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Prestressing effects on the ultimate flexural strength of composite box sections

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ABSTRACT

Application of prestresssing as an effective means of enhancing the structural performance of composite box sections is presented. A primary objective of prestressing, in application to composite structures subjected to flexural loading, is to reduce the compressive stresses developed under critical loading conditions. This would increase the flexural strength of composite structures by delaying the prevalent compressive modes of failure. Theoretical models were developed for predicting the contributions of prestressing to the flexural performance of composites. Methodologies were developed for prestressing composite box sections. Flexure tests performed on prestressed (and similar non-prestressed) composite box sections verified the theoretical predictions. In the example composite structure considered here, prestressing produced 74% gain in flexural strength when compared with a similar non-prestressed box section (which embodied the prestressing tooling). The prestressed section produced 89% gain in flexural strength when compared with the box section without the prestressing tooling which carried 15% weight penalty.

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1. Introduction

Landing, takeoff and other maneuvers subject the aircraft wing structure to pull-up and push-down forces of somewhat comparable magnitudes [1]. This near-reversible loading condition produces near-reversible stress systems within wing structures. For example, the pull-up and push-down forces applied to a wing structure would generate principal compressive and tensile stresses of almost comparable magnitudes at location “A” (Fig. 1) in the wing structure. This near-reversible nature of the wing stress system leads to important inefficiencies in design of wing structures, as outlined below.

i. Composite (and metal) wing structural components are thin-walled systems (Fig. 2a) which are prone to buckling modes of failure in compression (Fig. 2b) at stress levels that are smaller than their tensile strength [2]. Some gains in buckling strength of structural panels can be achieved through introduction of stiffeners (Fig. 2a) and adjustment of the element configurations [3–6] which carry important weight penalties. The effective compressive (buckling) strength of a composite element depends upon its geometry, mechanical properties and support conditions, the configuration of stiffeners and other supporting elements, and the specific modes of buckling. The effective compressive (buckling) strength is generally only a fraction of the tensile strength. Experimental results on the aircraft stiffened thin-sheet composite structures (an example is shown in Fig. 2c) indicate that the effective (buckling) strength is generally less than tensile strength [7–10]. The reversible nature of stress systems in thin-walled wing structures thus leads to designs governed by compression, leaving the superior tensile strength of composites under-utilized.
ii. Composites in general (and carbon fiber composites in particular) offer inherently inferior material properties in compression, which further aggravate the problems with their buckling modes of failure. Fig. 3a shows the inefficiency of compressive (versus tensile) strain transfer to fibers in composites (in spite of the prevention of the buckling modes of failure). The compressive behavior of composites is marked by a pronounced nonlinear behavior with serious loss of (tangent) modulus and relatively low strength. The inferior performance of composites in compression has been attributed to the intrinsically nonlinear compressive behavior of (carbon) fibers, formation of low-modulus (interphase) zones within matrix in the vicinity of fibers, gradual deterioration of shear transfer efficiency in compression, and formation of an unstable kink band (Fig. 3b), which is aggravated by

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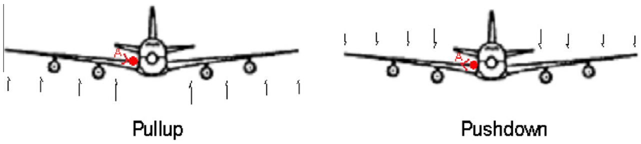
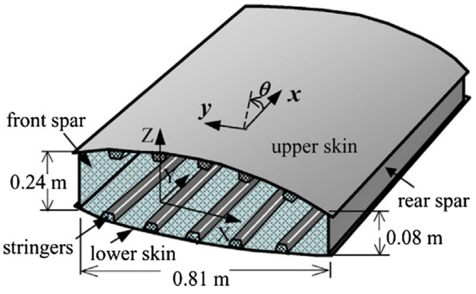
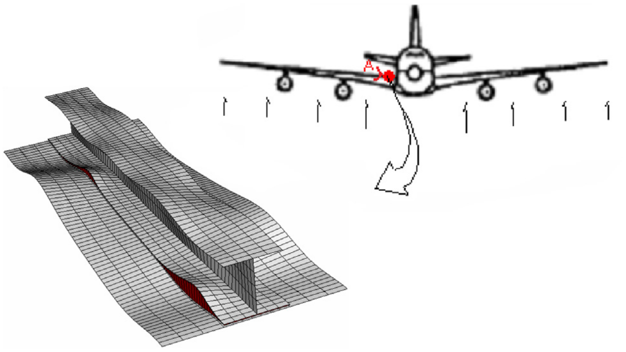


Fig. 1. Near-reversible loading of aircraft wings.

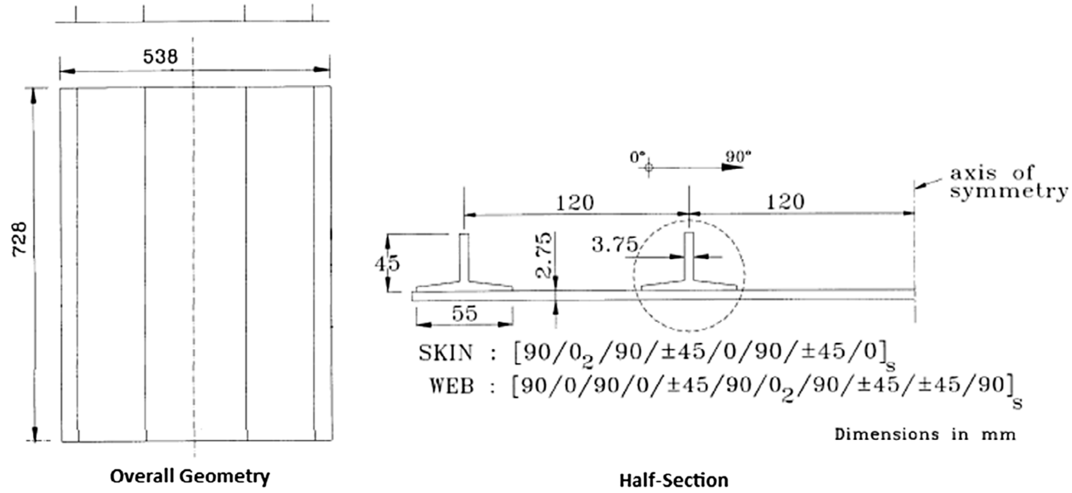
the geometric imperfections of fibers, producing matrix stress concentrations and debonding [11–15]. In addition, composite laminates are prone to delamination due to out-of-plane (low-velocity) impact, manufacturing errors, vibrations induced by the propulsion system, or many other common events. Delamination further undermines the compressive behavior of composites [16,17].



(a) An Example of aircraft composite wing structures [4]



(b) Buckling under compression



Laminate Tensile Strength: 1,100 MPa Laminate Compressive Strength: 660 MPa

Effective Compressive (post-buckling failure) Strength: 235 MPa

Effective Compressive Strength – to – Tensile Strength Ratio: 0.21

(c) An example of compressive-to-tensile strength ratio of aircraft stiffened composite laminates [7]

Fig. 2. Buckling behavior of composite aircraft structures.

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