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Experimental lateral-torsional buckling behaviour of web tapered I-section steel beams

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ABSTRACT

Tapered steel members are often chosen instead of prismatic due to a better cross-section utilization along the member, which makes them an interesting and more economical alternative. Although EN1993-1-1 offers several methodologies for the stability verification of steel members and frames, it does not provide a clear guidance for the stability design of such members.

Recently, the research group has provided simplified stability verification methodologies for tapered columns and beams. The developed methodologies are based on analytical derivations which were validated with advanced numerical simulations.

In order to improve the accuracy of the proposed procedures, full-scale experimental tests on tapered columns, beams and beam-column were carried out. The experiments are used to calibrate a numerical model, incorporating all relevant parameters, such as: geometrical imperfections (local and global) and material imperfections (residual stresses). In this paper, firstly a global overview of the experimental programme on web-tapered steel members is given. The key results from each experiment are summarized; they are further used for the calibration of an advanced numerical model.

1. Introduction

Steel members with variable cross-section along their length provide efficient solutions for large-span beams by adjusting the depth of the cross-sections to the bending moment distribution. In addition, non-uniform steel members also exhibit good aesthetic value in exposed structures such as large-span roofs or long cantilevers.

Steel members with variable cross-section are usually manufactured by automatic welding of steel plates in an economical manufacturing process, making it a viable alternative to the use of standard hot-rolled profiles.

Hence, if properly designed, non-uniform members, whether they have variable depth or flange widths, a polygonal longitudinal axis or an irregular distribution of bracings along the member length, allow for an improved distribution of the material, leading to a more uniform distribution of stresses and, therefore, a more economical structural solution. In this paper, focus is given to web-tapered beams.

The relevant feature that differentiates non-uniform members from their uniform counterparts is the stress distribution that arises in cross-sections of tapered members. In fact, given the taper ratio, non-uniform members in bending present longitudinal stresses that are normal to an arc which develops perpendicularly from one flange to the other and reach their highest values in the flanges and tangential stresses that result from static equilibrium (Fig. 1a). In 1932, Bleich [4] demonstrated that this curve may be approximated by a bilinear line when evaluating the elastic capacity for shear forces (Fig. 1b). It was later shown that these stresses only lead to considerable differences for taper angles α larger than 15° [5,6].

Unlike the stability analysis of uniform members with constant loading, a major difficulty in the analysis of non-uniform members arises in the choice of the design cross-section, which is subject to the highest stresses. These stresses are a combination of the effect of the applied first order forces and second order forces present in slender members. An illustration is shown in Fig. 2, for a uniform member subject to a constant bending moment. The design of the member is governed by the mid-section where the sum of the utilization ratios due to first ($\varepsilon^{I}(x)$) and second order ($\varepsilon^{II}(x)$) forces is maximum. The design rules for prismatic members take this into account in an implicit way.

In members with non-uniform cross-section, the location where the combination of first and second order stresses reaches a maximum is not known and it cannot be found using straight forward procedures, due to: (i) the amplitude and shape of the imperfection to consider; (ii)

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Nomenclature

Lowercase Latin letters

a_γ	auxiliary term to the taper ratio for application of LTB proposed methodology
b	cross section width
f_y	yield stress
h	cross section height
$h_{i,s}$	height of the shallow section
$h_{i,d}$	height of the deep section
t_f	flange thickness
t_w	web thickness
x_c^{I}	first order failure cross section
x_c^{II}	second order failure cross section
y-y	cross section axis parallel to the flanges
z-z	cross section axis perpendicular to the flanges

Uppercase Latin letters

A	cross section area
E	modulus of elasticity
L	member length
$M_{b,Rd}$	design buckling resistance moment
M_{Ed}	design bending moment
$M_{y,Ed}$	design bending moment, y-y axis
R_{eH}	upper yield strength
R_m	tensile strength

Lowercase Greek letters

α	angle of taper
$\alpha_b^{(Method)}$	load multiplier which leads to the resistance for a given method
α_{cr}	load multiplier which leads to the elastic critical resistance
$\alpha_{ult,k}$	minimum load amplifier of the design loads to reach the characteristic resistance of the most critical cross section
ε	utilization ratio at a given cross section
ε_M^{I}	utilization ratio regarding first order bending moment M
ε_M^{II}	utilization ratio regarding the second order bending moment
η	generalized imperfection
$\bar{\lambda}(x)$	non-dimensional slenderness at a given position
$\bar{\lambda}_z$	non-dimensional slenderness for flexural buckling, z-z axis
$\bar{\lambda}_{LT}$	non-dimensional slenderness for lateral-torsional buckling
φ	over-strength factor
χ	reduction factor
ψ	ratio between the maximum and minimum bending moment, for a linear bending moment distribution
ψ_{lim}	auxiliary term for application of LTB proposed methodology

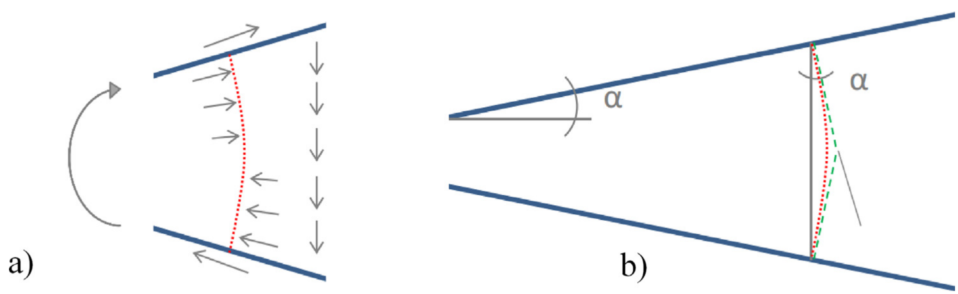

Fig. 1. Direction and equilibrium of forces in a tapered segment. (a) Normal and tangential stresses from bending moment; (b) bilinear approximation [4].

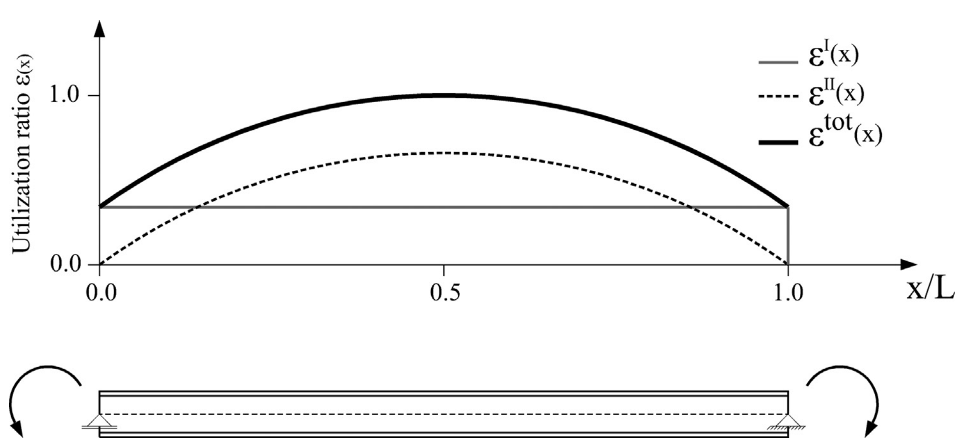

Fig. 2. Utilization ratio: prismatic members.

the variation of the cross-section class along the member length; (iii) the additional forces arising due to the inclination of the flange [8]. For these reasons, the rules for prismatic members do not accurately predict the resistance of non-uniform members. Fig. 3 illustrates these aspects for a web-tapered member, characterised by a taper ratio $\gamma = h_{max}/h_{min}$ or a taper angle α.

According to EN 1993-1-1 [1], the stability analysis of non-uniform members, either global or local, may be verified using the General Method given in clause 6.3.4. However, its applicability is limited and, in some aspects, inconsistent [9]. In structures built using non-uniform members, the imperfection factors are difficult to define and in some cases their definition using standard procedures may lead to either