Structures 3 (2015) 172–186

Contents lists available at ScienceDirect

Structures

journal homepage: http://www.elsevier.com/locate/structures

Imperfection sensitivity and geometric effects in stiffened plates susceptible to cellular buckling

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ARTICLE INFO

Article history:
Received 21 November 2014
Received in revised form 24 April 2015
Accepted 25 April 2015
Available online 1 May 2015

Keywords:
Stiffened plates
Mode interaction
Imperfection sensitivity
Structural mechanics
Structural stability
Analytical modelling
Nonlinear mechanics

ABSTRACT

An analytical model for axially loaded thin-walled stringer stiffened plates based on variational principles is exploited to study the sensitivity to initial geometric imperfections and the effects of altering geometric properties. Studies on different forms of global and local imperfections indicate that the post-buckling response governs the worst case imperfections. The investigation also focuses on the effect of changing the global and the local slendernesses on the post-buckling behaviour. The parametric space in which the stiffened plates are imperfection sensitive and susceptible to highly unstable cellular buckling is identified.

1. Introduction

A stiffened plate is an exemplar of an optimized structural component because although it is well known to be highly efficient at carrying external loads, it is equally well known to be susceptible to complex instabilities under certain circumstances [1–4]. Stiffened plates are commonly found in long-span bridge decks [5], ships and offshore structures [6], and in aerospace structures [7]. Hence, understanding the behaviour of these components represents a structural problem of enormous practical significance [8–10]. Other significant structural components such as sandwich struts [11], built-up columns [12], corrugated plates [13] and other thin-walled components [14–18] are also similarly well-known to be vulnerable to such complex instabilities. In the current case, the interaction between global and local buckling modes is particularly pertinent.

A recently developed nonlinear analytical model for an axially loaded thin-walled stiffened plate made from a linear elastic material [19,20] is exploited. The nonlinear mode interaction [1,3] between global Euler buckling and local buckling of the stiffener as well as the main plate was fully described, which was then validated through comparisons with a finite element (FE) model formulated in Abaqus [21] and with existing physical experiments [2]. The studies [18,19] focused on the perfect elastic post-buckling response and highly unstable cellular buckling behaviour was highlighted [22].

In the current context, cellular buckling, also referred to as "snaking" in the applied mathematics literature [23–25], is a particular type of post-buckling response where a sequence of snap-backs is observed after an initial instability is triggered. The snap-backs tend to occur due to inherent destabilizing and stabilizing characteristics of the structure. In the present case, the primary source of destabilization is the nonlinear interaction between local and global buckling modes, whereas the primary source of restabilization is derived from the resulting plate buckling deformation. The physical signature of cellular buckling is a reduction in the load carrying capacity in conjunction with the gradual spreading of the local buckling mode, which begins as a localized mode and in the limit spreads throughout the structure and the post-buckling mode progressively changes (usually to a smaller) wavelength. The snap-backs, observed in the case where the main plate–stiffener joint was assumed to provide a rotationally flexible (or pinned) connection, have been found to diminish by increasing the joint rigidity, although the local buckling wavelength still reduces as the post-buckling deformation is increased [19]. The changing local buckling wavelength has been observed in physical experiments in closely related structures [26,17,18] but has been found to be difficult to detect using static finite element models [20,27].

The current work exploits the previously presented model [20] by studying the sensitivity to initial local and global geometric imperfections. This is followed by a parametric study to evaluate the most vulnerable geometric combinations of local and global slendernesses

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http://dx.doi.org/10.1016/j.istruc.2015.04.004

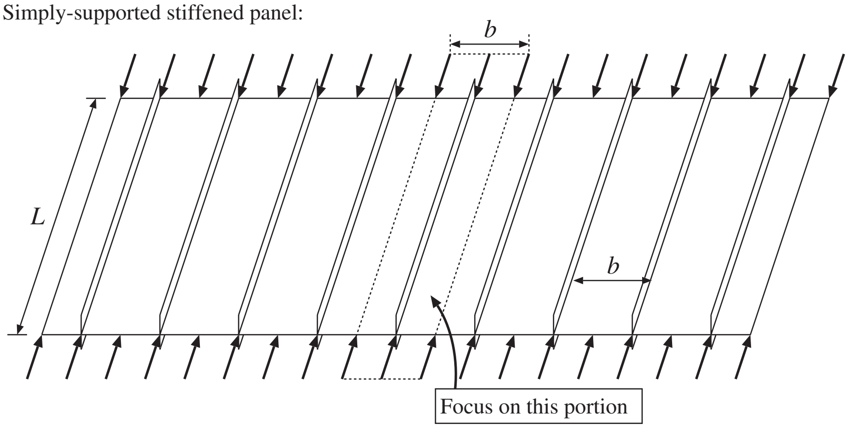

Fig. 1. An axially compressed simply-supported stiffened plated panel of length *L* and evenly spaced stiffeners separated by a distance *b*.

that trigger interactive buckling. The latter study provides a better practical understanding of where the interactive buckling behaviour of the stiffened plate is important in terms of the geometric properties, how it may be accounted and where it may be practically ignored.

2. Review of analytical model

Consider a thin-walled simply-supported plated panel that has uniformly spaced stiffeners above and below the main plate, as shown in Fig. 1, with panel length L and the spacing between the stiffeners being b. It is made from a linear elastic, homogeneous and isotropic material with Young's modulus E, Poisson's ratio v and shear modulus $G = E/[2(1 + \nu)]$. If the panel is significantly wider than long, i.e. $L \ll n_s b$, where n_s is the number of stiffeners in the panel, the critical buckling behaviour of the panel would be strut-like with a half-sine wave eigenmode along the length. There would also be a half-sine wave eigenmode across the width of the panel, the curvature of which would be considerably smaller than the corresponding curvature along the length. This, in turn, would allow a portion of the panel that is representative of its entirety to be isolated as a strut, as depicted in Fig. 1, since the transverse bending curvature of the panel during initial post-buckling would be insignificant over the width b of the central portion of the stiffened plate.

The coordinate system and the section properties for the strut are shown in Fig. 2. The axial load P is applied at the centroid of the whole cross-section denoted as the distance $\bar{y}$ from the centre line of the main plate; a rigid end plate transfers the point load as a uniform compressive pressure through the cross-section before any instability occurs. As in previous works [19,20], the rigidity of the connection between the main plate and the stiffeners is modelled with a rotational spring of stiffness c_p, as shown in Fig. 2(c). This spring reflects the relative rigidity of the actual connection, where a fully-penetrating butt-weld connecting the stiffener onto the main plate may practically allow a fully-rigid connection to be assumed. However, a fillet-welded, spot-welded [17] or even a riveted connection between the stiffener and the main plate (the latter sometimes found in aircraft construction) may only allow a basic pinned connection to be assumed. The analytical model that governs the imperfect system has been fully developed previously [20], a summary of which follows.

2.1. Modal descriptions

Two degrees of freedom, known as “sway” and “tilt” in the literature [28], are used to model the global buckling mode. The corresponding generalized coordinates are q_s and q_t respectively. The sway mode is represented by the lateral displacement W and the tilt mode is represented by the corresponding angle of inclination θ of the plane sections, as shown in Fig. 3(a). Based on linear theory, $W(z)$ and $\theta(z)$ are given by the following expressions [19]:

$$W(z) = -q_s L \sin\frac{\pi z}{L}, \quad \theta(z) = q_t \pi \cos\frac{\pi z}{L}. \tag{1}$$

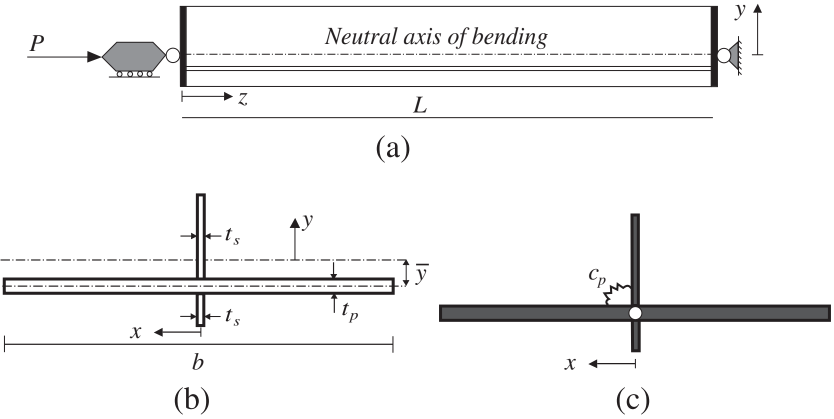

Fig. 2. (a) Elevation of the representative portion of the stiffened plate modelled as a pin-ended strut of length *L* that is compressed axially by a force *P*, the rigid end-plates shown transfer the point load into a uniform pressure through the cross-section depth but are also allowed to rotate. (b) Strut cross-section geometry. (c) Modelling the joint rigidity of the main plate–stiffener connection with a rotational spring of stiffness c_p.