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Post-buckling optimization of composite stiffened panels: Computations and experiments

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Abstract

A multi-objective optimization procedure for the design of composite stiffened panels capable to operate in post-buckling is presented. The procedure is based on Genetic Algorithms and three different methods of global optimization: Neural Networks, Radial Basis Functions and Kriging approximation. Response surfaces are used to approximate the post-buckling behaviour of the panels using a limited number of sample points. Optimization results underline the significance of non-dominated solutions, as the best panel configurations inside the domain of interest. Finally, one of the non-dominated solutions is selected, manufactured and tested up to collapse. The analyses, performed a priori without considering any kind of imperfection, are closed and in good agreement with the tests in terms of pre-buckling and post-buckling stiffness, as well as in terms of collapse loads. The introduction of imperfections reduced the percentage errors between computations and tests within 5% in so far as buckling and collapse loads are concerned. The obtained results prove the influence of the initial imperfections not only on the first-buckling load but also in the post-buckling range up to collapse.

Keywords: Composite stiffened panels; Post-buckling; Genetic Algorithm; Global approximation

1. Introduction

Stiffened panels constitute one of the most common structural elements in aerospace field. The extensive use of these elements is mainly motivated by their high efficiency in terms of stiffness to weight and strength to weight ratios.

As a matter of fact, stiffened structures are mainly realised in aluminium alloy and in few cases might be designed to work in the post-buckling field overcoming the first buckling load, especially in fuselages. In fact, it is well known that a proper design of longitudinal stiffeners and of panel skins may allow the structure to carry loads several times and even many higher than the first buckling one. This design philosophy has demonstrated significant potential for further weight reductions. On the other hand, the use of very efficient aluminium alloy structures is nowadays made possible by validated design procedures, analysis methods and by a widely large amount of experimental data, also in terms of strength capabilities and failure modalities collected since the beginning of the 1900.

For the last three decades, with the advent of the new composite materials, more and more effort is devoted to replace the classical aluminium stiffened panels with these new ones.

On the other hand, the improved design flexibility provided by the use of composite materials turns out to require more complex design methods. These methods have to account for the larger number of variables and constructive configurations, which should be analysed during the design phase, as well as the complex behaviour of composite materials [1,2] as well as their damage and failure mechanisms such as lamina bending, local fibre buckling and crack propagation [3].

Furthermore, when composite shells are considered, the prediction of post-buckling behaviour and of collapse appears to be very difficult and very time consuming, since

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the design procedures available at present are not reliable enough. Mainly for this reason, the use of composite stiffened panels, designed to work in the post-buckling range, appears very limited in spite of their promising capabilities.

In the last decade quite a number of research projects investigated the influence of geometrical and boundary imperfections on the buckling load of composite unstiffened shells. Their results were based on the continuous interactions between high-fidelity numerical analyses, experiments and imperfection measurements. Within this framework, significant contributions were provided by the NASA Langley Research Center [4,5] and by European research projects [6,7]. In 2002, an interesting and exhaustive review of results and future directions of these projects has been discussed by Arbocz and Starners [8].

At the same time, other researchers focalised their attention on the stability of composite stiffened panels to better understand the failure mechanisms causing the structural collapse and the interaction between panel skin and stiffeners [9–12].

Abramovich et al. [13] investigated the effects of repeated buckling on the geometrical imperfections of stiffened cylindrical shells. Other works deal with the optimum design of composite stiffened panels under buckling constraints. The authors of [14,15] proposed an analytical formula to predict the buckling load within optimisation process; other used numerical analyses as well as semi-analytical formulations. A minimum weight design was performed by Butler et al. using VICONOPT [16]. Similarly, Wiggenraad et al. [17] used PANOPT to carry out a minimum weight optimisation accounting for buckling load and strength constraints.

Quite a number of studies tried to underline the advantages offered by the use of Genetic Algorithms in the optimisation process, because of their ability to directly consider integer variables such as the number and the orientation of the layers of the shell skin and stiffeners, as well as the number of stiffeners [18,19].

In any case, a very limited number of researches focalises on new design methodologies able to expressively design structures operating in post-buckling and subjected to post-buckling constraints, such as collapse load and residual stiffness after local buckling.

Lillico et al. [20] considered the presence of constraints, not only on the buckling load but also on the maximum strength during a minimum weight optimisation involving aluminium alloy stiffened panels using VICONOPT. The results obtained by VICONOPT were then verified using ABAQUS.

There are at least two main difficulties to carry out this kind of optimisations. The first one is related to the high computational efforts required to predict the post-buckling behaviour of each configuration analysed throughout the optimisation process. The second reason is due to the presence of discrete variables and of non-linear constraints, which significantly increase the total number of configurations to be analysed by the optimisation algorithm.

To overcome these computational difficulties, optimization procedures based on global approximation strategies can be exploited [21]. In 2002, Rikards et al. [22] used polynomial approximation in post-buckling optimization of composite stiffened panels.

Similarly, the authors of the current research already used a system of Neural Networks in [23] as global approximation method aiming at the weight minimization of composite stiffened panels subjected to post-buckling constraints. That previous work has been here extended considering two further global approximation methods, namely Radial Basis Functions and Kriging, as well as performing multi-objective genetic searches.

2. Optimization strategy (method, technique)

As it happens in many practical situations, one of the most difficult task in the structural design is the definition of general design guidelines and the formulation of design criteria which might guide the identification of the optimal configurations.

In these cases, the use of multi-objective optimizations, capable to account for two or more objectives, the ones against the others, results a successful strategy to identify the most appealing configurations. Decision criteria might then be applied a posteriori basing on the designer's experience.

Such as approach has been followed in this work considering a low curvature panel configuration. Accordingly, in the following sections, the optimization methodology and the proposed global approximation techniques are briefly discussed. Thereafter, multi-objective optimizations have been performed exploiting the flexibility of the proposed global approximations in order to identify a set of promising panel configurations. Preliminary design guidelines have been then proposed and discussed. Finally, one of the identified configuration has been selected for further numerical and experimental validations.

2.1. Multi-objective Genetic Algorithm

The original formulation [24] of Genetic Algorithms, as proposed by Holland, is inspired to the natural evolution: better individuals have more possibilities to hand down their characteristics in future generations. The simplest formulation of the algorithm works manipulating a population of individuals throughout a series of successive generations. In this work, the single-objective formulation is extended to consider multi-objective problems. The searching for the Pareto set is performed using a ranking-selection technique that is based on the definition of non-dominated solutions and allows to consider two or more objectives, the ones against the others. Non-linear constraints have been accounted for introducing penalty functions as commonly done for the single-objective formulation of the algorithm.