Multi-Objective Optimization of Composite Stiffened Panels: Computations and Experiments

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Summary

This work proposes a multi-objective optimization procedure for the design of composite stiffened panels subjected to axial compression and capable to operate in post-buckling. The procedure is based on Genetic Algorithms and global approximation techniques. Accordingly, response surfaces are built to approximate the post-buckling behavior of the considered panel configurations using a limited number of sample points. The structural behavior of each sample point is analyzed by means of detailed finite element analyses. Optimization results underline the significance of non-dominated solutions, as the best panel configurations inside the optimization domain. Finally, one of the non-dominated solutions is selected, manufactured and tested up to collapse. The obtained numerical-experimental correlation seems satisfactory in terms of the equilibrium path, the out-of-plane deformations and the collapse modalities.

Introduction

One of the most promising perspective of aircraft industries is the possibility to extend the use of stiffened panels made of composite materials to primary structures with the intent to further reduction in structural weight. The design of stiffened composite panels, able to overcome the buckling load and to work in post-buckling field, represents one of the major challenges for aircraft industries. Studies have been carried out to obtain experimental data and to propose reliable design and analysis procedures for a faster evaluation of buckling and post-buckling capabilities of these structure elements [1-5].

This work proposes an optimisation procedure for the design of composite stiffened panels subjected to axial compression loads and post-buckling constraints. There are at least two main difficulties to carry out this kind of optimizations. The first one is related to the high computational efforts required to predict the post-buckling behavior of each configuration analyzed throughout the optimization process. In fact, detailed highly nonlinear analyses are commonly used. 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 analyzed by the optimization algorithm in order to identify optimal configurations.

To overcome these computational difficulties, optimization procedures based on global approximation strategies are here exploited [6-7].

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Panel Baseline Configuration and Domain of Interest

The geometrical shape of the panels, i.e. curvature radius as well as free length and width, are known from the preliminary design phases. Aircraft wings, fuselages, rocket frames and/or helicopter tails are but a few example of structures whose external shape is addressed to satisfy aerodynamic criteria. This assumption suggests not to consider among the design variables amenable of optimization those that are directly related to the overall external shape of the panels. Thus, the optimization procedure is applied to low curvature panels with curvature radius of 1500 *mm,* free length and cord of 700 *mm*, made of fiber reinforced plastic woven (CFRP). Stiffeners are L-shaped with equal sides, long as the panel is. The stiffeners are cured and riveted on panel skin.

The domain of interest consists of geometrical variables, i.e. number of stiffeners and their dimensions, and lay-up variables which are used to describe the stacking sequences of the panel skin and of the stiffeners. The number of stiffeners ranges from 3 to 6, while blades and flanges are assumed to have the same length, that ranges from 22 to 35 *mm*. The orientation angles in the lay-ups are limited to a discrete set of possibilities: 0°, 90° and +45°. The lay-up of the panel skin consists of an upper exterior layer and a lower exterior layer, both oriented at 0°, and of internal layers whose number ranges from 1 to 4. The total number of layers in the panel skin remains between 3 and 6 and, in the case of 4 or more layers, at least 2 layers have to be of +45° oriented. Symmetric stacking sequences are preferred. The number of layers in the stiffeners ranges from 4 to 12. The lay-up of the stiffeners consists only of 0° and 90° layers alternatively oriented.

Multi-Objective Genetic Algorithm

The original formulation [8] 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 algorithm works maintaining and manipulating a population of individuals throughout a series of successive generations. The single-objective formulation is extended to consider multi-objective problems. The searching for the Pareto set is carried out by 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.

Global Approximation: Radial Basis Functions

During the optimizations, the panel weight has been computed as an analytical function of the design variables, while the structural behavior of the panels is approximated using response surfaces to contain the computational efforts. The sample points, used to build the response surfaces, are allocated using the maximum distance algorithm. The structural behavior of each sample point is analyzed with ABAQUS®. S4R 4-node shell elements, with six degrees of freedom at each node, and three integration points along the thickness for each ply are used. The experimental conditions are modeled as precisely as possible. Radial Basis Functions are then built using a total number of 70 eigenvalue and 58 dynamic explicit analyses, leading to maximum errors lower than 5% as detailed described in [7].

Results of the Multi-Objective Optimizations

Multi-objective Genetic Algorithms are used to investigate the improvement in structural efficiency that can be ideally reached by composite stiffened panels capable to exploit the post-buckling regime. Two unconstrained multi-objective optimizations are then performed. From an industrial point of view, the Pareto set represents actual technological constraints. Indeed, manufacturing technologies that are available nowadays allow the construction of panels, which are located only below the Pareto set.

In the first optimization, the Pareto set for the panels with minimum weight and maximum buckling load is searched for. Being limited to the domain of interest already defined, the identified Pareto set is shown in Figure 1.a. Any further improvement of the buckling load of any point of the Pareto set necessarily implies an increase of the structural weight. Namely, if a greater buckling load is desired, a further weight increase has to be paid. The second multi-objective optimization is carried out by maximizing the collapse load and minimizing the panel weight. The Pareto set of this second optimization is presented in Figure 1.b.

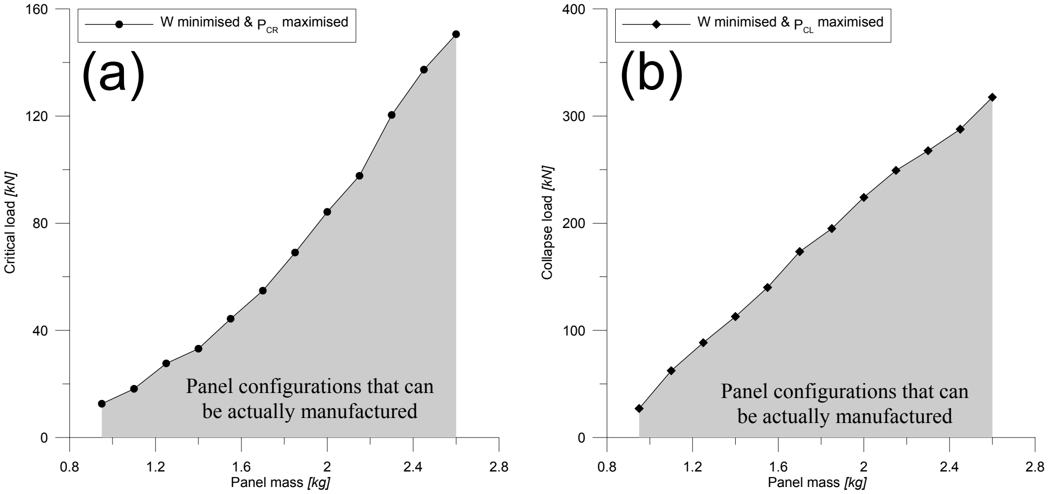

Figure 1: Pareto sets: (a) maximum critical loads versus minimum weight; (b) maximum collapse loads versus minimum weight.

Assuming that the value of the panel weight has been a priori fixed, the Pareto set of Figure 1.a. provides the maximum critical load that can be achieved inside the optimization domain. Similarly, the Pareto set of Figure 1.b provides the maximum collapse load that can be achieved inside the optimization domain. Thus, once the panel weight has been fixed, there are at least two distinct optimal panel configurations: the first one is obtained by maximizing the first critical load and the second one is obtained by maximizing the collapse load. It is reasonable to suppose that other distinct panel configurations might exist between the two previous ones. They all represent compromise solutions between maximum critical load and maximum collapse load. Thus, the panel configurations of weight between 1960 *gr*. and 1990 *gr*, have been searched for inside the domain of interest. The dimension of the stiffeners is treated as a discrete variable with step of 1 *mm* in order to limit the number of possible configurations. Figure 2.a reports all the identified configurations. The solutions characterized by maximum critical load and by maximum collapse load are marked using a grey square and a grey diamond, respectively.

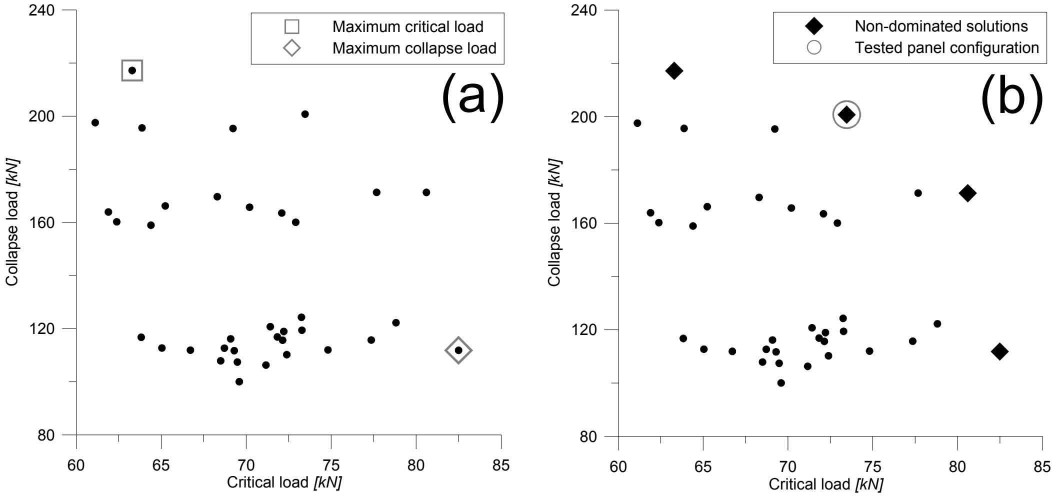

Figure 2: Panel configurations with weight between 1960 gr. and 1990 gr.

Figure 2 demonstrates that the non-dominated solutions among the identified configurations might be considered as the best panels. For these configurations, in fact, any further increase in the buckling load implies a decrease of the collapse load.

Numerical-Experimental Correlation

The panel configuration marked with a circle in Figure 2.b is then selected among the identified non-dominated solutions for further experimental investigations. The configuration presents 6 stiffeners, 28 *mm* wide of 9 layers, 0° and 90° alternatively oriented. The panel skin consists of 4 layers $[0°/45°]_S$ oriented. Two specimens are manufactured by AGUSTA and tested up to collapse at the *Dipartimento di Ingegneria Aerospaziale* of *Politecnico di Milano*.

Tests and preliminary numerical computations without considering any kind of initial imperfections are then compared. The numerical results, obtained a priori within the optimization procedure, are in good agreement with the experimental ones in terms of equilibrium path, out-of-plane deformations and failure modalities. In Figure 3 the experimental load-shortening curves are compared with that numerically computed. A good correlation level is also obtained when considering the out-of-plane deformations and the buckling patterns, as shown in Figure 4.

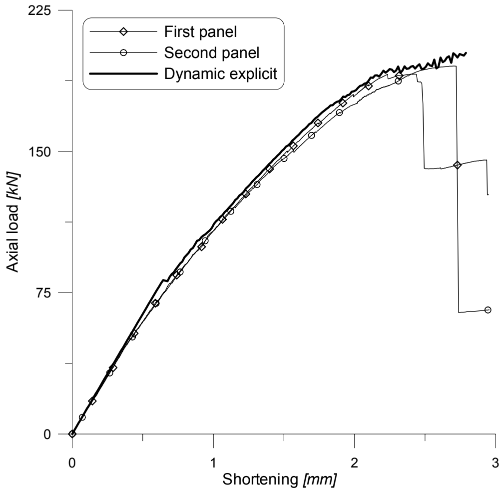

Figure 3: Load vs. shortening curves: experiments and computation.

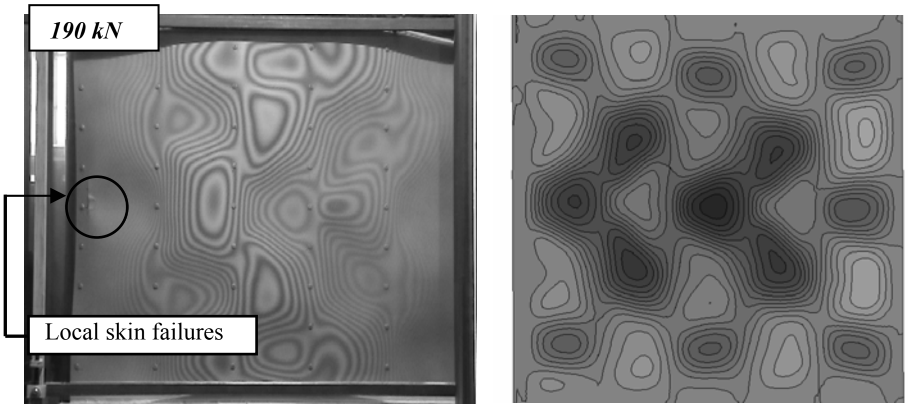

Figure 4: Out-of-plane deformations tested panel P4: Moirè fringes and numerical computation.

Half wave number and amplitude are correctly identified for both of the tested panels. Stiffener deformations are well predicted by the numerical computations. Interesting observations resulted from failure mechanisms, which mainly involved the panel stiffeners and lead to structure collapse. Minor damage areas were localized on the un-stiffened surface of the panel skin close to the stiffener flanges, just before the structure collapse.

Conclusive Remarks

Multi-objective optimizations are used to draw out general design criteria and considerations on the advantages offered by exploiting post-buckling operability of composite stiffened panels. The importance of non-dominated solutions inside the optimization domain is explained and discussed. Accordingly, one of the identified non-dominated solutions is then manufactured and tested up to collapse. Numerical-experimental correlation seems satisfactory in terms of equilibrium path, out-of-plane deformations and failure modalities. The buckling loads, which are numerically predicted during the optimization are greater than those observed experimentally. This discrepancy is explained by the presence of initial geometrical imperfections.

Reference

1. Stevens, K.A, Ricci, R. and Davies G.O. (1995): “Buckling and postbuckling of composite structures”, *Composites: Part B*, Vol. 26, pp.189-199.

2. Falzon, B.G, Stevens, K.A. and Davies, G.O. (2000): “Postbuckling behaviour of a blade-stiffened composite panel loaded in uniaxial compression”, *Composites: Part A,* Vol. 31, pp. 459-468.

3. Park, O, Haftka, R.T, Sankar, B.V, Starnes. J.H.Jr. and Nagendra, S. (2001): “Analytical-experimental correlation for a stiffened composite panel loaded in axial compression”, *Journal of Aircraft*, Vol. 38, pp. 379-387.

4. Chiarelli, M, Lancetti, A. and Lanzotti, L. (1996): “Compression behaviour of flat stiffened panels made of composite material”, *Composite Structures*, Vol.36, pp.161-169.

5. Abramovich, H, Singer, J. and, Weller T. (2002): “Repeated buckling and its influence on the geometrical imperfections of stiffened cylindrical shells under combined loading”, *Int. J. Non-Linear Mechanics*, Vol. 37, pp.577-588.

6. Khoo, L.P. and Chen, C.H. (2001): “Integration of response surface methodology with genetic algorithms”. *J. Advanced Manufacturing Technology*, Vol.18, pp. 483-489.

7. Lanzi, L. (2004): “Optimisation of composite stiffened panels under post-buckling constraints,” *Ph.D. Dissertation*, *Dip. Ingegneria Aerospaziale, Politecnico di Milano*.

8. Goldberg, D.E. (1989): *Genetic algorithms in search, optimization and machine learning*. London: Addison-Wesley.