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GBT-based elastic–plastic post-buckling analysis of stainless steel thin-walled members

Miguel Abambres [a], Dinar Camotim [a,*], Nuno Silvestre [b]

[a] Department of Civil Engineering and Architecture, ICIST, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] Department of Mechanical Engineering, IDMEC/IST, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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ABSTRACT

When compared with carbon steel, stainless steel exhibits a more pronounced non-linearity and no well-defined yield plateau, as well as appealing features such as aesthetics, higher corrosion resistance and lower life cycle cost. Due to its considerably high ductility/strength and cost, stainless steel structural solutions tend to be adopted mostly for slender/light structures, thus rendering the assessment of their structural behaviour rather complex, chiefly because of the high susceptibility to instability phenomena. The first objective of this paper is to present the main concepts and procedures involved in the development of a geometrically and materially non-linear Generalised Beam Theory (GBT) formulation and numerical implementation (code), intended to analyse the behaviour and collapse of thin-walled members made of materials with a highly non-linear stress–strain curve (e.g., stainless steel or aluminium). The second objective is to validate and illustrate the application of the proposed GBT formulation, by comparing its results (equilibrium paths, ultimate loads, deformed configurations, displacement profiles and stress distributions) with those provided by shell finite element analyses of two lean duplex square hollow section (SHS) columns previously investigated, both experimentally and numerically, by Theofanous and Gardner (Eng Struct 2009; 31(12): 3047–3058.). The stainless steel material behaviour is modelled as non-linear isotropic and the GBT analysis includes initial geometrical imperfections, but neglects corner strength enhancements and membrane residual stresses. It is shown that the GBT unique modal nature makes it possible to acquire in-depth knowledge concerning the mechanics of the column behaviour, by providing "structural x-rays" of the (elastic or elastic–plastic) equilibrium configurations: modal participation diagrams showing the quantitative contributions of the global, local, warping shear and transverse extension deformation modes - moreover, this feature makes it possible to exclude, from future similar GBT analyses, those deformation modes found to play a negligible role in the mechanics of the behaviour under scrutiny, thus further reducing the number of degrees of freedom involved in a GBT analysis, i.e., increasing its computational efficiency.

1. Introduction

Stainless steel has been used in the construction industry for over 70 years, even if its wide application has been severely restricted by fairly large productions costs (e.g., much larger than for carbon steel). However, recent developments in material technology [2] are changing this situation quite rapidly, thus (i) making stainless steel nowadays one of the world's most profitably recycled material [3] and (ii) leading to a renewed interest in stainless steel structural members and systems – since the year 2000, there has been an increasing number of significant structural applications of stainless steel [4,5].

Stainless steel types are classified according to their main alloy constituents and the austenitic and duplex (or austenitic–ferritic) alloys are, by far, the most frequently used alloys in building and construction. Nonetheless, in spite of the several attractive features of stainless steel, when compared with carbon steel, such as better appearance, higher corrosion resistance and more cost-effective and longer life cycle, an increased use of stainless steel in common applications, such as office or residential buildings, requires (i) the development of efficient and safe design rules that can fully exploit the stainless steel structural potential and (ii) the dissemination of easy-to-use tools to perform the structural design. Concerning the first aspect, Eurocode 3, part 1.4 (EN 1993-1-4 [6]) was published in 2006 as a full European standard prescribing supplementary rules for the design of stainless steel structures. However, it is well known that some of its rules are mere extensions of similar rules for carbon steel design, included in Eurocode 3, part 1.1 (EN 1993-1-1 [7]). For instance, an aspect

* Corresponding author. Tel.: +351 218 418 403; fax: +351 218 497 650.
E-mail addresses: miguel.abambres@tecnico.ulisboa.pt (M. Abambres), dcamotim@civil.ist.utl.pt (D. Camotim), nsilvestre@ist.utl.pt (N. Silvestre).

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that might severely hamper the design of stainless steel elements is the assumption of an elastic-perfectly plastic constitutive relation, which is particularly punitive for stocky elements [8]. Indeed, there are great differences concerning the material behaviours of carbon and stainless steel alloys, since the latter are characterised by (i) the absence of a well-defined yield plateau, and (ii) a pronounced non-linearity beyond the proportional limit, generally associated with the presence of a significant amount of strain-hardening.

Due to its considerably high ductility, strength and cost, stainless steel structural solutions tend to be adopted mostly for slender/light structures (e.g., formed by thin-walled members), thus achieving a sizeable weight economy that is often combined with a strong visual impact. Nevertheless, the high slenderness of thin-walled structural members makes them prone to instability (geometrically non-linear) phenomena, thus rendering the assessment of their buckling/collapse behaviour a very complex task. Since experimental investigations are invariably limited, due to their very high cost and time consumption (including the careful preparation of the test set-up and specimens), alternative complementary approaches must be sought. The most universally employed approach is to perform sophisticated shell finite element analyses (SFEA), using non-linear constitutive laws and incremental–iterative techniques. However, this approach has some drawbacks, namely (i) the excessively high computational effort, (ii) the time-consuming and error-prone data input, and (iii) laborious output data processing and interpretation, particularly in the context of one-dimensional members (bars), for which the results consist of nodal stresses, instead of cross-section stress resultants (axial force, bending moment, etc.), which are the traditional and more perceptible "language" usually adopted by the technical/scientific community. Despite its relatively narrow field of application (prismatic, straight and non-perforated thin-walled members) and fairly limited dissemination, generalised beam theory (GBT) has been widely recognised as a powerful, versatile, elegant and efficient approach to analyse thin-walled members and structural systems. The elegance and efficiency arise mostly from the modal nature of this approach-the displacement field is expressed as a linear combination of cross-section deformation modes with amplitudes varying along the member length. GBT has attracted the interest of several researchers worldwide, leading to the development of new formulations and applications. In particular, GBT has been extensively developed at the Technical University of Lisbon [9,10], where it has been applied to different (i) types of analysis (first-order, buckling, vibration, post-buckling, dynamic), (ii) boundary and loading conditions (e.g., localized supports and non-uniform internal forces and moments) and (iii) materials (steel, steel-concrete, FRP). With a few exceptions, the material models adopted in these works were always elastic, with no degradation (plasticity) involved. A materially non-linear GBT formulation was first reported by Gonçalves and Camotim [11] in the context of elastic–plastic bifurcation analyses – more recently, the same authors [12,13] proposed GBT beam finite elements based on the J_2-flow plasticity theory and aimed at performing member first-order and second-order elastic–plastic analyses. In parallel, Abambres et al. [14–16] developed alternative elastic – plastic GBT formulations, also based on the J_2-flow plasticity theory, that differ from the previous ones by the fact that (i) the deformation modes are determined by means of the procedure proposed by Silva et al. [17] and (ii) an additional novel degree of freedom (warping rotation) is considered.

The aim of this paper is two-fold: (i) to present the main concepts and procedures involved in the development of a materially and geometrically non-linear GBT formulation and numerical implementation (code) intended to analyse the behaviour and collapse of thin-walled members made of highly non-linear materials, and (ii) to illustrate its application and potential, by analysing the post-buckling behaviour of lean duplex stainless steel square hollow section (SHS) columns that were experimentally and numerically investigated by Theofanous and Gardner [1]. The GBT analyses include initial geometrical imperfections, exhibiting a local and/or global nature, but does not account for membrane residual stresses and corner strength enhancement effects. The stainless steel material behaviour is modelled as non-linear isotropic using the three-stage stress–strain curve proposed by Quach et al. [18], involving only three parameters (Young modulus E, 0.2% proof stress $\sigma_{0.2}$ and strain-hardening power n). The GBT results obtained (equilibrium paths, ultimate loads, deformed configurations, displacement profiles and stress distributions) are compared with the values provided by SFEA performed in the code ABAQUS [19]. Moreover, in order to assess how membrane residual stresses and corner strength enhancements affect the column structural response, the GBT results are compared with the experimental ones reported in [1].

2. Brief overview of the GBT kinematics

Consider the local coordinate system (x, s, z) at each wall mid-surface of a thin-walled bar (Fig. 1(a)), where x, s and z are, respectively, the longitudinal coordinate ($0 \le x \le L$, L is the member length), the transverse coordinate ($0 \le s \le b$, b is the wall width), and the through-thickness coordinate ($-t/2 \le z \le t/2$, t is the wall thickness). The corresponding displacements are u

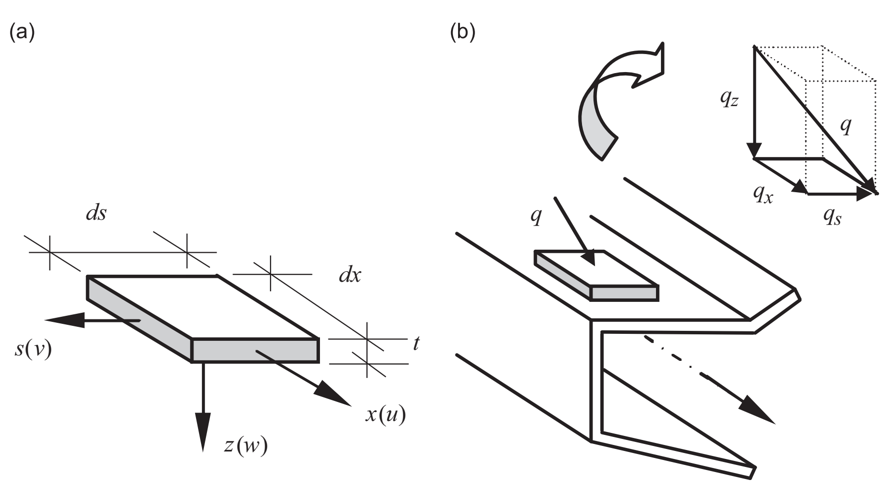

Fig. 1. (a) Local coordinate system at each wall mid-surface and (b) general applied/external distributed load $q(x,s)$.