Thin-Walled Structures 106 (2016) 228–243

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Mode interaction in perfect and imperfect thin-walled I-section struts susceptible to global buckling about the strong axis

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ARTICLE INFO

Article history:
Received 22 January 2016
Accepted 30 April 2016

Keywords:
Analytical modelling
Mode interaction
Imperfection sensitivity
Nonlinear mechanics
Strong axis global buckling

ABSTRACT

A recently developed analytical model for a perfect I-section strut experiencing a nonlinear interaction between local buckling and global buckling about the strong axis is enhanced and subsequently extended. The initial enhancement is achieved by devising a simplified and calibrated model that provides an improved prediction of the local buckling load. A purely numerical model is then constructed within the commercial finite element (FE) software Abaqus for validation purposes and excellent comparisons are observed, demonstrating that the analytical model is considerably improved on previous work. The model for interactive buckling is then developed subsequently to include the effects of global and local geometric imperfections, which are introduced individually and in combination. The strut is found to be sensitive to all considered shapes of imperfection and the combined imperfection case correlates excellently with an equivalent FE model, particularly in the neighbourhood of the secondary instability that leads to mode interaction. This demonstrates that the enhanced analytical model predicts the actual load carrying capacity and the structural mechanics accurately.

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1. Introduction

It is well known that struts and columns constructed from thin-walled elements under compression are practically vulnerable to a range of different elastic buckling instabilities [1–4]. Particularly in cases where global and local instability modes have similar critical loads, nonlinear modal interactions are often observed in the post-buckling response of such structures. This can lead to unstable behaviour and may cause a significant decrease in load carrying capacity when compared to the predicted capacities for each individual mode [5–9]. Several studies on similar components exist that employ experimental techniques and finite element (FE) analysis to study global and local mode interaction in thin-walled carbon steel and stainless steel columns [10–13]. It is also the case that such systems have previously exhibited a high sensitivity to initial global and local geometric imperfections [14–18]. However, thin-walled structures have attractively high strength to weight ratios and are therefore used extensively in industry, particularly in the maritime, aeronautical and civil engineering sectors [1,19]. It is essential therefore that continually improved understanding of the physical behaviour of these practically important component types is developed.

In the authors' previous work, an I-section strut with a rigid flange–web connection was investigated using an analytical approach where nonlinear mode interaction was observed between the critical global buckling mode about the strong axis and a local plate buckling mode [20]. The post-buckling behaviour of the strut was found to be highly unstable and led to lower load carrying capacities than would be anticipated for either individual buckling mode. A changing wavelength was also observed in the local out-of-plane displacement profile of the strut flange and web elements with results being compared to an equivalent model constructed in the commercial FE package Abaqus [21], giving reasonable comparisons particularly at and immediately beyond the secondary bifurcation point where interactive buckling is triggered.

The global buckling load was well predicted by the analytical model, matching the FE prediction to within 1%. However, the local buckling load was less well predicted, largely owing to the relative uncertainty of the actual rotational stiffness provided by the flange–web connection, previously assumed to be completely rigid in the analytical model. The initial aim of the current work is to enhance the previous model by providing a more accurate analytical prediction of the local buckling load. An analytical model is duly presented that describes the behaviour of an I-section strut experiencing local buckling only. A parameter κ determines the actual level of rigidity provided by the flange–web connection. This parameter is calibrated by comparing the analytically predicted local buckling load to an equivalent FE model formulated in the commercial package Abaqus [21]. This calibrated

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http://dx.doi.org/10.1016/j.tws.2016.04.027
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value is then used to enhance the previous model of a perfect, long strut, where global buckling is critical [20], which interacts with the local buckling mode resulting in significantly improved comparisons with the FE model for the interactive buckling case.

Moreover, in previous work, only global geometric imperfections were introduced into the analytical formulation in the form of initial stress-relieved out-of-straightness deformations. The study that was conducted for the fully rigid flange–web joint is revisited presently with the calibration implemented. The strut is still found to be sensitive to initial out-of-straightness geometric imperfections, which results in a decreasing ultimate load as the magnitude of the initial imperfection is increased. The currently enhanced analytical model is then extended further to include initial local imperfections, individually and in combination with the global imperfection. An imperfection sensitivity study is then conducted for a variety of out-of-plane imperfection profiles. The model shows sensitivity to all shapes of the local imperfections prescribed, with a greater decrease in the ultimate load for localized imperfections reflecting previous work on other similarly behaving structural systems [22–24]. This finding is also validated by the FE model showing excellent comparisons, particularly in the initial post-buckling range. The study has the potential to be extended to determine the model parameter ranges where interactive buckling is significant; this is currently under development and the authors hope to report on this in due course.

2. Analytical formulation

The strut studied currently is shown in Fig. 1 and is assumed to be restrained from buckling globally about the weaker y-axis. The formulation of the analytical model begins by defining the displacement functions for global buckling modes, as well as the local buckling modes in the in-plane u and out-of-plane w directions. Note that deflections in the third dimension v are very small and are therefore neglected currently [2].

2.1. Global buckling modes

The two global degrees of freedom defined in previous work [20], so-called 'sway' and 'tilt', are shown in Fig. 2. and are defined thus:

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

The difference between the two modal amplitudes q_s and q_t allows shear strains to be accounted for in the strut, which is essential to capture any interactive behaviour occurring during post-buckling [25]. In order to include an initial, stress-relieved, out-of-straightness as a global imperfection, the functions W_0 and θ_0 are also introduced:

$$W_0(z) = q_{s0} L \sin\left(\frac{\pi z}{L}\right), \quad \theta_0 = q_{t0} \pi \cos\left(\frac{\pi z}{L}\right), \tag{2}$$

where q_{s0} and q_{t0} are the respective amplitudes, also shown in Fig. 2, corresponding to those from the sway and tilt degrees of freedom.

2.2. Local buckling modes

For the local buckling displacements, there are up to six separate functions that need to be introduced, depending on whether global or local buckling is critical. Fig. 3 shows these displacement functions and are defined thus:

$$u_{fli}(x, z) = u_{fi}(z), \qquad u_{wl}(y, z) = -\left(\frac{y}{h}\right) u_{w1}(z) + \left(1 + \frac{y}{h}\right) u_{w2}(z), \tag{3}$$

$$w_{fli}(x, z) = f_i(x) w_{fi}(z), \qquad w_{wl}(y, z) = g_1(y) w_{w1}(z) + g_2(y) w_{w2}(z), \tag{4}$$

for the in-plane flange and web displacements, as well as the out-of-plane flange and web displacements respectively. Here, $i = \{1, 2\}$ to account for the respective deflections of both the bottom and top flanges, as shown in Fig. 3. For the case where global buckling is critical, it is assumed that the less compressed top flange remains undeflected throughout post-buckling, as shown in Fig. 4. Hence, in this case, all local displacement profiles associated with the less compressed flange (i.e. with subscript 2) are assumed to be zero, reducing the number of local buckling displacement functions from eight to four.

The functions $f_i(x)$ and $g_i(y)$ are selected such that they satisfy the boundary conditions for each individual component, as well as giving a good representation of the deflected shape of the component. The out-of-plane deflection profile of the flange is approximated to be linear, resulting in the function $f_i(x) = (-1)^i (2x/b)$ [20]. The out-of-plane displacement of the web

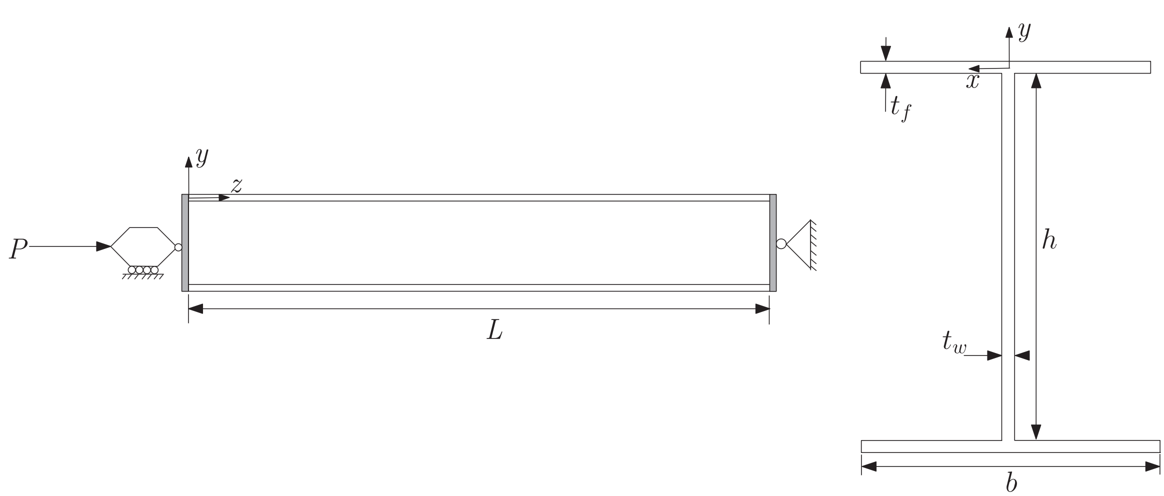

Fig. 1. An I-section under axial loading P, shown using the elevation (left) and the cross-section (right). The ends are simply supported and a rigid end plate transfers the load equally to the flanges from the supports.

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