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Sensitivity of elastic thin-walled rectangular hollow section struts to manufacturing tolerance level imperfections

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ABSTRACT

Finite element models for elastic thin-walled rectangular hollow section (RHS) struts with pre-defined local and global geometric imperfections are developed within the commercial package ABAQUS. A unified local imperfection measurement based on equal local bending energy is proposed. The effects of imperfect cross-section profiles, imperfection wavelength in the longitudinal direction and the degree of imperfection localization on the ultimate load and equilibrium path are investigated and the most severe imperfection profiles are determined. A parametric study on the wavelength of the most severe local imperfection profile is conducted and a semi-empirical equation to approximate the corresponding wavelength is proposed. Moreover, an equation to calculate the global buckling load of thin-walled RHS struts with tolerance level doubly-symmetric cross-section local imperfections is proposed.

1. Introduction

Buckling instabilities are the principal failure mode for structural members made from materials with high strength-to-weight ratios [1–5]. Moreover, compression members made from thin-walled plated elements are prone to suffer from a variety of different elastic instability phenomena [6–10]. Even though these modes may exhibit neutral or stable post-buckling behaviour when triggered individually, the interaction of these modes may lead to dangerously unstable post-buckling behaviour [11–15]. More importantly, such structures can also show extreme sensitivity to imperfections [16–21], *i.e.* a tiny imperfection in the initial geometry may lead to significant erosion in the load-carrying capacity.

Owing to its relative simplicity and the lack of efficient and advanced computational tools, early researchers mainly adopted a local imperfection profile that was affine to the lowest local buckling eigenmode to investigate the imperfection sensitivity of thin-walled compression members susceptible to mode interaction [6,22,23]. These works identified the serious erosion in the load-carrying capacity for the cases where the local and global buckling loads are in close proximity. Moreover, these provided the ultimate load prediction with good accuracy for the cases studied. Therefore, it is still one of the most widely used methodologies [24].

In spite of its convenience, local imperfections modelled with this approach may not reflect the actual imperfection profiles in physical reality. Equally importantly, they may not represent the most severe local imperfection profile [25,24]. With the advance of computational tools and physical testing techniques, numerous investigations on the effects of local imperfection profiles on the ultimate load and post-buckling behaviour have been conducted. Rasmussen and Hancock [26] proposed an analytical technique to expand the measured geometric imperfections in the longitudinal and cross-sectional dimensions based on the buckling modes. In particular, the secondary local buckling components triggered by the interaction of global and local buckling modes were also considered, *i.e.* the modulated longitudinal profile and the mono-symmetric cross-section profile.

Dubina and Ungureanu [27] studied the effects of cross-section imperfection profiles on the load erosion of channel section columns susceptible to mode interaction using the finite element (FE) method. They found that the ultimate loads for example struts with symmetrical and asymmetrical cross-section imperfection profiles, which are affine to the lowest and higher local buckling modes, are 12% lower and 15% higher than the test results respectively. They also emphasized that using the sinusoidal shape from linear buckling analysis may not represent the most appropriate imperfection mode introduced in nonlinear analysis.

Zeinoddini and Schafer [28] introduced three methods to simulate the geometric imperfections in cold-formed steel members and compared their effects for predicting the peak load and final failure mode using geometric and materially nonlinear FE models. All three methods were based on the imperfection spectra [29], which is built on a large number of imperfection measurement tests. It was found that the ‘1D

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Modal Spectra Method', which adopted the cross-section imperfection component from linear buckling analysis and the longitudinal component from spectral analysis, provided the most accurate prediction for the ultimate load and final failure mode.

Trouncer and Rasmussen [30] conducted a spectral analysis of the ultimate load as a function of imperfection spectra for 20 storage rack columns susceptible to mode interaction. From a large number of FE simulations, they found that local imperfections in the shape of higher order modes with half-wavelengths in close proximity to the half-wavelength of the critical buckling mode have little effect on the ultimate load; this also applies if the local imperfections were introduced to the cross-section non-symmetrically, which would naturally break the symmetry and hence trigger mode interaction.

Zagari et al. [31] investigated the imperfection sensitivity of thin-walled perforated rack members in compression using an FE implementation of the Koiter method in conjunction with a Monte Carlo simulation. The most severe combination of imperfections and the erosion of the ultimate load due to imperfections were identified. From the probability distribution of the ultimate load for specimens exhibiting mode interaction, it was found that the deviation is very small, which implies that the imperfection profile has very minor effects on the ultimate load for such cases. However, even though a great number of imperfection combinations were adopted in the study, only the geometric imperfections in the space of the linear buckling modes were considered.

Wadee and his collaborators investigated the most severe imperfection profile of thin-walled I-section struts [20,21] and stiffened panels [19] exhibiting mode interaction using an analytical approach. By introducing a local imperfection function that matches the least stable localized post-buckling mode for the strut on a softening foundation – derived from a first order approximation of a multiple scale perturbation solution [32], the most severe local imperfection profiles have been determined in terms of the wavelength of the oscillating component and the degree of localization. Unlike preceding work that compared different imperfection profiles with the same amplitude, a unified and consistent approach was implemented adopting the concept of initial end-shortening of the extreme fibre of flange plate $\mathscr{E}_0$. This was initially proposed by Wadee [25] for identifying the most severe local imperfection profile in sandwich panels under compression that are susceptible to local–global mode interaction. These works also determined that localized imperfections are even more severe than those that are affine to the local buckling eigenmodes.

There has also been a great deal of effort in determining the local imperfection distribution and magnitude quantitatively [29,33,34], analysing the measurement data using statistical tools [29,30] and developing methodologies such that the local imperfections studied reflect those in physical reality [28]. However, since local imperfections are affected by many factors, *i.e.* the manufacturing method, handling, material properties and cross-section properties, they are essentially stochastic parameters. A large number of analyses are necessary to obtain statistically significant results [35].

As for the specific work on the imperfection sensitivity of thin-walled RHS columns, Degée et al. [36] investigated the effects of residual stresses, local and global geometric imperfections on the load-carrying capacity through the experimental and FE studies. Based on the results, equivalent geometric imperfections were proposed to replace geometric imperfections and residual stresses in modelling welded RHS struts. Pavlovčič et al. [37] implemented actual geometric imperfections as well as residual stresses in FE models, which were validated with experimental studies and showed excellent comparisons. With the validated FE model, various equivalent geometric imperfections recommended by the previous study [36] and Eurocode 3 [38] were assessed. Yang et al. [39] investigated the imperfection sensitivity of welded thin-walled box-section columns based on an FE model validated from experimental studies. It was found that the local imperfections had a greater effect on columns with higher width–thickness ratios and global imperfections had a profound effect on columns with higher slendernesses.

Recently, the authors investigated the imperfection sensitivity of thin-walled RHS struts based on a variational model [40]. Sensitivity of struts to purely local imperfections, purely global imperfections and their combination was investigated. Curves were fitted to describe the ultimate load–imperfection size relationship. It revealed that local and global imperfections are relatively more significant where global and local buckling are critical respectively.

The current article is a continuation of the aforementioned work [40] and it focuses on the behaviour of such elastic struts with imperfections, the sizes of which are related to manufacturing tolerances. A nonlinear FE model with pre-defined local and global imperfections is developed within the commercial package ABAQUS [41]. A measurement method for different local imperfection profiles based on the concept of equal local bending strain energy is proposed. The effects of the imperfection profile, *i.e.* cross-section profile, the longitudinal wavelength and the degree of localization, on the ultimate load and equilibrium path of four characteristic length struts are investigated and the most severe local imperfection forms are identified. The effects of localized imperfections on the behaviour of struts are also discussed. A parametric study on the wavelength of the most severe imperfection profile is conducted and a semi-empirical relationship to determine the corresponding wavelength is proposed. The mechanism of global buckling in struts with tolerance level doubly-symmetric local imperfections is discussed and an explicit equation to calculate the global buckling load is proposed. The current work provides a better understanding of the behaviour of thin-walled RHS struts with tolerance level imperfections, which would facilitate the development of robust design guidelines for such structural members in future.

2. Development of the finite element model

A thin-walled rectangular hollow section strut of length L with simply-supported boundary conditions under an axial load P is considered, as shown in Fig. 1. The web depth and flange width are d and b;

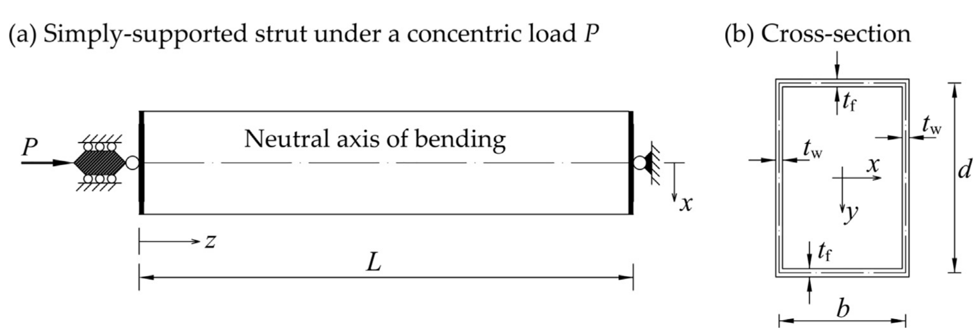

Fig. 1. (a) Plan view of the thin-walled RHS strut of length L under an axial load P. Lateral and longitudinal coordinates are x and z respectively. (b) Cross-section properties of the strut; the vertical coordinate is y.