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Optimal design of composite lateral wing upper covers. Part II: Nonlinear buckling analysis

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A B S T R A C T

The present investigation is devoted to a development of new optimal design concepts of aircraft lateral wing upper covers made of advanced composite materials. In the second part a stiffened composite panel with the best weight/design performance obtained from the linear buckling analysis (Part I) is verified by the nonlinear buckling analysis and re-optimized in the case of necessity. Additionally an effect of shear and fuel pressure as well as an effect of skin post-buckling on its performance is investigated. Three rib bays laminated composite panels with HAT-stiffeners were modeled with ANSYS finite element code to study their buckling behavior as a function of skin and stiffener lay-ups, stiffener height, stiffener top and root width. Due to the large dimension of numerical problems to be solved, an optimization methodology was developed employing the method of experimental design and response surface technique. Weight optimization problems were solved for four load levels, taking into account manufacturing, repairability and damage tolerance requirements. Optimal results were verified successfully using ANSYS shared-node model.

1. Introduction

The European Aeronautics Industry's Strategic Research Agenda addresses the reduction in operating costs of relevant European aerospace products by 15% through the cost effective application of carbon fiber composites to aircraft primary structure and taking into account systems integration. This can be achieved by realizing the weight saving potential of advanced composite materials, by reducing the manufacturing costs of composite components and by reducing subsequent product maintenance costs. Due to increasing application of advanced composites in aircraft structures, a significant progress was achieved recently in the buckling and post-buckling analyses of stiffened laminated composite panels [1–3].

To carry out accurate and reliable simulations for stiffened fiber composite panels under compression loads, the improved analysis tools validated by experiments for post-buckling analysis up to collapse were developed in papers [4,5]. The effect of simplified models in structural design [6] and the effects of geometric scaling on stiffened composite flat panels loaded in axial compression using quarter-, half- and full-scale specimens [7] were studied using test results and finite element simulations. All these investigations demonstrate that analytical results obtained from nonlinear finite element analysis correlate fairly well with experimental results up to failure.

Since a weight reduction is the final purpose of utilization of composite materials in aerospace structures, some optimization methodologies were developed based on the response surface technique or using Genetic Algorithms. Unfortunately the definition of optimization procedure in this case becomes complicated due to the large computational effort required to predict the nonlinear buckling behavior of stiffened composite panels and the presence of nonlinear constraints. To overcome these difficulties, an optimization procedure based on a global approximation strategy was developed in paper [8], where the structure response is approximated by a system of neural networks trained by means of nonlinear finite element analyses. In paper [9] the minimum weight design of compressively loaded stiffened composite panels was performed using a nonlinear finite element code and modified Genetic Algorithm with parallel computing scheme to accelerate the optimization procedure.

Optimization techniques based on the global [10,11] and local [10] approximation strategies were applied to study the post-buckling behavior of stiffened composite panels. In paper [10] the optimization procedure is based on the building of surrogate models employing the experimental design and response surface methodology. These meta-models are produced using contin-

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Table 1
Optimal parameters of composite panels with HAT-stiffeners and stiffener pitch 240 mm obtained with linear buckling analysis.

Load, kN	100	500	1000	1500
Skin lay-up	$(\pm45, 0_4, 90, 0)_s$	$(\pm45_2, 0_4, 90, 0)_s$	$(\pm45, (0_4, 90)_2, 0)_s$	$(\pm45, (0_4, 90)_3, 0)_s$
Stiffener lay-up	$(\pm45, 0_4, 90, 0)_s$	$(\pm45, 0_4, 90, 0)_s$	$(\pm45, 0_4, 90, 0)_s$	$(\pm45, (0_4, 90)_2, 0)_s$
H_W, mm	30	48.5	55.5	56
W_{HF}, mm	25	44.5	60	25.5
W_{LF}, mm	18.5	28.5	30.5	32
A, mm^2	1472	2026	2526	3532

uous and discrete quantitative parameters, and approximated with global and local nonparametric approximations. Such methodology gave the possibility to implement a data set of natural experiments into surrogate models and by this way to improve an estimation of the post-buckling behavior of stiffened composite panels. The multi-objective optimization procedure based on Genetic Algorithms and three different methods of global optimization: Neural Networks, Radial Basis Functions and Kriging approximation is presented in paper [11], where the response surfaces were applied to approximate the post-buckling behavior of stiffened composite panels using a limited number of sample points.

Two-level composite wing structural optimization methodology using response surfaces was applied for the design of a simple wing box structure subjected to strength and buckling constraints in paper [12]. The procedure is based on continuous optimization at the wing level using a finite element model and genetic optimization at the panel level. A response surface of optimal panel buckling load was used for communication between the two levels. Unfortunately the wing in this paper is assumed to consist of unstiffened composite panels. It is necessary to note that most present studies are devoted to the design of primary fiber composite fuselage structures and focused on the weight optimization of stiffened composite panels under axial compression loads.

The methodology based on the planning of experiments, response surface technique and linear buckling analysis for optimal design of stiffened laminated composite panels with special emphasis on more close conformity of the finite element analysis and operational requirements for aircraft lateral wing upper covers was developed in paper [13]. This study gave the possibility to compare properly optimal solutions obtained for the laminated composite panels with different type of stiffeners: T, I and HAT, and to choose a panel with the best weight/design performance for the further development. It is necessary to note that in application to the ALCAS lateral wing upper cover developed in the project "**A**dvanced **L**ow **C**ost **A**ircraft **S**tructures" (ALCAS), the chosen panel with HAT-stiffeners and larger stiffener pitch (240 mm) would constitute the best overall option since a larger stiffener pitch implies less stiffeners in the cover, requiring fewer rib-to-cover connecting units, and decreasing ribs complexity, which when all considered lead to a reduced manufacturing and assembly costs and time. Moreover covers with a larger stiffener pitch represent increased space available for skin ply drop-off regions between stiffeners (since chord-wise skin ramps located under the stiffener feet need to be avoided due to cover-to-ribs assembly issues), contributing to a more optimized overall weight of the skin at the thickness transition zones.

The present investigation is a continuation of the optimal design of composite lateral wing upper covers described in the Part I [13]. In the Part II the chosen composite panel with HAT-stiffeners is verified by the nonlinear buckling analysis taking into account effects of shear and fuel pressure, and skin post-buckling. The developed approach gives the possibility to estimate an influence of the results of linear and nonlinear buckling analyses, different load set-ups and allowed skin post-buckling on the optimal weight solution obtained for the stiffened composite panel and lateral wing upper cover.

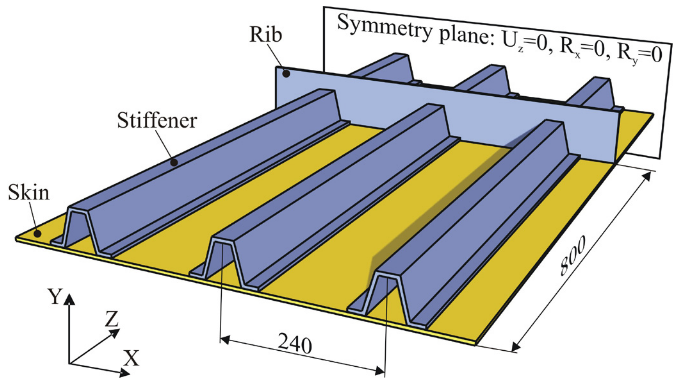

Fig. 1. Composite panel with HAT-stiffeners.

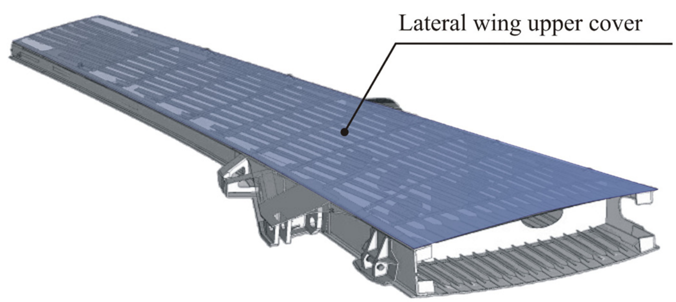

Fig. 2. Lateral wing of aircraft.

2. Construction of lateral wing upper cover

The stiffened composite panel (Fig. 1) with the best weight/design performance (Table 1) obtained from the linear buckling analysis and optimization in the Part I [13] is used in the present study. This panel is examined as a part of the aircraft lateral wing upper cover (Fig. 2) and consists of skin, ribs and HAT-stiffeners made from unidirectional Intermediate Modulus carbon fiber prepreg tapes (T800/M21 or IMS/977-2) with the following material properties: $E_1 = 157$ GPa, $E_2 = 8.5$ GPa, $G_{12} = 4.2$ GPa, $\upsilon_{12} = 0.35$, $\rho = 1600 \frac{\text{kg}}{\text{m}^3}$ and thickness of one cured ply $t = 0.25$ mm. These values are used in the damage tolerance analysis, but in the nonlinear buckling analysis material properties are reduced by the value of safety coefficient $k = 1.2$. The stiffened panel is attached to the wing box structure by ribs (Fig. 3) perpendicular to stiffeners with the rib pitch 800 mm. The effect of rib attachment to stiffener webs on the performance of stiffened panels in terms of buckling behavior was investigated in paper [14]. The nonlinear buckling analysis with a set of four load cases (100, 500, 1000 and 1500 kN per stiffener bay) is carried out for the panels with HAT-stiffeners (Fig. 4) and stiffener pitch 240 mm to verify the optimal weight design obtained with the linear buckling analysis and to study an effect of shear and fuel pressure on the performance of stiffened composite panels, and to investigate their behavior under skin post-buckling.