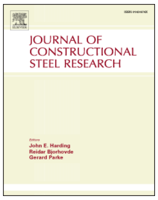
Journal of Constructional Steel Research 126 (2016) 187–200

Contents lists available at ScienceDirect

Journal of Constructional Steel Research



Development and assessment of a practical stiffness reduction method for the in-plane design of steel frames

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ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 19 May 2016
Accepted 6 June 2016
Available online xxxx

Keywords:
Stiffness reduction
Steel frames
Steel beam-columns
Inelastic buckling
Imperfections
Residual stresses

ABSTRACT

In this paper, the development and assessment of a stiffness reduction method for the in-plane design of steel frames is presented. The adopted stiffness reduction approach is implemented by reducing the flexural stiffnesses (*EI*) of the members of a steel frame by considering the first-order forces they are subjected to through the stiffness reduction functions and performing Geometrically Nonlinear Analysis (i.e. second-order elastic analysis). Since the presented approach uses stiffness reduction functions that fully take into account the deleterious influence of imperfections and the spread of plasticity on the structural response and member strengths, it obviates the need of using member design equations, and only requires cross-section strength checks. The accuracy of the presented approach is illustrated for individual steel members and non-redundant and redundant benchmark steel frames from the literature. In all the considered cases, the presented method is verified against the results obtained from nonlinear finite element modelling. A comparison of the presented approach against the notional load method of the European structural steel design code EN 1993-1-1 and the direct analysis method of the US structural steel design code AISC 360-10 is also provided.

1. Introduction

The development and spread of plasticity, aggravated by the presence of residual stresses and geometrical imperfections, causes the stiffness of steel structures to be significantly eroded under applied loading, which detrimentally influences their stability and strength. In conventional structural steel design carried out in accordance with the current steel design specifications [1–3], the influence of these adverse effects is typically taken into account through semi-empirical member design equations and adopting the effective length or notional load concepts. Though it is rather straightforward to apply, this type of structural design approach is quite an indirect way of considering the effects of plasticity and imperfections on the response of steel structures. It also generally ignores the changes of forces and moments within the structural elements due to the different extents of stiffness reduction (i.e. plasticity) experienced.

To consider the detrimental influence of the spread of plasticity on the response of a steel structure in a more direct manner, the reduction of stiffness of its members on the basis of the forces and moments they withstand has been recommended by Liew et al. [4,5], Ziemian and McGuire [6] and Zubydan [7,8]. These proposals do however require the explicit modelling of the initial member out-of-straightnesses, which can be a quite tedious process due to the need to determine the most unfavourable shape and direction of imperfection for each single member under various loading conditions. Kim and Chen [9,10] proposed the application of further stiffness reduction to the stiffness reduction scheme of [4,5], thereby taking into account the influence of the member out-of-straightness on the behaviour and eliminating the need for its modelling. Nevertheless, this method is based on the refined plastic hinge analysis approach requiring specific software which is not widely available in practice. Surovek-Maleck and White [11,12] put forward a method that can be applied through conventional structural analysis software by performing Geometrically Nonlinear Analysis with reduced stiffness, thereby considering the influence of the spread of plasticity on the structural response and eliminating the need to use sway buckling mode effective lengths in the determination of the strengths of the steel members. With minor changes, this method has now been included in the two most recent versions of the AISC 360 specification, including AISC 360-10 [2], where it is referred to as the direct analysis method. However, since the stiffness reduction scheme of the direct analysis method does not fully consider the erosion of strength in imperfect inelastic columns, it still requires the use of column strength equations in design. Moreover, it leads to overly-conservative results in some cases as it disregards the influence of bending moment shape on the development of plasticity.

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http://dx.doi.org/10.1016/j.jcsr.2016.06.002
0143-974X/

In Kucukler et al. [13], a stiffness reduction method for the in-plane design of structural steel members is proposed. Stiffness reduction functions capable of taking into account fully the deleterious influence of the spread of plasticity, residual stresses and geometrical imperfections and of considering the influence of bending moment shape on the development of plasticity were developed. Unlike the direct analysis method of AISC 360-10 [2], the stiffness reduction method of [13], which was verified against the results obtained from nonlinear finite element modelling for a wide range of cases, eliminated the need of using column strength equations, requiring only cross-section strength checks. However, Kucukler et al. [13] only focused on the assessment of the accuracy of their method for individual members and did not apply it to the design of steel frames.

The current paper extends the stiffness reduction method of Kucukler et al. [13], which applies to individual elements, to the design of steel frames. The assessment and verification of the stiffness reduction approach against nonlinear finite element modelling is presented for a series of steel frames. In the proposed approach, Geometrically Nonlinear Analysis of the structure, whose members' flexural stiffnesses (*EI*) have been reduced on the basis of the forces they are resisting in a prior first-order analysis, is performed. The internal forces determined through the Geometrically Nonlinear Analysis are then used to carry out cross-section checks. Provided the ultimate cross-section strength is not exceeded within the structure, the design is satisfactory. Since the influence of the spread of plasticity and imperfections is fully accounted for by stiffness reduction, there is no need to use column strength equations. The proposed approach also does not require the modelling of member out-of-straightnesses, thus removing the need to identify their most detrimental shape and direction. The stiffness reduction approach presented herein is intended to be used with that proposed for out-of-plane design in Kucukler et al. [14,15] within a design framework based on the separation of the in-plane and out-of-plane analyses of steel frames subjected to in-plane loading.

In the following sections of this paper, the application and accuracy of the presented stiffness reduction method are illustrated by comparing its results against those obtained from Geometrically and Materially Nonlinear Analysis with Imperfections (GMNIA) of finite element models for individual steel members and non-redundant and redundant benchmark steel frames from the literature. To assess the qualities and limitations of the proposed method against other structural steel design approaches, comparisons are also made with the notional load method of EN 1993-1-1 [1] and the direct analysis method of AISC 360-10 [2], both of which require individual member buckling checks.

2. Finite element modelling

In this section, the details of the finite element modelling approach adopted in this study are presented. In the subsequent sections, the finite element models, which account for geometrical and material nonlinearities and include geometrical imperfections and residual stresses, are used to verify the proposed stiffness reduction method.

2.1. Development of finite element models

In this study, beam elements were employed to create finite element models through the finite element analysis software Abaqus [16]. The linear Timoshenko beam element referred to as B31OS in the Abaqus element library and capable of considering shear deformations and the warping degree of freedom is used in all the numerical simulations. Thirty-three integration points were used within each flange and web of an I section so that the stress and strain variations within the cross-section and the spread of plasticity could be accurately captured. The default Simpson integration method with one integration point located in the middle of an element was chosen for the numerical integration along the element length. The tri-linear elastic-plastic stress-strain relationship shown in Fig. 1 was employed, 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 the onset of strain hardening. The parameters f_u and ϵ_u correspond to the ultimate stress and strain 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] for hot-rolled structural steel. The von Mises yield criterion with associated plastic flow and isotropic hardening were assumed in the finite element models. Unless otherwise indicated, grade S235 steel was used in all the simulations.

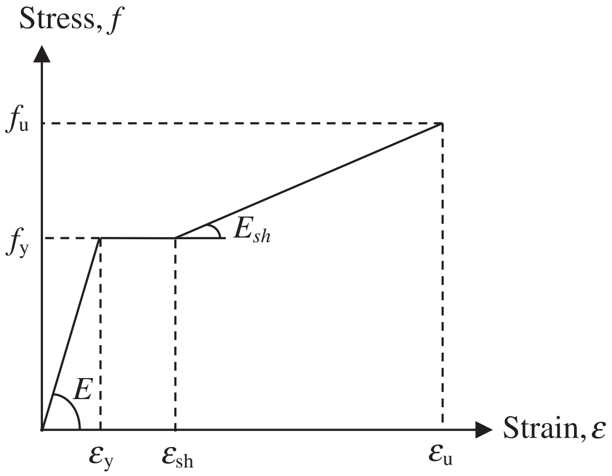

Fig. 1. Material stress-strain curves used in finite element models.

The ECCS [17] residual stress patterns illustrated in Fig. 2 were applied to the finite element models by defining the initial stress values at the section integration points through the SIGINI user subroutine [16]. The initial member out-of-straightness was assumed to be a half-sine wave in shape and 1/1000 of the corresponding member length in magnitude, while the initial frame out-of-plumbness was assumed to be 0.002 rad [18]. These geometrical imperfections were defined in the most unfavourable directions considering the loading conditions in all the numerical simulations: the initial out-of-straightness was modelled in the direction that the member deforms for single curvature bending cases and mostly deforms for double curvature bending cases, while the initial out-of-plumbness of the frame was modelled in the direction of sway deformation. It is worth noting that for the investigated highly redundant sway frames, it was observed that the out-of-plumbness was the dominant geometrical imperfection in comparison to the member out-of-straightness, which is in accordance with the observations of Ziemian et al. [19] and Maleck [20]. In the finite element models, 100 elements were used to model each individual member of the considered frames. Since this paper investigates the application of the proposed stiffness reduction approach to the in-plane design of steel frames, all the finite element models were fully restrained in the out-of-plane direction.

2.2. Validation of finite element models

In Kucukler [21], a series of steel frame and individual member experiments from the literature were employed to verify the finite element modelling approach adopted in this paper. A wide range of validation studies was performed where it was observed that the finite element models are able to replicate accurately the actual response of steel frames and members influenced by geometrical and material nonlinearities and imperfections.

3. Description of the stiffness reduction method

This section describes the application of the proposed stiffness reduction method to steel frames. Initially, stiffness reduction functions