Thin-Walled Structures 75 (2014) 87–102

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Experimental determination of critical loads in thin-walled bars with Z-section subjected to warping torsion

Zbigniew Kowal, Andrzej Szychowski *

Faculty of Civil Engineering and Architecture, Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

ARTICLE INFO

Article history:
Received 5 July 2013
Received in revised form
22 October 2013
Accepted 22 October 2013
Available online 28 November 2013

Keywords:
Thin-walled Z-section
Warping torsion
Local buckling
Critical load
Local critical bimoment
Experimental methods

ABSTRACT

Critical loads were determined experimentally from the condition of the local buckling of thin-walled bars with Z-section subjected to warping torsion. The experimental investigations were carried out using simply supported models, loaded with a concentrated torsional moment at the mid-span. A method of determining the so-called "local ordered deflection interval" was developed. In this interval, the modeled deflection of the component plates (walls) of a thin-walled bar with random wall geometrical imperfections is compliant with the local buckling mode. The "local ordered deflection interval" makes it possible to adjust the known experimental methods so that they could be used to determine critical torsional loads and local critical bimoments. Experimental investigations showed the occurrence of two local critical bimoments in bars with Z-section. The bimoments are different in their absolute values, depending on the sense (sign) of the torsional load. Experimentally determined critical loads were compared with theoretical results.

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1. Introduction

In cold formed thin-walled members with open cross-section, cases are found, in which the form of stability loss is determined by the local buckling of the section components walls. After the critical load is reached, the component plates (walls of the section) undergo local deflections that are transverse to the stress direction. The inevitable random geometric (general and local) imperfections affect the load-carrying capacity and stiffness, and also the stress distribution in the open cross-sections of thin-walled bars.

Experimental investigations into the local buckling of thin-walled bars with open cross-sections described in the literature concern mainly members that are axially and eccentrically compressed, or bent and sheared. Warping torsion is generally disregarded. Only a few studies, e.g. [1–4], describe the experimental investigations and provide theoretical analyses of open thin-walled bars subjected to transverse bending, in which the plane of bending does not pass through the shear center of the section. Such a load causes additional torsion of bars. In those investigations, the impact of warping normal stresses on the local buckling of thin-walled members was observed.

In study [5], the occurrence of the local stability loss in open thin-walled bars subjected to warping torsion, without the participation of other components of the section load was proved experimentally and confirmed theoretically. In [5], the local critical bimoment inducing the local buckling of a thin-walled bar was defined. The theoretical method of determining local critical bimoments in a thin-walled bar, subjected to warping torsion, with an arbitrary open cross-section built from flat walls (thin plates) was described in [6].

The Southwell method is most often used for experimentally determining critical loads in bars, e.g. [7], plates, e.g. [8,9], or thin-walled bars composed of flat walls (thin plates), e.g. [10]. In the classical approach, the method was used to experimentally determine the buckling load in compressed bars with geometrical imperfections, the form of which was close to the buckling mode.

When the Southwell method is used in experimental investigations into the local buckling of isolated plates or thin-walled bars made from plates, the accuracy of results may depend on the form of initial geometrical imperfections of the plate (or walls of the section). If the form of the plate imperfections is similar to the buckling mode in accordance with the least critical load (the first eigenvalue), the deflections that have shapes corresponding to the plate buckling mode become dominant from the beginning of the loading process. Then, the Southwell graph, determined for even small loads, makes it possible to estimate the critical load in a satisfactory manner [9].

Shortcomings of the Southwell method, applied to the experimental investigations into plates or thin-walled bars built from plates, result from the fact that the form of random geometrical imperfections in plates or walls of the thin-walled section that actually occur can differ considerably from the "ordered" shape of buckling of such elements. Kowal and Szychowski [11] conducted

* Corresponding author. Tel.: +48 41 342 4575; fax: +48 41 344 3784.
E-mail address: aszychow@tu.kielce.pl (A. Szychowski).

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http://dx.doi.org/10.1016/j.tws.2013.10.020

Nomenclature

b_s, t_s width, thickness of the plate (walls s)
B bimoment
B_{cr}, $B_{cr,L}$, $B_{cr,R}$ local critical bimoment, ("left" – positive; "right" – negative)
B_{cr}^e, B_{cr}^T experimental value, theoretical value of the local critical bimoment
$B_{cr}^{1,2,3,4}$ successive eigenvalues of the local critical bimoment
B_y first yield bimoment
E, $\overline{E}$ Young's modulus, mean value determined experimentally
G shear modulus of elasticity
i, j index, natural number
I_ω warping section constant
I_t St-Venant torsion constant
k_ω, $k_{\omega,L}$, $k_{\omega,R}$ coefficients of critical warping stresses
L length of a thin-walled bar
l_s length of a bar segment, length of a plate (wall s)
M_t, $M_{t,L}$, $M_{t,R}$ load of a concentrated torsional moment ("left", "right")
$M_{t,cr}$, $M_{t,cr}^e$, $M_{t,cr}^T$ critical torsional moment (external) from the condition of the local buckling, experimental value, theoretical value
u_i local deflection of a plate
u_0 pointer of the initial deflection of a plate
x_s,y_s,z_s Cartesian coordinates of a plate (wall s)
ϕ angle of twist rotation
ν, $\overline{\nu}$ Poisson's ratio, mean value determined experimentally
$\sigma_{\omega,cr}$ critical warping stress in accordance with [6]
$\sigma_{E,s}$ Euler's stress for a plate (wall s)
x_i, $\overline{x}$, $s_{x,n-1}$ ith measurement, mean value of measurement, standard deviation.
ω, ω_c sectorial coordinate, a sectorial coordinate corresponding to the critical stress $\sigma_{\omega,cr}$
$\kappa = \sqrt{GI_t/EI_\omega}$ flexural – torsional coefficient of a cross-section
R_{eH}, R_{eL} yield stress of the steel (basic material): upper, lower
R_m ultimate tensile strength

numerical investigations and showed the causes of discrepancies between the experimental results for plate critical loads obtained with the classical Southwell method and the theoretical results.

Tereszkowski [12] proposed a method, different from the classical Southwell approach, for determining the critical load in uniformly compressed plates within the elastic range. The point of departure for the Tereszkowski method is von Karman nonlinear plate theory [13]. In order to determine the critical load with this method, it is necessary to take into consideration the coordinates $(u_i - N_i)$ (deflection-load) of the three "measurement points" of the plate static equilibrium path determined in the experiment. An advantage of the Tereszkowski method is the possibility of using deflections from the pre-buckling and post-buckling load range. The author [12] obtained the solution to the problem for two variants of the shape of geometrical imperfections. In the first variant, the form of initial imperfections corresponds to the buckling mode, and can be described by the same function. Formulas derived for this case make it possible to experimentally determine the critical load. The other variant of the method assumes that the form of initial imperfections is specified by a function different from the one describing the plate buckling mode. In this instance, the procedure proposed in [12] makes it possible to estimate the lower and the upper limits, within which the experimental critical load of the plate is contained.

In the experimental investigations into thin-walled bars, composed of thin plates [5], subjected to warping torsion, it was found that the form of geometrical imperfections significantly affects plate deflections in the load pre-buckling range. In many cases, the form of imperfections differed much from the "ordered" (theoretical) shape of the local buckling in the examined thin-walled bars. For very close successive eigenvalues of critical loads, that can result in the least buckling load being undetected with classical methods because every experimental model renders an individual set of random geometrical imperfections. The analysis of such experimental situations demonstrate the significance of the phenomenon of the so-called "ordering of deflections" [5,11].

The present study gives the results of experimentally determined critical loads from the condition of the local buckling of thin-walled bars with Z-section, subjected to warping torsion. These bars showed wall random geometrical imperfections. Only loads which generate normal stresses from warping torsion were considered. Assuming such a mode of loading allowed the experimental determination of the critical torsional load and the local critical bimoment.

2. The experimental investigations

2.1. The test stand and test models

A simply supported thin-walled bar with Z-section was used for the experimental investigations. The model was loaded with a concentrated torsional moment at the mid-span, with opposite senses in succession, in accordance with the diagram shown in Fig. 1a. Z-section is characterized by different behavior in the local critical state, depending on the sense of the torsional load [5,6].

In order to facilitate a comparison of experimental results with the theoretical ones presented in [6], a simplified bimoment notation was used (Fig. 1a). The bimoment, which generated warping compressive (positive) stresses in the Z-section on the free edges of the plates b1 and b3 (flanges), is denoted as B_L – "left" (with the sign "+"). The bimoment inducing the compression of the plate b2 (web) in the Z-section is denoted as B_R – "right" (with the sign "–"). The bimoment B_L (or B_R) is produced by loading the thin-walled bar with the concentrated torsional moment $M_{t,L}$ (with the sign "+"), or $M_{t,R}$ (with the sign "–").

Cold-formed galvanized sheet (Z-275-I-1 × 1000 × 2000) of nominal thickness $t_n = 1$ mm, was used to construct the models (*mZ*1–*mZ*6). The average steel core thickness, after deduction for the zinc coating, was $\overline{t}_{cor} = 0.97$ mm. Computational dimensions of the model composed of component plates: b1, b2 and b3 (Fig. 1b) were assumed for the midline of the cross-section. Warping (Fig. 1d) and torsional characteristics, determined on this basis, are listed in Table 1.

The test stand (Fig. 1c) made it possible to load each model with concentrated torsion moment M_t with alternately opposite sense, following the diagram shown in Fig. 1a. Six models with Z-section were examined altogether in more than 18 experiments in accordance with the following program:

1. Loading with the "left" torsional moment ($M_{t,L}$) – experiment 1*L*. Measurements were taken for the loads exceeding approx.

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