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Design of laterally restrained web-tapered steel structures through a stiffness reduction method

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ABSTRACT

A stiffness reduction method for the design of laterally restrained web-tapered steel structures fabricated through the welding of individual steel plates is presented in this paper. Stiffness reduction functions for welded members, accounting fully for the deleterious influence of the spread of plasticity and imperfections on the structural resistance, are developed. The method is implemented through (i) dividing tapered members into prismatic segments along their lengths, (ii) reducing the flexural stiffness of each segment by means of the developed stiffness reduction functions considering the first-order forces and cross-section properties of each segment, (iii) performing Geometrically Nonlinear Analysis and (iv) making cross-section strength checks. Essentially, it is proposed to replace the current typical approach to structural design of conducting a simple elastic (with nominal stiffness) structural analysis followed by elaborate member checks with an integrated process utilising more sophisticated second-order analysis (with stiffness reduction) but very simple design checks. The distribution of internal forces within the structure is captured more accurately due to the allowance for imperfections, residual stresses and plasticity through stiffness reduction and the allowance for frame and member instability effects through the use of second-order analysis. The need for determining effective lengths and for conducting member buckling checks is also eliminated. Verification of the proposed approach against the results obtained from nonlinear shell finite element modelling is presented for various tapering geometries, slenderness values and loading conditions. Assessment of the proposed method against the European and North American steel design codes for tapered steel structures is also provided.

1. Introduction

To achieve greater economy in material use, web-tapered steel members, where deeper cross-sections are used within the regions subjected to larger internal forces, are commonly employed within steel structures. However, the methods provided in current structural steel design specifications [1,2] for the instability assessment of web-tapered steel members are based largely on those developed for prismatic steel members, often leading to overly-conservative estimations of their ultimate strengths and thus limiting the efficiency gains achieved through their use.

For the purpose of establishing accurate methods for the design of tapered steel members, various design approaches have been proposed in the literature. Shiomi and Kurata [3] recommended empirical formulae for the transformation of tapered members into prismatic members with equivalent lengths. This method is straightforward to apply but leads to rather conservative results, particularly for tapered beam-columns due to its adoption of a linear interaction equation. Raftoyiannis and Ermopoulos [4] proposed the use of the equivalent geometrical imperfections provided in Ref. [1] for the design of eccentrically loaded tapered columns. Salem et al. [5] put forward an empirical equation for the flexural buckling assessment of tapered columns with slender cross-sections. Braham and Hanikenne [6] adopted the Merchant-Rankine equation for the lateral-torsional buckling assessment of tapered beams. Though these approaches led to strength predictions close to those obtained through nonlinear finite element modelling, they were only investigated for rather few cases. Marques et al. [7] put forward design equations with a clear mechanical background, which were calibrated to the results of a large number of finite element analyses. This method [7] is straightforward to apply for the design of tapered columns, but becomes more complex and less accurate in the case of tapered beam-columns.

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The primary objective of this paper is to develop a both practical and accurate method for the in-plane design of web-tapered steel structures fabricated through the welding of individual plates, extending the stiffness reduction approach proposed by Kucukler et al. [8,9] for hot-rolled members to welded tapered structures. Stiffness reduction functions for welded members able to fully consider the detrimental influence of plasticity and imperfections are derived. The proposed approach is applied, using beam elements, through (i) the division of tapered members into prismatic segments, (ii) the reduction of flexural stiffness of each prismatic segment through the developed stiffness reduction functions considering the first-order forces at the middle of the segment, (iii) performing Geometrically Nonlinear Analysis (GNA-SR) and (iv) making cross-section strength checks. Owing to the full consideration of the deleterious influence of the spread of plasticity, geometrical imperfections and residual stresses on the structural resistance through the developed stiffness reduction functions, the proposed method only requires cross-section checks after structural analysis with stiffness reduction. Hence the conventional analysis and design stages are merged, obviating the need to determine effective lengths or conduct elaborate member design checks, which can be particularly complicated for tapered structures [10,11]. The practicality of the use of stiffness reduction in the design of both irregular and regular steel members has also been recognised by Refs. [12–14]. Since the proposed approach is based on the division of tapered members into prismatic segments, it can be applied through any conventional structural analysis software capable of performing elastic Geometrically Nonlinear Analysis on beam element models. The approach proposed in this paper constitutes part of a design framework based on the separation of in-plane (i.e. in the plane of bending) and out-of-plane instability assessments of tapered steel structures. Since the latter is not required for laterally restrained structures, the method developed in this study can be applied in their design without the need for any further global instability assessment. Similar to Marques et al. [7], the global instability response of tapered steel structures is considered in this study assuming the cross-sections are able to reach their full plastic strengths; the proposed approach is therefore currently applicable to Class 1 and 2 cross-sections only, but will be extended to consider the interaction of local and global instability effects in future work.

In the following sections, shell finite element models of tapered members and frames with different geometries are created and then utilised to assess the accuracy of the proposed approach. The development of the stiffness reduction functions is illustrated and comparisons are also made against the design methods provided in EN 1993-1-1 [1] and AISC Design Guide 25 [15] for both tapered members and frames. A range of slendernesses, loading cases and tapering geometries are considered for thorough verification of the proposed approach.

2. Finite element modelling

The results of shell finite element modelling are used to verify the stiffness reduction design approach proposed in this study. Details of the adopted finite element modelling approach are described in this section. The finite element models were created through the finite element analysis software Abaqus [16]. A four-node reduced integration shell element, which is designated as S4R in the Abaqus [16] element library and takes into account transverse shear deformations and finite membrane strains, was used in all the numerical simulations. 16 elements were employed for each flange and web plate so that the spread of plasticity through the depth of the cross-sections could be accurately considered. To avoid overlapping of the flange and web plates, the web plates were offset considering the thickness of the flanges. The default Simpson integration method was used, with five integration points through the thickness of each element. The Poisson's ratio was taken as 0.3 in the elastic range and 0.5 in the plastic range by defining the effective Poisson's ratio as 0.5 to allow for the change of cross-sectional area under load. A tri-linear stress-strain relationship was used in the adopted material model, which is shown in Fig. 1, where E is the Young's modulus, E_{sh} is the strain hardening modulus, f_y and ϵ_y are the yield stress and strain respectively and ϵ_{sh} is the strain value at which strain hardening commences. The parameters f_u and ϵ_u correspond to the ultimate stress and strain values respectively. E_{sh} was assumed to be 2 % of E and ϵ_{sh} was taken as $10\epsilon_y$, conforming to the ECCS recommendations [17], though more representative values for these two parameters have recently been proposed [18], which will be considered in future studies. In the finite element models, isotropic strain hardening and the Von Mises yield criterion with the associated flow rule were employed. Since the constitutive formulations of Abaqus [16] adopt the Cauchy (true) stress-strain assumption for shell finite elements, the engineering stress-strain relationship shown in Fig. 1 was transformed into a true stress-strain relationship. Unless otherwise indicated, S235 steel was considered in all the simulations. Using the default convergence criteria recommended by Abaqus [16], the load-displacement response of the finite element models was determined by means of GMNIA (Geometrically and Materially Nonlinear Analysis with Imperfections) using the modified Riks method [19,20].

The ECCS residual stress pattern [17], illustrated in Fig. 2, which is recommended for cross-sections fabricated through the welding of plates was applied to the finite element models. It should be noted that the welds were conservatively not modelled in the finite element simulations, only the residual stresses resulting from the welding were accounted for. Geometrical imperfections were assigned to the models in the shape of the lowest global buckling mode, with the maximum imperfection scaled to 1/1000 of the member length. Since the present study is limited to the global in-plane instability response of tapered structures, local imperfections were not considered and the finite element models were fully restrained in the out-of-plane direction; a similar approach was followed in Ref. [7]. Note though that for tapered members with slender cross-sections, local buckling can control the design and will be considered in future work. Comprehensive validation of the adopted finite element modelling approach against results from a range of experimental studies reported in the literature has been provided by Kucukler [21], for both individual steel members and frames containing nonprismatic segments.

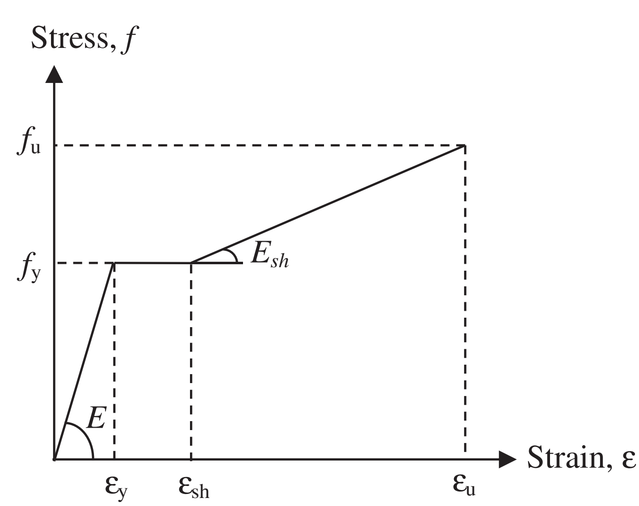

Fig. 1. Material stress-strain curve used in finite element models.