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Experimental buckling behaviour of web tapered I-section steel columns

Trayana Tankova *, João Pedro Martins, Luís Simões da Silva, Rui Simões, Helder D. Craveiro

ISISE – Department of Civil Engineering, University of Coimbra, Coimbra, Portugal

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ABSTRACT

Tapered steel members offer a better cross-section utilization along the member, which makes them an interesting and more economical alternative to prismatic ones. Yet, the design methodologies available do not provide a clear and sufficient guidance for the stability verification of such members.
Alternatively, nowadays, the existing computer capacity and software programs provide an accessible and rapid means of reproducing the structural performance of members and systems, although they require beforehand validation to assure the plausibility of their predictions. For that, a full-scale experimental programme on non-uniform members was carried out, covering column, beam and beam-column tests. The test results are used to validate a numerical model commonly used for the assessment of stability design rules.
In this paper, firstly, a global overview of the experimental tests is presented, which covers the test layout, member dimensions and the supplementary tests, essentially characterization of material properties, geometrical dimensions and imperfections, and residual stresses. The key results from each experiment are presented and discussed, they are further compared with numerical and analytical estimations of the member resistance. Finally, the experimental results provide physical validation of the design method proposed in Marques et al. (2012) for web-tapered columns.

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1. Introduction

Several practical applications of steel members do not fully exploit the capacity of their cross-section along the length. In fact, in almost all applications, the design internal forces are not constant and assuming constant resistant properties along the length (i.e. constant cross-section) is often not the optimal structural arrangement, especially for large span structures. An efficient solution is, therefore, to vary the member dimensions along its length by adjusting them to the demand for cross-section resistance. The most straight forward application are columns with stepped section, more aesthetical applications are tapered members, either with varying depth and/or flange widths. Moreover, members with irregular distribution of restraints can also be classified as non-uniform. (Fig. 1).

Often, in practice, due to architectural reasons either related to the functional performance of the building or driven by aesthetic criteria, it is not possible to have regular structures which further increases the need for an efficient design of irregular structures. From a fabrication point of view, non-uniform members are seen as competitive since, nowadays, automatic welding processes of steel plates is an economical manufacturing process. However, as in any other structural solution, these advantages depend directly upon the correct use of suitable tools (numerical, analytical and/or code-like formulae) by the designer. In this sense, it is highlighted the lack of design rules, guidance and validated solution for non-uniform members.

Therefore, having the aim of providing practical solutions, and acknowledging the fact that experimental results are crucial for the correct characterization of the real behaviour of tapered steel members, this paper presents the results of four full-scale experiments on web tapered columns and a beam-column carried out by the authors. Additionally, these experimental results are further used for the calibration and validation of the numerical [2] and analytical [5] models for the flexural and lateral-torsional buckling resistance of tapered beam-columns. Finally, regarding the stability behaviour, it is noted that the characterization of imperfections (geometric and residual stresses) is essential. In fact, these imperfections are known to be the main source of discrepancies between theoretical and real values of the load carrying capacity of steel members. Therefore, these imperfections were measured and taken into account during the calibration of the numerical model.

2. Tapered columns: analytical and experimental work by others

Due to the possible economic advantages, the buckling behaviour of non-uniform columns has attracted the interest of researchers since the last century. At first, contributions were focused on analytical solutions for the elastic critical behaviour of such members.

* Corresponding author at: Department of Civil Engineering, University of Coimbra, Polo II, Pinhal de Marrocos, 3030-290 Coimbra, Portugal.
E-mail address: ttankova@uc.pt (T. Tankova).

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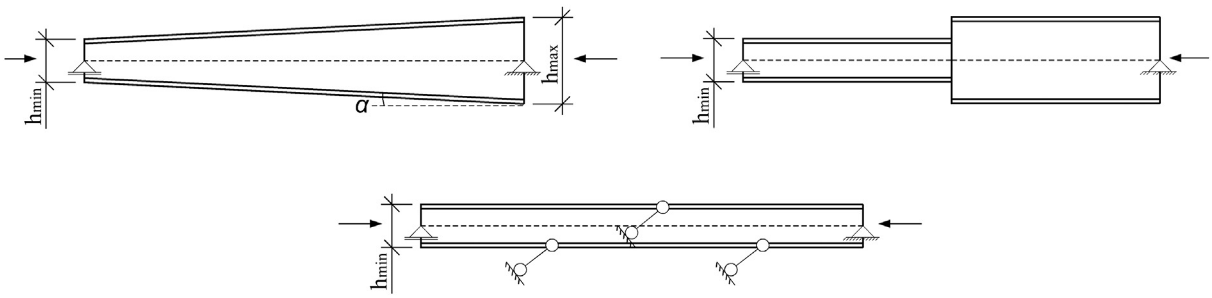

Fig. 1. Non-uniform members.

Timoshenko & Gere [6] proposed numerical solutions of the differential equations for the determination of critical loads for stepped columns and bars with linearly varying cross-section. The proposed solutions are given in the following form:

$$P_{cr} = m\frac{EI_{\max}}{L^2} \tag{1}$$

where the factor m is a tabulated value depending on the ratio between the minimum and the maximum moments of inertia and the ratio between the lengths of the column segments. The solution for members with linearly varying cross-section is given in the same format, whereby the tabulated values of m depend only on the ratio between the minimum and the maximum moments of inertia. A similar approach for was used for the calibration of a solution for tapered columns under stepped loading profile in [7].

Another approach, proposed by *Lee* et al. [4,8], is based on a modification factor g of the tapered member length which transforms it into an equivalent prismatic member with a uniform cross-section equal to the shallow tapered member end, as shown on Fig. 2. The critical load is then calculated based on the shallow cross-section Eq. (2) and the g factor was calibrated as a function of the taper ratio γ, Eq. (3).

$$P_{cr} = \frac{\pi^2 EI_{\min}}{(gL)^2} \tag{2}$$

$$g = 1-0.375\gamma + 0.08\gamma^2(1-0.0775\gamma) \tag{3}$$

where for linearly tapered member γ defines the cross-section height h_i at any distance x from the smaller end as

$$h_i = h_{min}\left(1+\frac{x}{L}\gamma\right) \tag{4}$$

Ermopoulos [10] established the elastic non-linear equilibrium equations of non-uniform members in frames under compression for non-sway and sway modes. These equations were solved using an iterative procedure and the corresponding critical loads and equivalent length factors were presented in forms of tables and graphs similar to the classical effective length graphs by *Wood* [11].

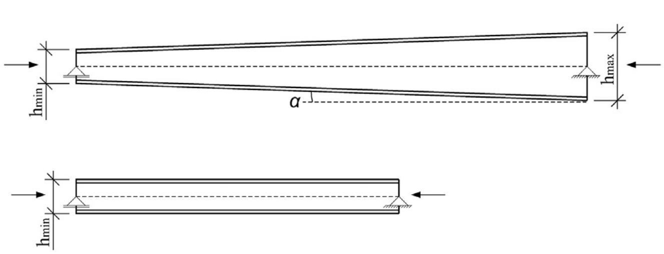

Fig. 2. Equivalent prismatic member.

Hirt & Crisinel [12] proposed an expression for determination of an equivalent moment of inertia of tapered columns, I_{eq}, with I-shaped cross sections, depending on the type of web variation:

$$P_{cr} = \frac{\pi^2 EI_{\mathrm{eq}}}{(L)^2} \tag{5}$$

with

$$I_{eq} = CI_{y,\max} \quad C = 0.08 + 0.92r \quad r = \sqrt{\frac{I_{y,\min}}{I_{y,\max}}} \tag{6}$$

Marques (2012) derived closed-form expressions for the critical load of web-tapered columns:

$$\begin{aligned} &N_{cr,Tap} = A \cdot N_{cr,\min} \rightarrow A = \gamma_I^{0.56}\left(1-0.04\cdot\tan^{-1}(\gamma_I-1)\right) \\ &\gamma_I = I_{y.\max}/I_{y.\min} \end{aligned} \tag{7}$$

Concerning the ultimate resistance of non-uniform columns, some studies were carried out. *Salter* et al. [9] carried out tests on web-tapered steel columns. The specimens were loaded in axial compression and major axis bending moment. In total, eight tests were performed. In three of the tests, lateral restraint was provided to one flange at mid-height. The initial out-of-straightness was measured only for the minor column axis and was comparatively high. The specimens were about half to one third of their full size. The test results were compared with numerical non-linear analyses for which good agreement was reported. Regarding the code estimations for the resistance of such columns, the authors concluded that they were safe sided with possibility for improvement.

Baptista & Muzeau [13] adjusted the Eurocode 3 design rules for flexural buckling of columns to tapered members by an additional coefficient k. This coefficient was calibrated numerically and given in the form of an abacus, is applied to the reduction factor of a column with the smallest cross section.

Raftoyiannis & Ermopoulos [14] proposed an analytical formulation based on the differential equation of imperfect linearly tapered and

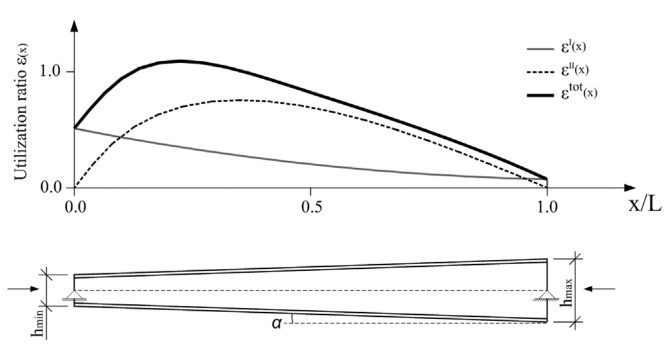

Fig. 3. Utilization ratio: non-uniform members.

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