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Geometric factors affecting I-section struts experiencing local and strong-axis global buckling mode interaction

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ABSTRACT

A recent analytical model describing the post-buckling behaviour of an I-section strut experiencing strong axis global–local buckling interaction is extended to investigate the effects of modifying the strut geometry. Using a combination of analytical and finite element (FE) methods, the global and local slendernesses are varied parametrically, in turn, to determine the geometries leading to regions of interactive behaviour. The effect of stress relieved initial global imperfections are also investigated. It is observed that the strut can exhibit one of five distinct post-buckling behaviours, the geometries for which are identified. The strut can exhibit global buckling only, local buckling only, global–local buckling interaction with either the global or local mode being triggered first or the most severe case where both global and local buckling modes are triggered simultaneously. The strut is found to be highly sensitive to initial imperfections in the interactive region; the implications for imperfection sensitivity on the design and the practical use of such components are discussed.

1. Introduction

The use of thin-walled structural steel components is widespread in the engineering industry and is popular due to their advantageous load capacity to self-weight ratios. However, thin-walled components are often prone to complex failure mechanisms that can have potentially dangerous consequences [1–4]. Geometric effects and initial imperfections can also have a large impact on the behaviour of thin-walled components due to their relative vulnerability to structural instability [5–12]. In the authors' previous work, an analytical model describing the interactive post-buckling behaviour of an I-section strut under compression is formulated [13,14]. The strut buckles globally about the strong axis of bending, interacting with local buckling in both the flange and web. In the current paper, the previously formulated analytical model is summarized and subsequently exploited to analyse the effects of modifying the geometry of the I-section strut. In a similar study on an idealized strut by van der Neut [5], it was found that the post-buckling behaviour of the strut may be neutral, stable or unstable depending on the geometric properties, as shown in Fig. 1, and it is anticipated that a similar response will be observed presently while varying the geometric properties of the I-section strut.

A series of parametric studies is conducted to investigate the effects of modifying the global slenderness first by varying the length of the strut, and subsequently the local slenderness of the web by varying the cross-section height. A combination of analytical and finite element (FE) methods are used. Initially, the perfect, elastic strut is considered with no material or geometric imperfections. The effect of an initial global out-of-straightness imperfection is subsequently investigated. The detailed effects of local imperfections were discussed in previous work [14] and are not considered currently for the sake of brevity. Their inclusion would require a detailed study of the worst case imperfection shape for different strut lengths to ensure a fair comparison and this has been left for future work. However, it is postulated that the effect on the load carrying capacity from local imperfections would be largely similar to that from global imperfections.

It is found that there are four distinct regions of post-buckling behaviour that can be identified for both cases where the strut length or the cross-section height is changed. For the case where the global buckling load is much greater than the local buckling load, i.e. for stocky columns or deep cross-sections, local buckling is dominant and the post-buckling behaviour of the strut is stable. Conversely, when the global buckling load is much smaller than the local buckling load, i.e. for long columns or shallow cross-sections, global buckling is dominant and the post-buckling behaviour is approximately neutral. An interactive region can be identified between these two bounds, where strong axis global–local mode interaction is observed. This region can be further sub-divided into one part where the local buckling mode is critical and a second part where the global buckling mode is critical. The different characteristics of each region are examined in detail and subsequently discussed. Moreover, the potential effects of plasticity are

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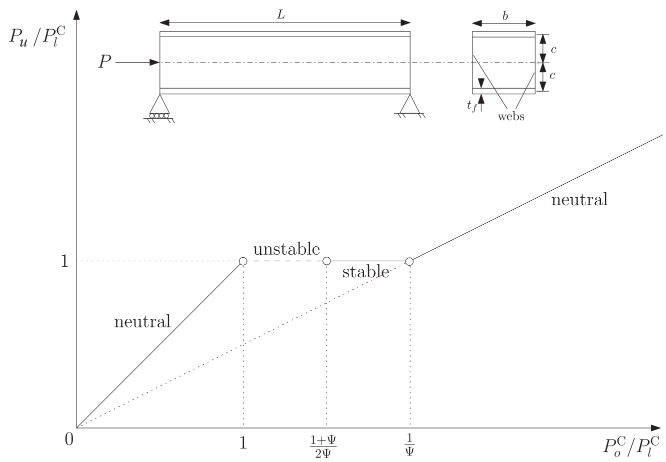

Fig. 1. The van der Neut graph [5] for the post-buckling response of a strut with two load bearing flanges of width b and length L. The quantity Ψ is a stiffness reduction factor and P is the applied compression load with P_u, P_o^C and P_l^C being the ultimate, global and local buckling loads respectively. The webs of height $2c$ are laterally rigid and so the separation of the flanges is invariant along the length. Moreover, the webs are assumed to have zero longitudinal stiffness.

discussed by identifying when first yield would occur. This adds a more practical dimension to the current study by identifying the limiting slendernesses where plasticity effects take hold.

2. Analytical model

The elevation and cross-section of the strut under consideration, along with the notation used, are shown in Fig. 2. The strut is constructed from a linear elastic, homogeneous and isotropic material and it is assumed that the strut is prevented from buckling about the weaker y-axis, a practice often used in design to increase the load carrying capacity of structural components, thereby increasing its economy. The strut is therefore forced to buckle globally about the x-axis and the load is applied concentrically as shown. Long struts are primarily considered for the analytical model; it is assumed, therefore, that global buckling is critical.

2.1. Buckling modes

The analytical model begins by defining the functions used to describe the global and local buckling shapes, as detailed in [14]. The global mode is decomposed into two components such that shear strains can be taken into account; $W(z)$ for the 'sway' and $\theta(z)$ for the

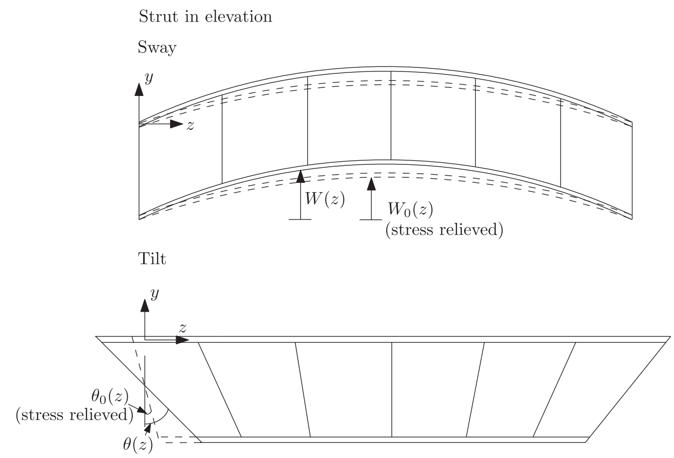

Fig. 3. Global buckling modal components with (a) the sway component $W(z)$ and (b) the tilt component $\theta(z)$ shown about the global strong axis, along with their respective geometric imperfections $W_0(z)$ and $\theta_0(z)$.

'tilt', with magnitudes of q_s and q_t defining their respective amplitudes. Additionally, the displacements $W_0(z)$ and $\theta_0(z)$ are also defined to represent their respective stress-relieved global initial imperfections, with initial displacements q_{sO} and q_{tO}. The global buckling modes, along with the respective imperfections, are shown in Fig. 3 and the corresponding expressions are written thus:

$$W(z) = q_s L \sin\left(\frac{\pi z}{L}\right), \quad \theta(z) = q_t \pi \cos\left(\frac{\pi z}{L}\right),$$
$$W_0(z) = q_{s0} L \sin\left(\frac{\pi z}{L}\right), \quad \theta_0(z) = q_{t0} \pi \cos\left(\frac{\pi z}{L}\right). \tag{1}$$

Out-of-plane and in-plane deflected shapes are also defined for the local modes. The in-plane deflected shape is assumed to be constant in the x-axis and varies linearly with the y-axis, in keeping with Timoshenko beam theory; this is used in the current formulation since shear strains have been shown to be essential for capturing interactive buckling behaviour [15]. The local out-of-plane deflection shapes are selected such that they give a good representation of the deflected shape of the element in the transverse direction, while also satisfying the boundary conditions given by the joints in the cross-section. The local buckling modes can be expressed mathematically thus:

$$u_{fl}(x, z) = u_f(z), \quad u_{wl}(y, z) = -\left(\frac{y}{h}\right) u_w(z),$$
$$w_{fl}(x, z) = f(x) w_f(z) = -\left(\frac{2x}{b}\right),$$
$$w_{wl}(y, z) = g(y) w_w(z) = \left[\frac{\pi}{2} + \frac{\pi y}{h} - \sin\left(\frac{\pi y}{h}\right) - \frac{\pi}{2}\cos\left(\frac{\pi y}{h}\right)\right] w_w(z), \tag{2}$$

where u is an in-plane deflection in the z-direction and w is an out-of-

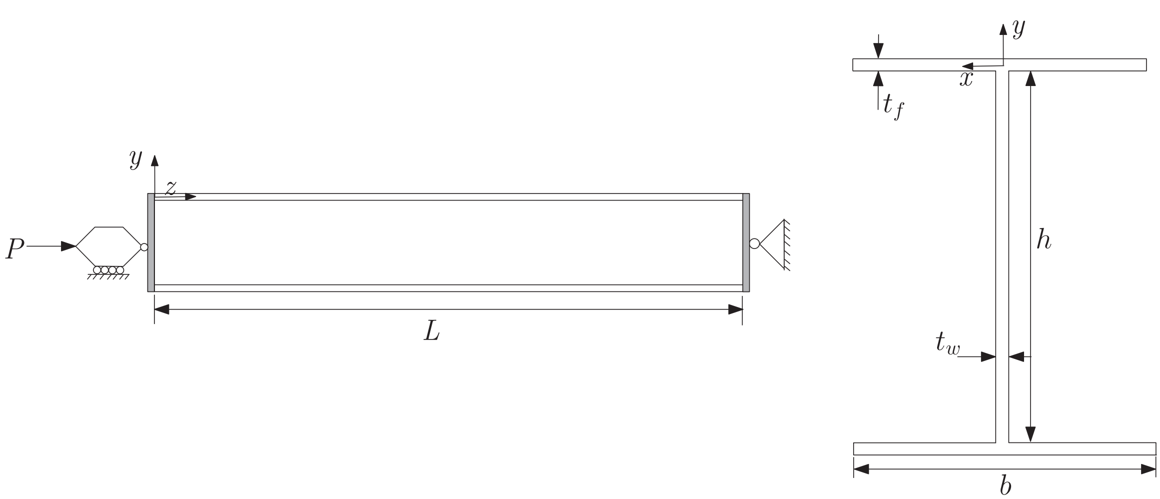

Fig. 2. An I-section strut under axial loading P, elevation (left) and cross-section (right) shown. The notation and coordinate system used throughout are shown.