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Compressive buckling for symmetric TWB with non-zero warping stiffness

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ABSTRACT

Torsion and bending/torsion buckling may occur for compressed thin-walled open profiles used in engineering and architecture applications. We report experimental results provided by PZT pickups stuck on thin-walled aluminium beams with open modified cruciform cross-section, exhibiting non-zero warping stiffness. The buckling loads and the natural frequencies corresponding to various compressive forces were detected for free and (at least partially) restrained warping of the ends of the specimens. The results are compared with those of a FEM (commercial) and an *in-house* numerical code that examines the stability of non-trivial equilibrium paths in a dynamic setting. The results seem new and confirm that: (a) PZT pickups can be efficient in extracting modal parameters of thin-walled beams; (b) the numerical simulations are robust and accurate in finding the buckling loads in all analyzed configurations.

1. Introduction

The main feature of open thin-walled beams is high bending stiffness about at least one principal axis of inertia, but negligible torsion rigidity. The centres of area and shear are usually different, hence: bending is coupled with torsion in both the linear and non-linear range; buckling modes are mixed; and the post-buckling behaviour is unstable [1]. In addition, their geometry makes Saint-Venant's principle not valid, and boundary effects propagate throughout the beam length [2]: thus, warping and warping constraints become appreciable, or dominant [2,3]. The numerous applications of such profiles in engineering give interest to the study of their critical load; some of the authors have published on this [4–6]. Such profiles are used, e.g., as compressed members (columns) in civil engineering: see the New National Gallery in Berlin, designed by L. Mies van der Rohe and realized between 1962 and 1968; and the New De Cecco Headquarters in Pescara (Italy), designed by M. Fuksas and realized between 2001 and 2008.

It is usually assumed that pre-buckling equilibrium paths are trivial: the load does not actually deform the member [1–3]. This is acceptable for solid beams, with high axial stiffness and negligible warping effects and bending/torsion coupling. In thin-walled beams the pre-buckling paths can affect the critical load, and studies on non-trivial equilibrium paths before buckling are interesting. The beam model in [4–6] was the basis for the studies in [7–9] by an *in-house* finite difference code. Refinements of the model are in [10], and refinements of the code are in progress, to account for full non-conservative loads.

Some of the authors, with a vast laboratory experience, studied numerically and experimentally how the natural frequencies of compressed beams vary with the load [11,12]. Indeed, in the applications the detection of this variation may be useful for design, monitoring, and damage identification. Moreover, the critical load is attained when the relevant natural frequency vanishes (ideal, perfect systems) [13–20], or is a minimum (real, imperfect systems) [11,20–24] as the load increases (i.e., the apparent beam stiffness goes down). Therefore, measures of fundamental frequency for different compressive forces can also be used for buckling load prediction through non-destructive testing [20,25–28].

An experimental campaign for open thin-walled beams was designed, aiming at: (a) generalizing the already performed experiments, to account for warping and warping constraints; (b) designing and realizing suitable end constraints to match the analytical conditions of the numerical investigation; (c) finding experimental validation of the numerical results obtained so far; and (d) highlighting, by experimental evidence, the role of pre-buckling equilibrium paths, usually neglected in the literature.

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Table 1
Geometrical and mechanical properties of the specimens.

Unconstrained length (mm)	Section width (mm)	Section thickness (mm)	Young's modulus ($N\ m^{-2}$)	Poisson's ratio (–)	Mass density ($kg\ m^{-3}$)
950	50	1.2 (web), 1.4 (flanges)	69×10^9	0.3	2600

The authors investigated the effect of compressive loads operated by an MTS machine on specimens constrained by end devices designed and manufactured to account for warping. The specimens were aluminium beams with symmetric cruciform section and negligible warping stiffness [1–3]. In [29] the experimental and numerical results were thoroughly described and compared. The laboratory set-up was tested, with details on the end constraints and the technique to identify natural frequencies; the *in-house* code was validated. In [11] some of us used a laser to detect the natural frequencies of beams that were slightly bent so to simulate an imperfection, or a pre-buckling path, while in [29–31] piezoelectric pickups of musical technologies were used and found to be effective, precise, robust, and reliable.

In this paper we use the same experimental setup, and new end devices designed and realized to extend the study to a new specimen with doubly symmetric cross-section of non-zero warping stiffness. Thus, we can highlight how warping and warping constraints affect the natural frequencies and buckling loads of a larger class of open thin-walled profiles. We considered two different boundary conditions on warping, and compared the results with numerical ones. The main feature of this study is the measurement of the effects of axial forces on the non-uniform torsion vibration and buckling of a symmetric open thin-walled profile: such investigations are rarely found in the literature.

2. Experimental setup

The specimens were aluminium thin-walled open profiles (6060 T5 alloy), designed and realized on purpose for the experimental campaign, the geometrical and mechanical properties of which are in Table 1. The cross-section of the specimens (see Fig. 1) has the shape of a double I, implying high bending stiffness, modest torsion stiffness, and non-negligible warping stiffness. Thus, such profiles, if not much slender, are prone to buckling more in torsion than in bending [1–3].

Fig. 2 shows the experimental setup of the tests: the loading was operated by a servo-hydraulic MTS testing machine, with a closed-loop electronic control and a maximum loading capacity of 250 kN. The specimens were vertical, constrained to the machine by connections controlling displacements, rotations and twist of the end sections. Four brass elements were designed and manufactured as end connections, so to allow the insertion of the ends of the beam and permit, or prevent (at least partially), the warping of the end sections, Fig. 3. In Fig. 3a (free warping condition) we see how the web only is constrained, while the flanges are left free. Conversely, in Fig. 3b (restrained warping), the whole section is inserted into the brass joint and both the web and the flanges are constrained. Actually, in this case penetration is prevented but detachment is allowed: thus, we have a kind of semi-restrained warping. The position of the lower joint can be adjusted in the horizontal plane so to ensure the required vertical alignment with the upper joint, Fig. 3. The tests were performed controlling the displacement of the lower end of the beam operated by the hydraulic jack, thus providing the loading.

Measures were operated by piezoelectric pickups: their features are such that very accurate dynamic identification tests can be performed without sensibly varying the specimens' mass. A PZT transducer produces an electric signal when subjected to dynamic deformation (direct piezoelectric effect), thus it does not need any supply. The signal can be amplified (if necessary), acquired by audio or usual devices, then recorded and post-processed. The sensor is stuck to the surface of the specimen by glue or a thin film of gel, and does not require specific calibration. A preliminary assessment of the capabilities of PZT disks for experimental modal analysis can be found in [30], while more accurate and complete analysis and results are reported in [31]. Further results and comparisons can be found in [29]. The main features of the adopted PZT sensor are reported in Table 2: its operating frequency range is very large and its weight is extremely low, which makes it particularly suitable for this experimental campaign.

During the tests, four PZT sensors were mounted on each specimen (their locations are marked in Fig. 2). Indeed, even though in principle one sensor is enough to detect the natural frequencies, more sensors were adopted to increase the measure redundancy.

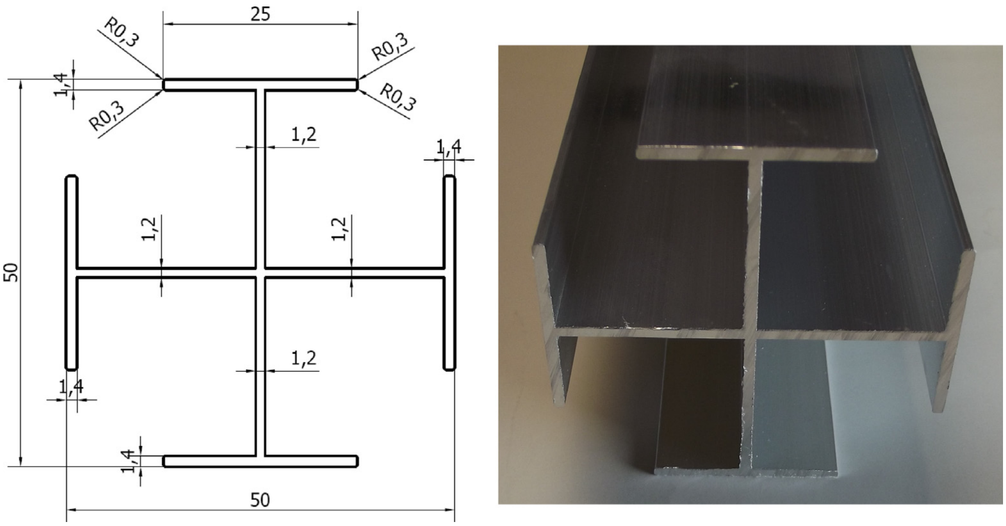

Fig. 1. Specimens cross-section: drawing (dimensions in mm) and picture.