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DESIGN OPTIMIZATION OF COMPOSITE AEROSPACE STRUCTURES

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1. INTRODUCTION

Thin-walled elements are widely utilized in the design of aerospace structures as they allow to obtain lightweight structures. However, while the structures so designed may be sufficient to carry the in-plane tensile loads and satisfy strength requirements, they are often prone to fail under buckling induced by compressive or shear loads. Buckling is a highly non-linear phenomenon caused by the sudden conversion of a large amount of in-plane strain energy into bending strain energy [1]. This process may be expressed in different modes. For example, global buckling is said the catastrophic collapse of the entire structure; local buckling affects a portion of the skin; stiffener buckling occurs in correspondence of stiffener segments. Other "special" buckling modes are typical of sandwich structures (wrinkling, dimpling, etc.).

In order to guarantee structural safety against buckling, reinforcing elements (stiffeners) running in the longitudinal and transverse directions are added to the panel skin to increase the stiffness of the structure. The proper selection of the stiffening configuration and materials leads to minimize structural weight thus maximizing payload. A number of trade studies on the sensitivity of structural weight of stiffened panels to parameters such as stiffener geometry, materials, and type of construction and manufacturing methods were presented in literature (see for example, [2,3]). Design concepts are usually compared and preliminarily selected to be further developed later on the basis of their structural weight (typically, the weight per unit area) which is minimized by means of optimization methods.

Structural optimization is mandatory in the design of aerospace structures. Design variables are repeatedly perturbed to satisfy non-linear constraints on displacements, stresses and critical buckling loads. Optimization methods can be divided in two main groups: Approximate Optimization Methods (AOM) and Global Optimization Methods (GOM). AOM formulate and solve a set of sub-problems where the original non-linear functions of the optimization problem are replaced by linear, quadratic or higher order approximations built including gradient information. Larger fractions of design space can be explored using multi-start approximate optimization (MSAO) where different optimization runs are performed starting from points generated randomly. The main difficulty of approximate optimization is to keep the quality of the approximation as highest as possible and always reliable in the region of design space currently being searched. Furthermore, approximate models should change during the optimization process based on the sequence in which design constraints become active.

Global optimization methods search the optimum design by generating randomly a certain number of trial designs. This is done in purpose to expand the portion of design space explored by the optimizer thus increasing the probability of finding the global optimum without being stuck in local optima. Meta-heuristic optimization methods are more efficient than purely random search as they generate trial designs based on some inspiring principle taken from physics, biology, astronomy, evolution theory, music, social sciences etc [4].

While stiffeners increase the bending stiffness of thin-walled members, they add an extra dimension of complexity to the model compared to unstiffened plates and shells. Furthermore, stiffened structures often employ a repeating stiffener pattern. The repeated (periodic) nature of the geometry allows the use of simplifying assumptions to obtain approximate analyses.

As is mentioned before, design is repeatedly perturbed in order to find the optimal configuration. Hence, optimization of aerospace structures may entail several thousands of finite element analyses including hundreds of thousands of elements and computationally expensive tasks such as nonlinear buckling analysis. Because this may be openly in contrast with constraints on time and computational resources, engineers must dispose of surrogate models able to quickly evaluate structural response under loading conditions. However, surrogate models may err on the conservative side thus leading to unnecessarily heavy designs. Furthermore, optimizers may exploit any weakness or deficiency in modeling. Finally, the level of refinement adopted in discretizing models may affect computation of sensitivities in terms of a certain amount of noise introduced in the optimization process. In view of this, the structural optimization problem must include additional constraints to keep the design search in regions where modeling assumptions on which surrogate models lay may hold true.

The design of composite stiffened panels presents even more challenges due the additional failure modes and anisotropy effects introduced by composite materials [2-3, 5]. Optimizing ply orientations in preliminary design is not recommended for a number of reasons. Composite laminates have failure modes that are difficult or expensive to model and analyze during design optimization. Furthermore, preliminary design optimizations are generally performed by considering a small number of load cases. Optimizing ply orientations using a small set of design load cases and simple analyses can produce laminates that will fail under neglected failure modes or loading conditions.

In addition to sizing optimization for fixed laminate thickness and stacking sequence, individual ply thicknesses can be optimized keeping the same stacking sequence. These optimizations require two iterations. In the first iteration, the ply thickness and size variables such as stiffener dimensions and spacing are optimized as continuous variables. The optimum ply thickness from the continuous optimization is rounded to the nearest integer multiple of pre-preg ply thickness. The panel design variables, excluding ply thicknesses are once again optimized to ensure that the ply thickness rounding did not result in suboptimal or infeasible designs.

Composite stiffened shells hence permit optimization on more design variables because the individual ply thickness can be changed in addition to the stiffener sizes and spacing. Increasing the number of optimization variables (design freedom) allows to design lighter structures but also increases the imperfection sensitivity of the optimum designs and makes them less robust.

Composite designs may be significantly affected by thermal considerations. The optimized design results from a complex combination between structural safety requirements, imperfection sensitivity and the layout and materials of thermal insulation/protection systems. For examples, sandwich shells may be not very efficient in terms of weight if face-sheets must be designed thick enough to avoid permeation of liquid propellants. Using non-symmetric layup constructions permits to overcome this limitation but introduces issues on structural stability.

This paper will review the most important aspects involved in the design optimization of composite stiffened structures for aerospace applications. It will be shown how structural weight may be affected not only by the number of design variables but also by the level of accuracy of the surrogate models employed in the structural analysis. An example of trade study carried out on composite stiffened panels utilized for second generation reusable launch vehicles is included in the discussion. A comparison between deterministic optimization and probabilistic optimization is presented as well.

Finally, a general approach to structural design of composite aerospace structures is discussed. This approach is based on a multi-level architecture. In Level 1, a series of detailed finite element analyses of the entire structure or segments/parts serve to establish exact correlations between numerical models and experimental tests. This information is included in Level 2 which is based on the use of approximate analysis methods corrected by response surfaces depending on design variables. In Level 3, software tools developed in Level 2 serve to optimize the structure ensuring that the constraints put on structural response reproduce reliably the overall behaviour of the structure. In Level 4, optimized designs found in Level 3 must be verified by means of the detailed finite element model built in Level 1. Sensitivity of optimized design configurations with respect to design variables (for example, in terms of changes in critical buckling loads for small design perturbations in the neighbourhood the optimum design) is evaluated. Sub-optimal designs could even be chosen if they were judged more affordable in terms of manufacturing processes.

BASIC REFERENCES

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