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Two-step procedure for fast post-buckling analysis of composite stiffened panels

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ABSTRACT

The paper presents an analytical formulation for the post-buckling analysis of composite aeronautical panels with omega stiffeners loaded in compression and shear. The formulation relies on an energy principle and the method of Ritz. In the first step, the panel is an assembly of plate elements, and the buckling analysis is performed. In the second step, the panel is an elastically restrained skin, and the post-buckling behaviour is studied. The comparisons with finite element analyses and experimental results from the literature reveal the ability of the formulation to assess the post-buckling response.

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1. Introduction

The European consortium MAAXIMUS (More Affordable Aircraft structure through eXtended, Integrated, & Mature nUmerical Sizing) [1], consisting of 58 industries and universities, works to demonstrate the fast development of a highly-optimized composite airframe. The project is divided into a physical platform, focused on the development of composite technologies for low weight aircraft, and a virtual platform aiming to reduce the time required for the identification of the best structural solutions.

This paper presents part of the activity performed by Politecnico di Milano during MAAXIMUS in the context of the virtual platform. The work focuses on the development of a fast computational method, which can be used to assess the post-buckling response of composite stiffened panels during the early design stages. The fast tool aims to improve the computational efficiency of the current design procedure, which mainly relies on expensive finite element analyses. Not only the tool can be used for a fast optimization of composite fuselages, but also to account for more degrees of freedom compared to today standard practice. Indeed, the amount of design solutions to be explored can be increased, and consequently the efficiency of the final design can be improved. For this reason, the availability of a fast method represents a crucial aspect to move from a more costly and empirical optimization to a faster structural design optimization loop.

Among the fast design methods in the literature, analytical and semi-analytical formulations represent an attractive strategy thanks to their computational efficiency.

The simplest approach to study a stiffened panel is to consider the portion of the skin between the stiffeners, assuming the edges as simply supported or clamped. For these cases, closed-form solutions are available both for isotropic [2,3] and composite materials [4–6].

A more refined level of approximation consists in representing the stiffener as an elastic restraint, such as in the analytical formulations of Rhodes and Harvey [7] and van der Neut [8] for isotropic panels and by Mittelstedt and Beerhorst [9] for composite panels subjected to compression loadings. The post-buckling of isotropic stiffened panels is studied with a semi-analytical procedure where the stiffener is modeled as a beam by Brubak and Hellesland [10,11] and Mijukovic et al. [12]. Two of the few analytical works focusing on the post-buckling of elastically restrained composite panels are those ones presented by Chai et al. [13] and by Boay and Wah [14]. The methods of analysis are based on the semi-energy approach in combination with von Kármán large deflection equations. The post-buckling of panels elastically restrained by torsion bars and torsion springs was studied by Bisagni and Vescovini for the analysis of composite stiffened panels, developing a semi-analytical procedure [15] and closed-form solutions [16].

An even more refined modeling strategy consists in describing the stiffened panel as an assembly of plate elements. The main advantage is the ability of the formulation to capture local stiffener instabilities, providing at the same time an accurate representation of the skin/stiffener interaction. The drawback of the plate assembly approach is represented by a higher number of degrees of freedom, which turns in a reduction of the computational effectiveness of the analytical procedure.

A plate assembly approach is presented by Byklum and Amdahl [3], who developed a computational model for local post-buckling analysis of stiffened isotropic panels. The model considers *J*-stiff-

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ened panels where the web is modeled as a two dimensional plate element. Buermann et al. [17] extended the approach to the case of curved isotropic stiffened panels, including in the model also frames and skin doublers by means of a beam representation. Both the formulations of Refs. [3,17] are limited to isotropic materials.

Despite the relatively large amount of analytical and semi-analytical methods, quite a few of them allow the study of flat and curved composite panels under combined loading conditions.

The present work discusses the development of a fast tool for the analysis of the post-buckling response of stiffened panels. The tool offers the advantage of considering a wide set of configurations, including composite and isotropic materials, flat and curved panels, as well as loading conditions of compression and shear. The formulation tries to combine the advantages of the plate assembly representation with the ones of the elastic restraint approach.

The use of the fast tool is discussed for the assessment of the buckling and post-buckling response of omega stiffened panels. The analysis procedure is illustrated by describing the input data phase. The results are provided in terms of force–displacement curves, out of plane displacements and maximum stress failure index. The accuracy of the results is demonstrated by comparison with finite element analyses and with experimental data taken from the literature.

2. Description of the formulation

The analytical formulation is developed for the buckling and post-buckling analysis of composite flat and curved panels stiffened with omega stringers. The loading conditions are compression and shear, that can be applied separately or in combination.

The formulation is divided into two steps, as shown in Fig. 1, and the problem is formulated with an energy approach together with the method of Ritz.

In the first step the buckling analysis is performed referring to a structural model based on a plate discretization of the stiffened panel. The approach guarantees a refined description of the panel, and both the skin and the stiffener are explicitly represented as plate elements.

The number of degrees of freedom required by the plate representation can be easy handled in the context of a linear analysis, where the buckling load is obtained from the solution of an eigenvalue problem. When assessing the post-buckling response, the governing equations are nonlinear, and it is important to guarantee the computational efficiency through a proper reduction of the number of unknowns. For this reason, the second step is based on a simpler structural model, where the stiffened panel is modeled by considering the portion of skin between two stiffeners. The elasticity of the restraint provided by the stiffeners at the skin longitudinal edges is accounted for by means of torsion springs along the longitudinal edges, whose stiffness is determined from

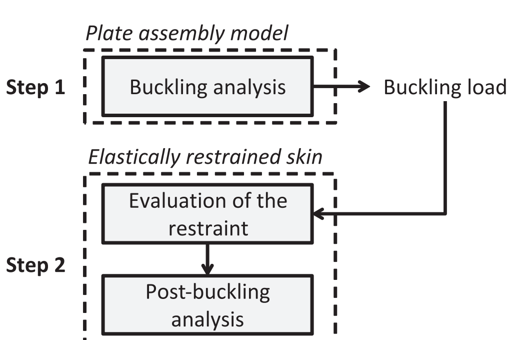

Fig. 1. Overview of the two-step post-buckling procedure.

the buckling analysis. The choice of the elastically restrained skin model is justified by the fact that the first structural instability of aeronautical panels usually regards the skin. For this reason, the initial post-buckling response can be studied by considering the nonlinear behaviour of the skin, while the response of the stiffener can be reasonably assumed linear.

The laminates composing the stiffened panel have an arbitrary number of layers. They are modeled as thin plate elements referring to Kirchhoff hypothesis together with classical lamination theory [18,19]. The effect of transverse shear deformation is not taken into account, and the formulation can be applied to study the behaviour of panels for which the buckling halfwave length is larger compared to the panel thickness. The constitutive equation of each laminate is:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \\ -w_{,xx} \\ -w_{,yy} \\ -2w_{,xy} \end{Bmatrix} \tag{1}$$

where N_x,N_y,N_{xy} are the membrane forces per unit length, M_x,M_y,M_{xy} the bending and twisting moments per unit length, ϵ_x,ϵ_y,γ_{xy} the membrane strains, w the out of plane displacement and the derivatives of w represent the curvatures. The comma followed by the coordinate denotes the differentiation with respect to that coordinate. The coefficients A_{ik} and D_{ik} define the in plane and out of plane stiffness of the laminate, respectively, and the coefficients B_{ik} determine the coupling between in plane and out-of-plane behaviour.

Each laminate composing the panel can be made of an arbitrary number of layers under the assumptions that:

- the laminate is symmetric with respect to the midplane, i.e., $B_{ik} = 0$
- the coupling between extension and shear is null, i.e., $A_{16} = A_{26} = 0$

The formulation accounts for the terms D_{16} and D_{26} as typical aeronautical panels can exhibit coupling between bending and twisting.

3. Linear buckling analysis

In the first step, the buckling analysis is performed referring to a plate representation of the panel cross section. The approach analyzes a multistiffened panel by studying a representative unit composed of two stiffeners, one bay and two half-bays. An example is reported in Fig. 2(a), where the plate representation of an omega stiffened panel is shown with eleven plate elements. Five elements model the skin, including the portion of skin under the stiffeners, and six elements model the stiffeners. A generic plate element

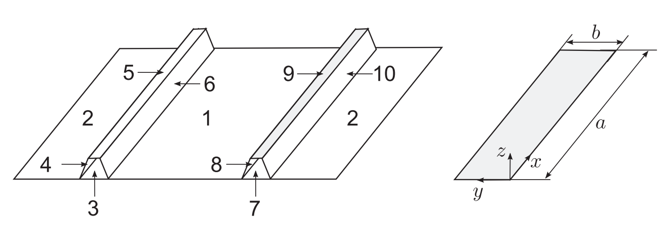

Fig. 2. Plate assembly representation of the stiffened panel: (a) subdivision in plate elements, (b) generic element dimensions and reference system.

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