the studies of oscillating-wing propulsion, a general three-dimensional version of this model with a discretized spanwise vorticity distribution, including comparisons with wind-tunnel and water-channel experimental data, is currently being tested at the Institute for Aerospace Studies, University of Toronto.

Acknowledgment

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Importance of Anisotropy on Design of Compression-Loaded Composite Corrugated Panels

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Introduction

As the use of composite materials in primary flight structures increases, so does the need to understand the effects of anisotropy on the structural response. This understanding is required in order to tailor designs that avoid the effects that degrade the structural efficiency and capitalize on those effects that improve efficiency. The study presented here investigates the importance of anisotropic terms in the design of composite corrugated panels for a range of axial compressive load intensities. Two corrugated panel configurations, namely, panels with tailored laminates and panels with a continuous laminate, were studied. These panels are of particular interest to the aircraft designer because they exhibit high structural efficiency and buckling resistance. However, because of their unique construction that allows thin laminates with few layers, they are prone to anisotropic effects and the extent to which anisotropy affects their performance is still not generally known.

Composite panels, even those constructed as balanced symmetric laminates, have anisotropic flexural stiffnesses whenever ply orientations other than 0 or 90 deg, with respect to the rectangular edges of the panel, are present in the laminate. During bending deformations of these plates, the D_{16} and D_{26} anisotropic terms cause a material-induced coupling between pure bending and twisting of the plate. In preliminary analysis of composite plates, it is common practice to ignore these anisotropic terms. Neglecting anisotropy substantially simplifies analysis and permits the analyst to use existing solutions for specially orthotropic structures and exploit symmetry in formulating the problem, thus reducing the computational cost and effort.[1]

In Ref. 1, the D_{16} and D_{26} anisotropic terms were shown to reduce the buckling resistance of balanced, symmetric, compression-loaded composite plates, and a criterion was presented for determining the conditions under which the anisotropic terms can be neglected in a buckling analysis. In the present study, the work of Ref. 1 is extended to demonstrate and determine the consequences of neglecting the D_{16} and D_{26} anisotropic terms during the optimal design of buckling critical corrugated composite panels composed of balanced, symmetric laminates.

The computer code PASCO[2,3] (panel analysis and sizing code), in which a corrugated panel is modeled as a series of linked plate elements, was used for design and analysis. PASCO allows structural analysis and optimization to be performed with or without the inclusion of the anisotropic terms. To determine the importance of the anisotropic terms, D_{16} and D_{26} were first neglected during the design analysis and then included in a final structural analysis of the optimized design. The importance of the anisotropic terms is measured by the difference between the design load and the buckling load obtained from the final structural analysis.

Design and Analyses

Of the two types of corrugated panel constructions considered in this study, the first type of construction, referred to as corrugation with tailored laminates, allows the designer to tailor the dimensions and laminate construction of the cap and

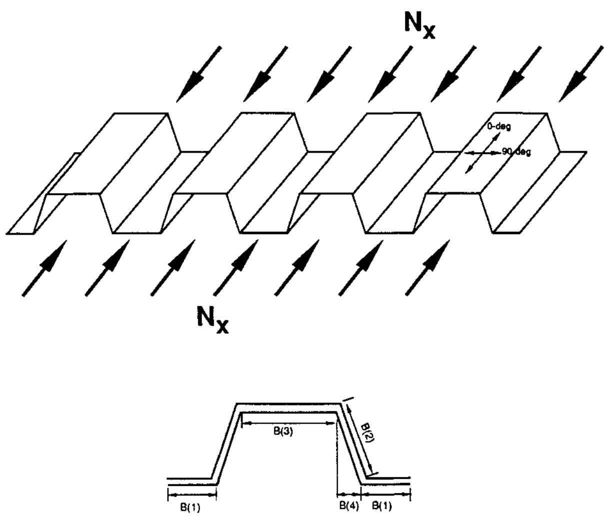

Fig. 1 General geometry of corrugated panel and repeating element.

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Table 1 Reduction in the buckling strength due to anisotropy[a] for corrugated panels with tailored laminates

Design load N_x, lb/in.	Width of $(\pm 45)_s$ web, in.	Critical local mode λ, in.	N_x critical with anisotropy, lb/in.	Reduction in buckling strength, %
10	5.44	5.6	7.5	25
100	2.11	3.5	85	15
350	1.59	1.3	275	22
1000	1.40	1.0	798	20
2800	1.37	1.0	2304	18
10,000	1.83	28.0	10,000	0
28,000	2.64	28.0	28,000	0

[a]Panels optimized neglecting the anisotropic terms, then the final designs analyzed including the anisotropic terms.

flange elements of the panel independent of the web elements. The second type of construction, referred to as corrugation with a continuous laminate, has a similar set of design variables except that a single laminate construction of constant thickness is used throughout the panel. The basic repeating element of the corrugated panel for both types of construction is the same and is shown in Fig. 1.

The laminate layups are all symmetric and balanced with individual ply orientations of either 0, 90, or ± 45 deg with respect to the longitudinal axis of the panel. The design variables for the optimization process are the ply thicknesses of individual layers and the dimensions of the repeating element, namely, $B(1)$, $B(2)$, $B(3)$, and $B(4)$ shown in Fig. 1. Material properties used are typical of graphite-epoxy with a longitudinal modulus $E_1 = 18.5 \times 10^6$ psi, a transverse modulus $E_2 = 1.6 \times 10^6$ psi, an in-plane shear modulus $G_{12} = 0.8 \times 10^6$, major Poisson's ratio $\nu_{12} = 0.35$, and a minimum gage ply thickness of 0.005 in. The overall panel dimensions are typical of an aircraft wing rib panel of length $L = 28$ in. and width $w \cong 80$ in. Corrugated panel designs were obtained using PASCO, with anisotropy neglected, for compressive axial loadings of $N_x = 10$, 100, 350, 1000, 2800, 10,000, and 28,000 lb/in.

A. Corrugation with Tailored Laminates

For this configuration, optimum panel designs obtained with anisotropy neglected have flange and cap elements with a $(\pm 45, 0)_s$ stacking sequence, web elements with a $(\pm 45)_s$ stacking sequence, and flange elements that are half the width

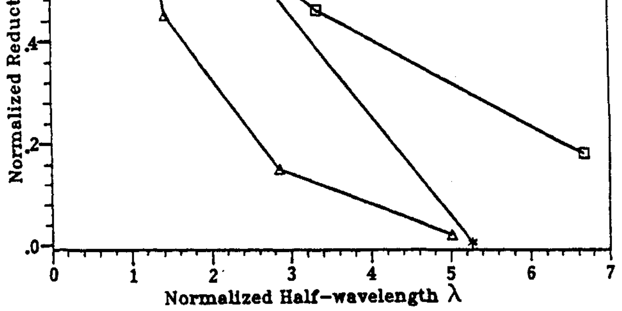

Fig. 2 Effect of anisotropy on the buckling loads of local modes for tailored corrugated panels.

of the cap element, i.e., $B(1) = 0.5B(3)$. These designs are consistent with the results of Ref. 4.

To determine the effect of anisotropy, these optimized designs were then analyzed using PASCO with anisotropy included. The results from the buckling analysis, with and without the anisotropic terms, are presented in Table 1. The design loads shown in the first column are the buckling loads of the panels if anisotropy is neglected. The reduction in buckling resistance associated with including the anisotropic effects in the PASCO analysis is given in the fifth column of Table 1.

Heavily loaded designs showed no effect of including the anisotropy. These designs were global buckling critical and strain failure critical. However, for the lightly loaded panels ($N_x = 10$–2800 lb/in.), strain failure was not critical, but rather a local buckling mode was critical along with the global mode. A closer look at the local buckling modes revealed that the web elements of the corrugated panels, rather than the cap or flange elements, were buckling critical. This result is important since the web elements of the panel are made of $(\pm 45)_s$ laminates that have large anisotropic bending stiffnesses, and are strongly influenced by those terms (see Ref. 1). The 25% reduction in buckling resistance for the loading of $N_x = 10$ lb/in. is consistent with the reduction in buckling resistance of a $(\pm 45)_s$ simply supported plate loaded in compression.[1] For larger values of panel loading, the effect of anisotropy becomes less significant. This change in importance of the anisotropy is believed to be associated with a change in cap stiffness. As the design load is increased, the optimized configurations had thicker, stiffer cap elements that prevent rotation at the end of the web and thus provide approximately clamped boundary conditions along the length of the web element. Indeed, PASCO analysis of a single $(\pm 45)_s$ plate indicated buckling load reductions, when anisotropy is included, of 20% for clamped plates compared to 26% for simply supported plates.

The result obtained for the case $N_x = 100$ lb/in., however, does not seem to follow the trend set by the other cases given in Table 1. The second and third columns of Table 1 give the width of the web elements and the half-wavelength λ of the local buckle mode shape, respectively. Unlike the other lightly loaded panels, the $N_x = 100$ lb/in. design has a half-wavelength of about 1.7 times the width of the web element. This observation suggests that the effect of anisotropy is dependent on the size of the buckling half-wavelength relative to the panel element widths.

To understand further the relationship between the importance of anisotropy and the buckling mode half-wavelength, buckling loads were calculated for higher local buckling modes for panels designed for $N_x = 10$, 100, and 1000 lb/in. Associated with each higher local buckling mode is a half-wavelength of the mode and a reduction in buckling load due to anisotropy. The plots shown in Fig. 2 summarize these results. The plots show a normalized buckling load reduction as a function of the half-wavelength of the buckle mode divided by the width of the web elements. The normalized load reduction is obtained by dividing the load reduction obtained for a particular loading case and buckle mode by the maxi-

Table 2 Continuous ($\pm 45, 0)_s$ corrugated panel results compared to results of simple plate analysis of the widest panel wall

N_x, lb/in.	Reduction in buckling strength of the corrugated panels, %	Reduction[a] in buckling strength of the widest wall, %
100	15	15.2
350	15	15.2
1000	5.8	5.9
2800	1.7	1.8
10,000	0.8	0.8
28,000	0.75	0.71

[a]Based on the simply supported plate analysis.

mum load reduction found for that loading case. The results in this figure indicate that the anisotropy becomes more important as the normalized half-wavelength becomes equal to, or less than, the width of the web elements.

The 20% error in predicting the buckling load when anisotropy is neglected in the design process results in a panel that would carry only 800 lb/in. without buckling locally rather than the design load of 1000 lb/in. In order to understand the structural modification that would be required to achieve the desired load-carrying capability, design optimization was performed for the load case of $N_x = 1000$ lb/in. with anisotropic terms included from the beginning. In this case, the design analysis detected the reduced buckling resistance of the web elements and made small design changes to shift the load path away from the web elements and avoid their early buckling. Specifically, the design optimization process reduced the width of the web elements and increased the widths of the flange and cap elements. Compared to the design which had been performed by optimization neglecting the anisotropic terms, there is only a 4% increase in weight, yet the the panel can carry the full 1000 lb/in. design load. The PASCO design optimization including anisotropy required, however, 82% more computer CPU time than the design run in which the anisotropy was neglected.

Another case relevant to the previous results is one in which some other design constraints force the corrugation geometry to be different from the optimum. The existence of such dimensional constraints can shift the local buckling mode away from panel elements that are sensitive to anisotropy, producing a panel less sensitive to anisotropic effects, thus allowing the anisotropic terms to be neglected in an analysis and reducing the computational effort.

B. Corrugation with a Continuous Laminate

For this class of panels, all of the walls are composed of the same laminate stacking sequence and thickness, with a laminate construction of $(\pm 45, 0)_s$ as suggested by the results in Ref. 4. These panels are much easier to manufacture than the panels with tailored walls, and are particulariy attractive candidates for thermoplastics since the manufacturer can lay up the panel in one large flat sheet and then thermoform its corrugated shape with a mold of predetermined shape. Corrugated panels with a continuous laminate are also substantially easier to analyze than panels with tailored laminates. With all walls having the same laminate construction, the importance of anisotropy is equally shared, and local buckling is likely to occur in the section of the corrugation with the largest width.

Results of the analysis with anisotropic terms of the designs optimized without anisotropic terms, indicated a reduction in the buckling strength of the panels, with the largest reduction for the lightly loaded panels (see Table 2). For all of the load levels, the reduction in buckling resistance associated with including the anisotropic terms corresponds to the reductions one would obtain in analyzing a $(\pm 45, 0)_s$ simply supported plate of width equal to the width of the widest element of the design (see Table 2). Therefore, the effect of anisotropy on the individual walls and entire panel is the same. This result suggests a simple method of incorporating the anisotropy into the optimization process by applying the criterion proposed in Ref. 1. Particularly, at the beginning of each optimization cycle, the nondimensional parameters developed in Ref. 1 could be assessed for the current layup of the panel walls and then an appropriate reduction factor could be used to compute the accurate local buckling strength of the walls. This would allow the optimization to account for the reduced buckling resistance of the walls associated with their anisotropic nature in a cost-effective manner, without actually including anisotropic terms in the analysis.

Concluding Remarks

This study was conducted to determine the extent to which anisotropy affects the buckling resistance of optimally designed compression-loaded corrugated composite panels. Two corrugated panel configurations were studied. Heavily loaded corrugated panels with tailored laminates were insensitive to anisotropic effects. At low load levels, the panels exhibited a local buckling mode corresponding to buckling of the web elements, and inclusion of anisotropic terms in the analysis indicated as much as a 25% reduction in the buckling strength of the panel. It was concluded that anisotropy influences the panel response in the presence of a local buckling mode, and that anisotropic effects are most significant for a mode with a half-wavelength less than the width of the web element.

The observation that anisotropy is more important in lightly loaded panels than in heavily loaded panels is significant in practical applications. It was shown in Ref. 1 that the effect of anisotropy on a thick $(\pm 45)_s$ laminate could be minimized by having an increased number of thin ply groups rather than a few thick ply groups. For example, $(\pm 45)_{3s}$ is much less sensitive to anisotropy than $(+45_3\ -45_3)_s$. For lightly loaded panels, the $(\pm 45)_s$ wall is at minimum gauge and, therefore, interspersing of ply orientations is not an alternative.

For the corrugated panels with a continuous laminate, anisotropy affected the buckling resistance of the individual panel elements and the entire panel structure equally, for all load levels. Based on this observation, a cost-effective method was proposed to use the nondimensional parameters of Ref. 1 to incorporate the effects of anisotropic terms into the design optimization. The more complicated configuration with tailored laminates does not seem to lend itself as well to this type of approach.

For those configurations with tailored laminates, including anisotropic terms during the design, optimization resulted in a final design that was only 4% heavier than the design obtained without the anisotropic terms, but was able to carry the full design load rather than a portion of it. Inclusion of anisotropic terms, however, increased the computational cost by 82%.

Acknowledgment

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