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Buckling and optimal design of cold-formed thin-walled beams: Review of selected problems

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ABSTRACT

The paper is devoted to cold-formed thin-walled channel beams with open or closed flanges. The global–local buckling and optimization of these beams are described. The review includes simple analytical description and calculations, numerical analysis, and the laboratory tests of selected beams. The buckling problems for flanges and webs of thin-walled beams are described in detail. Additionally, an objective comparison of the beams of different cross sections is presented. A quality measure of thin-walled beams is proposed. Comparison of selected thin-walled beams with use of the quality measure is presented in figures.

1. Introduction

Strength and buckling problems of thin-walled beams are observed since mid-20th century and described in many monographs, for example by Vlasov [1], Bleich [2], Timoshenko and Gere [3], Brzoska [4], Murray [5], Bažant and Cedolin [6], Weiss and Giżejowski [7], and Trahair [8], and Cheung [9] described the finite strip method in structural analysis. These problems are also studied today.

Besides monographs there are many other papers devoted to cold-formed thin-walled beams.

Towards the end of the 20th century, developments in technology and application were outlined by Davies [10]. Rondal [11] reviewed progresses in the field of cold-formed steel members. Particular emphasized progresses in the field of distortional buckling and in recent development of new types of joints. Hancock [12] summarized the major research developments in cold-formed steel structures and provided a brief summary of the Direct Strength Method (DSM). Schafer [13] provided a review of the development and progress in the Direct Strength Method (DSM) for cold-formed steel member design, and compared it with the Effective Width Method.

Analytical, numerical, and experimental studies of global, distortional, and local buckling of cold-formed thin-walled beams have taken wide place in literature. Ma and Hughes [14] developed an energy method for analysing the lateral buckling behaviour of I-beams. The accuracy of the method was verified by results obtained from FEM (finite element method). A general bifurcation analysis of locally buckled members was presented by Rasmussen [15] based on an assumption of small displacements theory. The governing equations were applied to doubly symmetric cross sections in compression and combined compression and bending, and in Young and Rasmussen [16] to singly symmetric cross sections in compression. Rogers and Schuster [17] investigated available analytical short half-wavelength distortional buckling methods, and a suitable design method which could be used to predict the bending moment resistance of cold-formed steel C-sections that are subject to flange/web distortional buckling. In addition, the available test data found in the literature were collected. The experimental results of the beam–column research were summarized by Hancock and Rasmussen [18]. Kounadis [19] presented the post-buckling analysis of simply supported bars with asymmetric thin-walled open cross sections under axial and eccentrically applied thrust. A design method that integrates distortional buckling into the unified effective width approach was presented by Schafer and Pekőz [20], and verified by FSM. Put et al. [21] described buckling tests on simply supported unbraced cold-formed lipped channel-section beams. Schafer [22] presented local, distortional, and Euler buckling. Narayanan and Mahendran [23] studied distortional buckling behaviour. Buckling properties of the column were determined using the FSM. The finite element analyses included relevant geometric imperfections and residual stresses. Teng et al. [24] studied distortional buckling, numerical results were compared with those form the FSM.

Trahair and Hancock [25] provided a simple advanced method of designing steel members against out-of-plane failure. The strength, stability, and local stability problems were considered by Magnucki et al. [26]. Stasiewicz et al. [27] described local buckling of a bent flange of a thin-walled beam. Young [28]

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conducted bifurcation analysis with the use of an elastic non-linear FSM. Silvestre et al. [29] studied distortional buckling of C- and Z-sections, GBT (generalized beam theory) to derive the distortional buckling formulae, its validation and application. Chu et al. [31][32] presented an analytical model for predicting the lateral–torsional, local and distortional buckling. Ádány and Schafer [33] studied a buckling mode decomposition, proposed an approach which enables general numerical methods (FEM and FSM) to directly calculate critical loads for pure buckling modes, and in [34] gave implementation details, and practical examples. Three different versions of the FSM were developed by Ovesy and Loughlan [35] for predicting the geometrically non-linear response of box sections with simply supported ends when subjected to uniform end shortening in their plane. Pala [36] proposed a neural network (NN) based formula for distortional buckling stress of C-sections. Rasmussen [37] derived the differential equations for bifurcation of locally buckled point symmetric columns. Ren et al. [38] presented accurate finite element models to predict the behaviour and ultimate strengths of cold-formed steel channels subjected to pure bending as well as combined bending and web crippling.

Kwon et al. [39] considered buckling interaction. Paczos et al. [40] studied local buckling of channel beams with edge bent. Cheng and Schafer [41] presented local and distortional buckling of C- and Z-section beams, a non-linear finite element model, and experimental results. Loughlan and Ahmed [42] studied multi-cell carbon fibre composite box beams subjected to torsion and conducted FE analysis. Mohri et al. [43] presented lateral buckling of thin-walled beam–column elements under combined axial and bending loads, buckling analysis solutions and FEM validation. Paczos et al. [44] analysed buckling of channel beams with sandwich flanges and drop flanges. Plastic mechanisms database for thin-walled cold-formed steel members in compression and bending were studied by Ungureanu et al. [45]. Wang and Ikarashi [46] studied coupled buckling strength of H-shaped steel beams under bending-shear. Moen and Schafer [47] studied the relation between elastic buckling and tested response of cold-formed steel columns with holes. Ádány [48] presented torsional buckling of thin-walled columns, analytical solution for the critical force based on shell model. Batista [49] presented local–global buckling interaction, the main idea was to allow integrating effective width and direct methods in the design procedure. Becque and Rasmusen [50,51] experimentally and numerically investigated the interaction of local and overall buckling in lipped channels under axial compression. Bambach [52] studied buckling modes and interactions in channels with edge-stiffened flanges under pure compression. Dinis et al. [53] conducted local, distortional, global interaction analysis in lipped channel columns. Li and Chen [54] proposed an analytical model for predicting the critical stress of distortional buckling validated by FSM. Magnucka-Blandzi and Magnucki [55] presented lateral and local buckling of open elliptic cross sections, and Paczos and Wasilewicz [56] buckling of lipped I-sections, and Paczos and Magnucki [57] buckling study of C-beams with open/close drop flange, and with or without polyurethane filler. Pastor and Roure [58,59] presented the post-collapse behaviour of open U- and sigma-sections subjected to pure bending. Magnucki [60] analysed global and local elastic buckling of cold-formed thin-walled channel beams with open or closed flanges, and Magnucki et al. [61] elastic buckling of channel beams with open or closed drop flanges.

Nowadays, three different numerical methods are usually applied to perform linear buckling analyses of cold-formed members: the finite strip method (FSM), the finite element methods (FEM), and the generalized beam theory (GBT—developed by Schardt [62]). Local, distortional, and flexural–torsional buckling problems of I-beams were presented by Hancock [63] with the use of FSM (finite strip method). Hancock [64] compared different methods for computing the elastic distortional buckling stress with accurate solutions based on the FSM, and presented a design method for computing the distortional buckling strength of the compression flange of C- and Z-sections. Numerical calculations were carried out by Kesti and Davies [65] in order to compare methods for determining the minimum elastic distortional buckling stress in compression. Ádány and Beregszászi [66] studied local and distortional buckling, and presented the differences in critical loads calculated by conventional finite strip method (FSM) and the constrained finite strip method (cFSM). Elastic distortional buckling of doubly symmetric I-shaped flexural members with slender webs was numerically analysed (FSM) by Zirakian [67], and lateral–distortional buckling of I-beams, and the extrapolation techniques in [68]. Pham and Hancock [69] described shear buckling analysis, buckling stresses of channel sections with and without lips (FSM), and Yap and Hancock [70] interaction of local and distortional buckling modes in lipped channel section columns with the use of DSM and FSM. Numerical methods FEM, FSM were applied by Macdonald et al. [71] to study local and distortional buckling. Dubina and Ungureanu [72] analysed the influence of imperfections on the behaviour of cold-formed steel members. Effects of anchoring tensile stresses in axially loaded plates and sections were the subject of Bambach and Rasmussen [73]. The paper of Samanta and Kumar [74] deals with distortional buckling of simply supported mono-symmetric I-beams under three types of load: a central point load, a uniformly distributed load and a uniform sagging moment. Rzeszut and Garstecki [75] presented FEM analysis of two sigma members connected in discrete points distributed along webs. Camotim and Dinis [76] studied post-buckling behaviour of lipped channel columns affected by coupled instabilities with distortional buckling (FEM). Casafont et al. [77] conducted FEM analysis procedure for calculation of pure distortional buckling loads of members subjected to compression, Li [78] presented distortional buckling of cold-formed purlins. Loughlan and Yidris [79] conducted FEM simulation is employed to examine the post buckling behaviour of the I-section compression members, form of elastic local buckling through the non-linear elastic and elasto-plastic post-buckling to final collapse and unloading. Moen and Schafer [80] studied elastic buckling of cold-formed steel columns and beams with holes. Silvestre et al. [81] estimated the ultimate load of CFRP-strengthened cold-formed steel lipped channel columns. Aydin [82] studied elastic flexural and lateral–torsional buckling of frames. Gonçalves et al. [83] presented semi-analytical solutions for the plastic bifurcation. Vieira et al. [84] simplified models that predict the longitudinal stresses that develop in C-section purlins in uplift.

Buckling problems were also studies with the use of Generalized Beam Theory (GBT). Camotim and Silvestre [85] presented the history of distortional buckling. Bebiano et al. [86] presented GBTUL 1.0 β, a code to perform buckling and vibration analyses of open-section thin-walled members. Ádány et al. [87] described elastic buckling behaviour of unbranched thin-walled members, provided a comparison between Generalized Beam Theory (GBT) and the constrained Finite Strip Method (cFSM). Dinis and Camotim [88], Camotim et al. [89] numerically investigated local-plate/distortional mode interaction, post-buckling behaviour, strength in cold formed steel lipped channel beams. Gonçalves [90] derived, validated and illustrated the application of GBT formulation to perform linear (first-order) and buckling analyses of thin-walled members with arbitrary cross-section shapes. In the context of GBT and FEM Camotim et al. [91] analysed the local and global buckling behaviour of thin-walled members with arbitrary loading and support conditions (lipped channel beams and I-sections), and Basaglia