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The effect of the warping deformation on the structural behaviour of thin-walled open section shear walls

Alberto Carpinteri [a], Giuseppe Lacidogna [a,*], Bartolomeo Montrucchio [b], Sandro Cammarano [a]

[a] Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] Department of Control and Computer Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

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ABSTRACT

Thin-walled open section beams are carefully analysed by Vlasov's theory of the sectorial areas. It allows to take into account their peculiar warping deformation which appears in the presence of torsional actions. This behaviour determines a further stress state along the axis of the element which is rarely considered in structural analyses. The aim of the present paper is the evaluation of the warping deformation of thin-walled open section beams subjected to torsion. Firstly, the analytical theory proposed by Vlasov is verified through an experimental test on a steel specimen defined by a U profile. Specific analyses are performed with the aim of a sophisticated optical device in order to assess the transverse distortion of the section. Then, the results obtained experimentally and confirmed by a Finite Element (FE) programme permit to validate a computer programme based on the analytical theory and devised to study the structural behaviour of high-rise buildings stiffened by thin-walled open section shear walls. In order to evaluate the effectiveness of the programme, an example which highlights the benefits provided by the present method compared to FE programme is carried out.

1. Introduction

In the design of high-rise building the identification of an adequate resistant system able to absorb the horizontal actions coming from earthquakes and wind is a crucial point of the design process. The structural schemes usually employed to stiffen horizontally a building are several and the choice of one of them is certainly function of the characteristics of the structure, in particular the total height. The evolution of the construction techniques as well as the limits imposed by legislation in terms of displacements have determined a clear distinction between all the possible structural solutions. Nevertheless, the choice of a specific solution can also depend on the functional needs required by the building occupants. In particular, the presence of systems which allow a rapid usability of the floor spaces may address the engineer's judgment. In this direction, indeed, thin-walled open sections bracings prove to be doubly convenient: from the usability point of view, they are able to house the elevator shaft and the stairwell, whereas, from the structural point of view, they contribute to the horizontal stiffness of the resistant skeleton and, therefore, to the stability of the construction.

It is well-known that such elements, if subjected to torsional actions, show a peculiar deformation, known as warping deformation, which is described by the distortion of the section out of its own plane. This phenomenon is caused by a particular internal action, called bimoment, which determines a further stress state having an intensity comparable to that coming from flexural actions.

Therefore, it is clear that an accurate design of these elements cannot disregard their unusual torsional deformation, especially in those situations in which their resistant contribution proves to be determinant for the lateral stability of the construction.

The early analytical formulations focused on the structural behaviour of thin-walled open section profiles were proposed, almost at the same time, by Vlasov [1–3] and Timoshenko [4]. In particular, the former examined in depth these elements, giving rise to a comprehensive theory of which the well-known Saint Venant theory proved to be a very special case. Many works related to this topic followed trying to extend this original formulation, which, however, remains a milestone in the study of structural mechanics.

To authors' best knowledge, papers regarding experimental tests for the assessment of the warping deformation of thin-walled open section beams subjected to torsional actions are almost absent in literature.

* Corresponding author. Tel.: +39 110904871; fax: +39 110904999.
E-mail addresses: alberto.carpinteri@polito.it (A. Carpinteri), giuseppe.lacidogna@polito.it (G. Lacidogna), bartolomeo.montrucchio@polito.it (B. Montrucchio), sandro.cammarano@polito.it (S. Cammarano).

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Some of them, based on Vlasov's theory, are related to the experimental evaluation of the free vibrations of these elements, which, due to their characteristic geometry, in the dynamic field show a coupled behaviour between the main flexural modes and between torsional and flexural modes. As example of this, among all the papers by Ambrosini [5,6] and Klausbruckner and Pryputniewicz [7] can be mentioned.

In the static field, experimental attempts for the identification of the warping deformations are very rare and, in some cases, not exactly focused on this goal. From this point of view, only two works can be underlined. The first one is represented by the paper by Rendek and Baláž [8]. In this case, the authors focused their attention on the evaluation of the effectiveness of an analytical formulation, called the generalized beam theory (GBT). To this aim, a strain-measuring test on a steel cantilever beam of complex non-symmetrical open section, subjected to various load conditions, was performed. The results obtained by the GBT method and by the experimental test were compared in terms of longitudinal stresses acquired by means of the presence of strain gauges located along the beam. Even if the test allowed to understand the influence of the out-of-plane distortion of the section on the overall capacity of the cantilever, no information regarding the warping deformation itself were specifically given by the authors. In the same way, also the paper by Dufort et al. [9] dealt with the cross-section warping of beams, but focusing the attention on a particular type of distortion which occurs in composite elements. In this case the displacement field was examined by means of an optical technique in conjunction with the use of microcomputer and methods of image analysis. Once the experimental test is performed, the warping of the section could be indirectly obtained through the difference between the measured longitudinal displacement and a linear displacement joining the longitudinal displacement related to the top and the bottom part of the section of the specimen.

Therefore, from the foregoing it is evident that a direct evaluation of the warping deformation of thin-walled open section profiles is still missing in literature. To this aim in the present paper a specific experimental analysis is performed. By means of a sophisticated optical device, the out-of-plane distortion of the section of an horizontal steel cantilever, loaded with transverse concentrated actions, is measured. The results obtained from the experimental test and from a Finite Element (FE) modelling allow to validate a computer programme based on the analytical theory of the sectorial areas and devised for the evaluation of the structural behaviour of high-rise buildings stiffened by any kind of horizontal bracings. This computer code implements the matrix formulation proposed by Carpinteri et al. [10–12] which identifies the transverse displacements of tall horizontally loaded buildings and clearly evaluates the external load distribution between the bracings constituting the resistant skeleton of the structure. The effectiveness of the method is finally highlighted through the execution of a numerical example in which the benefits provided by the analytical formulation compared to FE programme are evident.

2. Experimental investigation on warping deformation

The analytical formulation proposed by Vlasov, known as the theory of the sectorial areas, is quite used when thin-walled open section beams are taken into account. Nevertheless, even though in the literature many papers, focused on the structural behaviour of these elements, have been published, to authors' best knowledge, none proposed an specific experimental technique to evaluate first-hand their particular out-of-plane distortion, when subjected to torsional actions. In order to verify the theory of the sectorial areas, in the present section an experiment regarding a thin-walled open section profile subjected to flexural and torsional loads is performed. For this purpose, a steel beam showing a U profile has been realized. With the aim of an optical device, suitable for precision measurements, the warping deformation of the section, as a consequence of the application to different levels of torsional concentrated actions, can be defined. The evaluation of the effectiveness of the analytical formulation, therefore, consists in the comparison of the results obtained experimentally with those coming from two different methods: the first implements Vlasov's theory, whereas the second relies on the FE modelling.

First, a brief summary of the main passages of the analytical formulation which, based on the theory of the sectorial areas, allows to define the stiffness matrix of thin-walled open section beams subjected to transverse loads is provided below. Then, the main phases of the experimental test are described.

2.1. *Stiffness matrix of thin-walled open section beams subjected to transverse actions*

The warping deformation is an unusual distortion which characterizes thin-walled open section beams. This phenomenon, usually neglected for most of structural elements, appears in presence of transverse loads, in particular if they cause torsional effects.

Let us consider a linear-elastic isotropic and homogeneous beam having thin-walled open section in a right-handed reference system OXYZ (Fig. 1). Let ξ, η and ζ be the translations of the origin O along the direction X, Y and Z respectively; the term ϑ represents the rotation of the section around the Z axis.

In a general loading case, the equations of equilibrium of the beam are expressed by

$$\begin{aligned}
&E(\zeta'' A - \xi''' S_y - \eta''' S_x - \vartheta''' S_\omega) = q_z \\
&-E(\zeta''' S_y - \xi^{IV} I_y - \eta^{IV} I_{xy} - \vartheta^{IV} I_{\omega y}) = q_x \\
&-E(\zeta''' S_x - \xi^{IV} I_{xy} - \eta^{IV} I_x - \vartheta^{IV} I_{\omega x}) = q_y \\
&-E(\zeta''' S_\omega - \xi^{IV} I_{\omega y} - \eta^{IV} I_{\omega x} - \vartheta^{IV} I_\omega) - GJ_t \vartheta'' = m
\end{aligned} \quad (1)$$

in which the apex represents a derivative operation with respect to the z coordinate [3].

Nevertheless, this system can be simplified through some hypotheses regarding the reference system: if the origin O coincides with the centroid of the section, the static moments S_x and S_y become null. Similarly, if the axes X and Y are principal for the section, the product of inertia I_{xy} is also equal to zero. Finally, if the sectorial calculus considers the shear centre of the section as the sectorial pole and the sectorial diagram is evaluated starting from the principal sectorial origin, the sectorial static moment S_ω

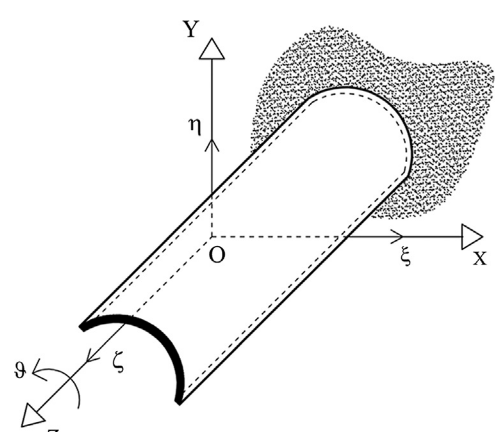

Fig. 1. Thin-walled open section beam in a right-handed coordinate system.