Thin-Walled Structures 47 (2009) 1457–1468

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Stiffened panel stability behaviour and performance gains with plate prismatic sub-stiffening

D. Quinn [a], A. Murphy [a,*], W. McEwan [a], F. Lemaitre [b]

[a] School of Mechanical and Aerospace Engineering, Queen's University Belfast, Ashby Building, Belfast. Northern Ireland BT9 5AH, UK
[b] Unité Aéronautique et Laminés Technique, Centre de Recherche de Voreppe, Centr'Alp, BP 27, 38341 Voreppe Cedex, France

ARTICLE INFO

Article history:
Received 8 January 2009
Received in revised form
15 July 2009
Accepted 15 July 2009
Available online 08 August 2009

Keywords:
Panel buckling
Sub-stiffening
Machined panels
Panel testing

ABSTRACT

To increase the structural efficiency of integrally machined aluminium alloy stiffened panels, it is plausible to introduce plate sub-stiffening to increase the local stability and thus panel static strength performance. Reported herein is the experimental validation of prismatic sub-stiffening, and the computational verification of such concepts within larger recurring structure. The experimental work demonstrates the potential to 'control' plate buckling modes. For the tested sub-stiffening design, an initial plate buckling performance gain of +89% over an equivalent mass design was measured. The numerical simulations, modelling the tested sub-stiffening design, demonstrate equivalent behaviour and performance gains (+66%) within larger structures consisting of recurring panels.

1. Introduction

1.1. Background

Aircraft stiffened panel structure, which is moderately loaded and as a result has 'thin' plate elements, is designed in such a way that local buckling of the plates between lateral and longitudinal stiffeners is allowed to occur at a fraction of the load required to cause panel collapse. This post-buckling strength capacity has significant potential for structural weight savings. In addition, recent advances in the strength and damage tolerance characteristics of aerospace metallic materials [1,2], offers further opportunity for increased panel working and limit stresses. To maximise these material improvements as weight savings on aircraft primary structures, it is desirable to enhance panel stability further. Improved panel structural efficiency is plausible by introducing plate element sub-stiffening [3]. In addition to potential panel stability improvements, sub-stiffening also has the potential to improve damage tolerance capabilities [4–6]. The concept of plate element sub-stiffening for static strength performance gains relies on the introduction of structural features which modify the initial plate buckling mode. This concept has yet to be fully validated experimentally and potential aircraft applications evaluated. Consequently this paper documents a combined experimental and numerical research programme undertaken to examine static strength performance gains attained with sub-stiffening on representative aircraft panels. Work is currently underway on advanced manufacturing methods, including welding, and non-prismatic sub-stiffening concepts under uniform compression and combined compression and shear loading. The global research objective is to assess the potential for plate sub-stiffening and develop the required design and analysis tools to allow the introduction of sub-stiffening in aircraft panel design.

1.2. Advanced manufacturing processes and materials

Traditionally, airframes are constructed with complete wing and fuselage components built-up from individually fabricated sub-components. To date, riveted assembly of stiffened panel sub-components has dominated in metallic airframes. A potential alternative is to manufacture sub-components as integral structures. The advantage of single piece integral panels over fabricated structures is the potential for cost savings associated with assembly labour and tooling [7,8]. The NASA 'Integral Airframe Structures' program [9] indicated that, as compared to conventional built-up fabrication methods, high-speed machining designs could yield recurring cost savings of 61%. Additionally, life cycle cost savings are possible through reduced part count for both the Original Equipment Manufacturer (OEM) and aircraft operator.

1.3. Panel sub-stiffening

One of the first applications of plate sub-stiffening was to improve fatigue crack growth in integral structures. In built-up

* Corresponding author. Tel.: +44 28 9097 4095; fax: +44 28 9066 1729.
E-mail address: a.murphy@qub.ac.uk (A. Murphy).

0263-8231/$ - see front matter
doi:10.1016/j.tws.2009.07.004

structures, attached stiffeners act as crack arresters restraining the propagation of fatigue crack growth. Conventional integral panel structures, however, do not have natural breaks to act as crack arresters and therefore fatigue crack propagation through an integral structure is potentially faster. The introduction of plate sub-stiffening can be shown to significantly decrease fatigue crack growth under constant amplitude loading [5]. Considering static strength, Bushnell and Rankin [10] demonstrated that including small sub-stiffeners between the conventional primary stiffeners can 'not only lead to an increased buckling resistance, but more importantly to a much more robust optimum in terms of stiffener pitch'. Murphy et al. [3] experimentally and computationally examined plate sub-stiffening, demonstrating potential combined performance gains for both initial plate buckling and panel post-buckling collapse. In more recent work, Watson et al. [11] applied the exact finite strip method to investigate 'extra' buckling modes which occur when sub-stiffeners or multiple stiffener sizes are introduced in stiffened panel designs. As with Bushnell and Rankin, it was found that mass savings are achieved by using stiffeners of more than one size and there is the potential for increased spacing of the primary longitudinal and transverse stiffeners.

1.4. Paper synopsis

The work presented herein is part of a larger research program which is investigating potential sub-stiffening concepts, manufacturing methods and developing design and analysis tools. The experimental work is focused at the sub-component level, examining multi stiffener panels between transverse stiffeners. Additional numerical studies focus on sub-component and component levels. The experimental work is validated before expanding the numerical analyses to evaluate potential performance gains when applied within larger panel structure. The present study focuses on prismatic sub-stiffening concepts for structures loaded under uniform compression, with specimen manufacture focused on integral machining. The following paper section provides an overview of the induced physical behaviour of panels with plate sub-stiffening. Having introduced the behaviour, the following section introduces the design of the experimental specimens considered herein. This is followed with details on the applied experimental and computational analysis procedures. The experimental data is presented, followed by results from the numerical investigation. The results are discussed and the paper concludes with a summary of the findings.

2. Panel stability

2.1. Conventional panel stability

2.1.1. Initial plate buckling

Stiffened panels are essentially an assemblage of plate and column elements. Plate sections, bounded by lateral and longitudinal stiffeners, behave according to plate theory with edge boundary conditions defined by the rotational rigidity of the bounding stiffeners. Considering for simplicity a flat rectangular plate, of uniform thickness, simply supported on all sides and under uniform compressive loading—the critical buckling load is given by

$$N_x = \frac{\pi^2 a^2 D}{m^2}\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)^2 \quad (1)$$

where

$$D = \frac{E \cdot t^3}{12(1-\nu^2)} \quad (2)$$

and a, b and t are the plate geometric properties (length, breadth and thickness respectively), E and ν are the material properties (Young's modulus and Poisson's ratio respectively) and m and n define the buckle waveform (m equalling the number of longitudinal half-waves and n equalling the number of lateral half-waves).

Now assuming typical aerospace lateral and longitudinal stiffener pitches and therefore plate element aspect ratios, the plate will buckle with one or more half-waves in the longitudinal direction and a single half-wave in the lateral direction. The relationship can then be reduced to

$$(N_x)_{m\geq 1, n=1} = \frac{\pi^2 \cdot D}{a^2}\left(m+\frac{1}{m}\frac{a^2}{b^2}\right)^2 \quad (3)$$

Then given a particular instance of a plate (fixed material and geometric properties), the relationship between the number of longitudinal half-waves (m) and the plate buckling stress can be examined, Fig. 1. On a conventional aircraft stiffened panel, where plate bays buckle with one lateral half-wave and m longitudinal half-waves, for strength assessment the value of m which generates the lowest critical stress, m_{critical}, is of key importance.

2.1.2. Post-buckling stability

Stiffened panel post-buckling stability is dictated by stiffener column behaviour. Longitudinal stiffener sections, in addition to a portion of the plate on either side, act as effective columns. According to Von Karmen [12], the width of the post-buckled effective plate is defined as

$$b_{\text{Effective}} = b\sqrt{\frac{\sigma_{\text{Buckle}}}{\sigma_{\text{Stiffener}}}} \quad (4)$$

where σ_{Buckle} is the stress at which the plate element initially buckles and $\sigma_{\text{Stiffener}}$ is the stress at the plate edge when the post-buckling effective stiffener column becomes unstable.

Stiffened panel collapse is a result of instability of the effective stiffener column. Critical stiffener instability stress may be determined using the secant formula, Eq. (5), with failure

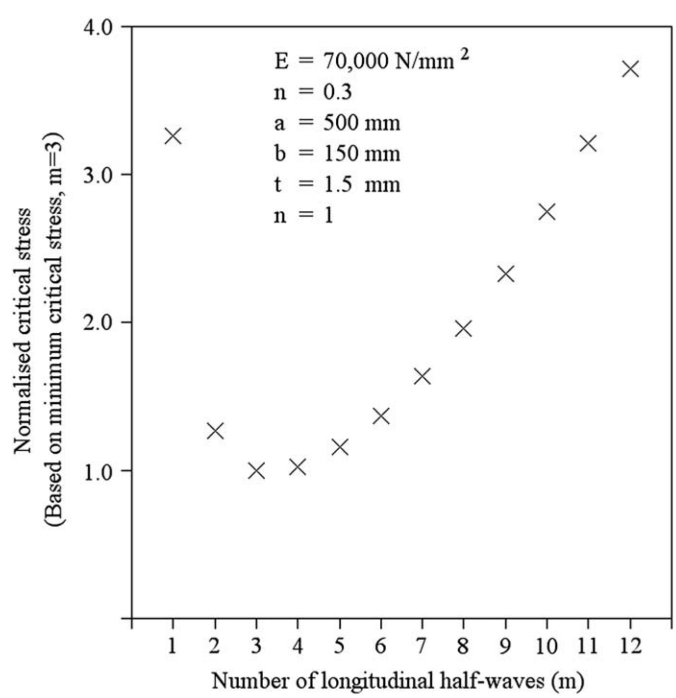

Fig. 1. Normalised compressive buckling stress for a flat rectangular plate simply supported on all edges.