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The experimental and analytical investigations of torsion phenomenon of thin-walled cold formed channel beams subjected to four-point bending

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ABSTRACT

Thin-walled beams have many practical applications. This stimulates practical and scientific researches on them. The recent developments in metal cold forming makes it possible to produce more complicated shapes to reduce the mass of structural members. However, vast variety of cross-section of such beams make their analysis difficult. In the paper the authors have investigated thin-walled cold formed steel beams with open section loaded subjected to pure bending. Experimental results were compared with analytical ones. This gave the answer why the actual tested beams rotated around the shear centre though they were subjected to pure bending. The authors described the factors which are responsible for the torsion moment in the investigated thin-walled steel beams with open sections subjected to pure bending. Two different cross-sections of thin-walled beams were investigated and the more resistant to torsion phenomena was indicated.

1. Introduction

Thin-walled and cold formed steel beams with open sections are common constructional elements which are used in a wide range of applications such as: civil engineering (e.g. hall roofs, buildings), automotive (e.g. car bodies), railway, aircraft and vessel industries. Cold formed elements may have complicated shapes of cross sections. The developments in this field refer to cold forming processes, machines, materials and production technologies.

Now using a cold forming process it is possible to make very complicated constructional elements that meet specific and individual requirements. The weight of thin-walled beams can be optimized by controlling the shape of cross section, the thickness of sheet metal and material properties.

Cold forming technology has many advantages: less energy is needed during forming processes, it is cheaper than traditional technologies, it can be used for metal sheets covered by anti-corrosion coatings. However, there are also some disadvantages. Such constructional elements are prone to buckling because the thickness of their walls is very small. Even small changes of working conditions (e.g. loads) may lead to loss of stability, especially if there are imperfections.

In this paper the authors investigated some thin-walled cold formed beams with open cross-sections subjected to pure bending. A strength test machine was used for experimental investigations. During tests the authors observed the beams behaviour and founded that beams rotated also around the longitudinal axis which crosses the temporary shear centre of the beam.

Ungureanu and Dubina [28] analysed the influence of imperfections on the behaviour of perforated pallet rack members in compression using non-linear FE simulations. The effect of imperfections, perforations and buckling modes reduces significantly the capacity of perforated members in compression, especially in the coupling range due to interaction. Rasmussen and Hancock [24] proposed numerical models to generate automatically the geometrical imperfection modes into the non-linear analysis. SudhirSastry et al. [26] performed the lateral buckling analysis of cold-formed thin-walled beams subjected to pure bending. The critical buckling loads were estimated on the basis of optimization criteria. The estimated critical buckling stresses were compared with the published results, these ones show the excellent agreement. Bienias et al. [3] presented the postbuckling behaviour and load carrying capacity of thin-walled composite channel sections

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Nomenclature

t	wall thickness of beam
b	width of flanges
c	height of boxes
d	distance between boxes
t	thickness of steel sheet
H	total height of beam
L	distance between concentrated forces. i. e. the length of the segment of beam subject to a constant bending moment
L_t	total length of beam
L_0	distance between support and force
C	torsional stiffness of cross-section
$\tilde{z}_s$	z-coordinate of the shear centre of cross-section
E	Young's modulus
ν	Poisson's ratio
R_{eH}	elastic limit (yield strength)
R_m	ultimate strength
$B2$	corrugated flange beams without height of boxes
$B3$	double box flange beams with height of boxes

subjected to uniform compression. The postbuckling behaviour and load carrying capacity of thin-walled channel section columns subjected to compression were determined using finite element method and ANSYS software. Chen et al. [7] presented the results of investigations of web crippling behaviour of cold-formed steel lipped channel beams subjected to end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF), and interior-two-flange (ITF) loading conditions. They tested 48 cold-formed steel lipped channel beams considering different boundary and loading conditions, bearing lengths and section heights. Experimental investigations, distribution of stresses and displacements of cold-formed thin-walled beams were presented by Paczos and Magnucki [15] and Belingardi and Scattina [1]. The other works on this subject were presented by Biegus et al. [2], Paczos and Wasilewicz [22], Mahendran and Jeyaragan [19].

Comparison of theoretical results with experimental ones helps to improve mathematical models of beams. Such approach was taken by e.g. Magnucki [13], who prepared a review of works on steel cold-formed structures. Similar problems were analysed all over the world and some results in this field were presented by Magnucka-Blandzi et al. [14] and Paczos et al. [15,17,20,21]. They showed their own experimental and numerical investigations of thin-walled channel beams with non-standard cross-sections.

Urbaniak and Kubiak [8,29] worked on the local dynamic buckling of simply supported C-shaped thin-walled girder segments subjected to bending. They considered various types of pulse loading like triangular, trapezoidal and rectangular loads with duration corresponding to the fundamental period of vibration [4]. Buckling of composite channel beams subjected to pure bending and buckling of channel columns subjected to uniform compression were described by Paszkiewicz and Kubiak [23]. The data necessary to determine buckling load were collected using optical strain gauge system Aramis 3D and a universal testing machine. The authors noticed that after the test it was possible to choose the point for finding relationship between load and deflection basing on deformed specimen. In this way they received better results because data was be collected for the point with the highest displacement normal to the beam or column wall (deflection). Dinis and Camotim [5] had estimated the local/distortional mode interaction concerning the post-buckling behaviour of cold-formed steel lipped channel beams subjected to uniform major axis bending using the shell finite element analysis in ABAQUS. Loughlan et al. [11] analysed the behaviour of compressed lipped channel profiles considering local-distortional interactions. Their models included material yielding and yield propagation to ultimate conditions and then to elastic-plastic unloading. The effects of geometric imperfections were also considered in the numerical simulations. Luo et al. presented [12] two computing models to analyse the distortional critical stress of cold-formed thin-walled inclined lipped channel beams subjected to bending about the minor axis, with the use of Generalised Beam Theory (GBT). The buckling and post buckling behaviour problems of thin-walled structures made of isotropic and orthotropic materials were investigated theoretically [27]. There are also some papers showing the results of analytical and experimental investigations of 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 strength tests of selected beams. The buckling problems of flanges and webs of thin-walled beams are described in detail. Moreover, an objective comparison of the beams of different cross sections was presented in [13]. Variational and parametric design of open cross-sections of thin-walled beams considering stability constraints was described by Magnucki and Magnucka-Blandzi [9]. The problem was described using variational calculus and solved by Runge–Kutta method.

Magnucki [10] studied analytical and numerical optimization of an open cross-section of a thin-walled beam with flat web and circular flange. His optimization model consisted of strength and stability constraints, moreover the cross-section area was assumed to be constant. The maximum bending moment was maximized and geometrical parameters of the cross-section were optimization variables. Critical stresses in open cylindrical shells with free edges were calculated by Magnucki, Lewiński and Maćkiewicz [16]. The authors searched for the optimal shape of the cross section of beam. The cross section of beam was characterized by dimensionless parameters, which were design variables. The dimensionless objective function was defined as a function of the area of cross section and maximum allowable bending moment. The constraints were based on the local buckling condition for corrugated flange and geometric restraints. The beams with different length-to-height ratio were analysed.

Optimum design of mono and anti-symmetrical cold-formed thin-walled I-beams with double flanges was discussed in [18]. The considered beams were simply supported and subjected to uniformly distributed vertical load. The shapes of I-sections were described by dimensionless parameters. The used objective function was also dimensionless.

Landesmann and Camotim [25] presented finite element analyses of the distortional post-buckling behaviour, ultimate strength and DSM design of cold-formed steel single-span lipped channel beams subjected to elevated temperatures. The cold-formed lipped channel beams were analysed using ANSYS. The used shell finite element model included nonlinear geometric relationships, nonlinear model of material and initial geometrical imperfections based on distorsional buckling mode.

Hancock [30] prepared the review of research on cold-formed steel structures published in 2013 and 2014 in three leading journals: the Journal of Structural Engineering, ASCE, Thin-Walled Structures and the Journal of Constructional Steel Research. He also discussed papers presented at the three main conferences in