the loads and constraints were as indicated in the \(xz\) view of the model shown in Fig. 2a. The model was symmetric about the \(yz\) plane and accordingly appropriate symmetry constraints were imposed on the relevant planes. In this study we considered the most critical load case, technically known as the ‘Combined Set 55’ [3], shown in Fig. 2a. In this load case, the loads at the wing attachment holes act in the horizontal direction under the in-service loading condition of the aircraft. The loads were modelled as bearing loads and applied on the semi-cylindrical surfaces of the holes. The resultant load in the upper hole was 100.869 KN acting horizontally towards left, and the same in the lower hole was 101.708 KN acting horizontally towards right.

![Fig. 2. (a) Loads and constraints on the bulkhead used in the analysis; (b) Locations of the holes in the bulkhead along with the von Mises stress distribution around them](image)

In this study the von Mises stress was taken as the ESO criterion. The von Mises stress distribution is shown in Fig. 2b. The maximum von Mises stress for the initial structure was 86.4 MPa. Highly stressed regions can be observed around hole D, and some portions around the flange hole. The loads from holes A and B were transmitted to the region around hole D and the left end of the structure along the upper and lower sections of the central flange hole. This resulted in some regions, such as the lower protruded portion below hole C, a part of the upper left region, and some portions around the flange hole boundary, being lowly stressed. These areas of the structure represented potential inefficient utilisation of material in sharing the loads.

A number of geometric constraints were imposed to meet the functionality requirements. The holes in the bulkhead serve different functions. For example, holes A and B (Fig. 2b) are used to transmit loads. The large central flange hole holds the bulkhead flange. Other holes are also used as various connection points. Hence, it was a design requirement that the hole boundaries be retained in the final topology. This was accomplished by dividing the structure into a ‘restricted domain’ and a ‘design domain’ using the FEMAP pre-processor. The restricted domain consisted of the regions around the hole boundaries,
whereas the rest of the structure constituted the design domain. Alteration of the topology was permitted only in the design domain, and the restricted domain was kept intact throughout the optimisation process.

4. Optimisation using ESO

The ESO algorithm was used to reduce the weight of the structure by removing inefficient material. At each optimisation cycle a finite element analysis was performed using NE-NASTRAN. The optimisation algorithm was then employed to modify the topology based on the von Mises stress field. At each iteration, a reference von Mises stress was calculated based on the current stress distribution. An element was then removed from the structure if its von Mises stress was lower than the reference stress.

The gradual evolution of the structural topology and the associated variation in the stress pattern, as the optimisation progressed, is illustrated by a few intermediate topologies in Fig. 3. The extent of material removal at various stages of optimisation was primarily governed by the relative stress levels among various portions of the structure. Topology evolution history is useful in exploring alternative designs. This history also helps in identifying innovative designs, which may not be easily realised using conventional design guidelines or common experience.

![](image)

(a) Iteration No. 30: $W/W_0 = 94.2\%$ (b) Iteration No. 50: $W/W_0 = 85.4\%$ (c) Iteration No. 80: $W/W_0 = 76.0\%$

Fig. 3. Evolution history of the bulkhead topology and the associated von Mises stress distribution

As material being removed, the maximum von Mises stress generated in each topology and the corresponding change in weight of the bulkhead are shown in Fig. 4. The optimum point can be located on the basis of the weight and maximum stress histories. The aim of the present study was to reduce the weight provided the maximum stress did not exceed an allowable value. This maximum allowable design stress is usually determined based on failure criteria, material properties, operating conditions, and an adequate factor of safety. Here the maximum acceptable design stress ($\sigma_a$) was set to be 95 MPa, which is ~10% higher than the initial maximum stress. It was required to find a ‘minimum’ weight structure for which the maximum stress was just below $\sigma_a$.

To this end, a constant stress line representing $\sigma_a = 95$ MPa was drawn in Fig. 4a. The design topology immediately preceding the point of intersection of this horizontal line with the stress history curve corresponded to a structure that had a maximum von Mises stress just lower than the permissible value. This point was taken as the final design. In this problem the ‘optimised’ structure was obtained at the 86th iteration. The maximum von Mises stress, under the given loads and constraints, associated with this
The resultant optimal topology is shown in Fig. 5. The material was removed from the lowly stressed regions. The hole boundaries were kept intact by enforcing the geometric constraints. The primary load paths for the optimal structure are indicated in Fig. 5b. The optimal topology has the following features:

- The region between holes A and B was lowly stressed in the original structure. In the improved (optimal) topology, a small amount of material was removed from this region, and the stress field became more uniform, see Fig. 5b.

- A major part of the load from holes A and B is now transmitted along load path 1 to the upper left end support. This is manifested by a slightly higher and a more uniform stress distribution in the top section (above the flange hole). Load is also transferred through load path 2, which passes through the section near point X in zone 2 (Fig. 5b), to eventually reach the region surrounding hole D. However, this section does not have sharp features that could have resulted in significant stress concentrations. Although in the original structure the left portion of the flange hole (zone 1 in Fig. 5b) did carry load, little load is transmitted through this section, i.e. along load path 3, in the optimal layout.

- From the optimal structure it can be noticed that most of the material was removed from the regions marked as zones 1, 2 and 3 in Fig. 5b. In the original structure zone 3 had very low stresses as it was not in the primary load paths, see Fig. 2b. Hence, considerable material was removed from this zone. Although zone 1 carried some load in the original structure, it was still inefficiently utilised, which led to the topology being altered in this zone. The lower left portion of the flange hole (in zone 2) did not effectively take part in sharing loads, and as a result material was taken away from this zone as well.

The topology obtained using ESO is a conceptual design and needs post-processing, which may include incorporation of additional design features or constraints, local modification of the structural geometry, shape optimisation of local features, etc. For example, we notice some partially ‘floating’ hole boundaries in the final topology. This is because of the imposed geometric constraints that the boundaries...
of all the holes in the original structure must remain unaltered to enable them to serve as attachment points. It may be noted that all the three zones indicated in Fig. 5b, including the regions around the holes, need redesigning to generate an acceptable final design.

![Schematic load paths](image)

Fig. 5. Optimal topology of the bulkhead along with the von Mises stress distribution

5. Conclusions

This paper has investigated the Evolutionary Structural Optimisation algorithm for topology generation of a complex industrial structure. The capabilities of the ESO algorithm were demonstrated by considering a topology optimisation problem encompassing layout design of a bulkhead of an F/A-18 aircraft. The ESO algorithm acted upon the existing design to generate an improved (topological) layout. Gradual material elimination from various parts of the structure led to the evolution of an improved topology. The ESO algorithm is found to be a reliable, robust, efficient, and practical tool for topology optimisation of real life complex structures. The ESO based techniques are relatively inexpensive, easy to implement and can serve as a good starting point for further design improvements by subsequently applying other (shape) optimisation techniques. A significant weight reduction of the structure can often be achieved without greatly compromising the strength below an acceptable limit. The ESO technique can thus be applied to obtain a structure with an improved material utilisation. This method attempts to reduce the variation in stress levels and produces a relatively uniformly stressed structure, thus leading to a more optimum material utilisation.

References

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