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Web-flange distortional buckling of partially restrained cold-formed steel purlins under uplift loading

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ABSTRACT

It is well-known that cold-formed steel (CFS) members of open section can buckle locally, distortionally and/or lateral-torsionally. Since they are usually used as the secondary structural members in buildings to support roof and side cladding or sheeting, CFS beams are mostly treated as the restrained beams either fully or partially in its lateral and/or rotational directions. For a thin-walled channel- or zed-section beam subjected to uplift loading, if its upper flange is fully restrained in its lateral and rotational directions, the beam will not buckle lateral-torsionally, but may have a web-flange distortional buckling. In the literature there is limited information on the web-flange distortional buckling and currently the critical stress for the web-flange distortional buckling is calculated mainly by using numerical methods. In this paper an analytical model is presented to describe the web-flange distortional buckling behavior of the partially restrained CFS beams when subjected to uplift loading. Formula used to calculate the critical stress of web-flange distortional buckling is derived. Comparisons of the predicted critical stresses with those obtained using finite strip and finite element methods are provided to demonstrate the appropriateness of the model proposed.

1. Introduction

Thin-walled, cold-formed steel (CFS) sections are mostly used as the intermediate members between the main structural frame and the corrugated roof or wall sheeting in which the upper flange of the section is connected to the sheeting by self-drilling or self-tapping screw fasteners, while the lower flange remains free. The most common sections are the channel, zed and sigma shapes, which may be plain or have lips. The lips are small additional elements provided to a section to improve its efficiency under compressive loads. The main features of the CFS section beams are the thin-thickness, open cross-section and large ratio between the two second moments of the cross-section area. These make the section susceptible to local, distortional and lateral-torsional buckling [1].

The local buckling is characterized by the ripples of relatively short half-wavelength of the order of magnitude of individual plate elements in the section and the buckling displacements only perpendicular to plane elements while the fold lines remain straight. The critical stress of the local buckling can be calculated using the formula of buckling of plates [1,2]. The distortional buckling occurs only in the structural members of open cross sections. Distortional buckling involves both translation and rotation at the sectional fold lines of a member leading to a distortion of the cross-section. The half-wavelength of the distortional buckling mode is typically several times larger than the largest characteristic dimension of the cross-section. Unlike the local buckling in which the critical stress is dependent only on the ratio of the width to thickness of the plate element, the distortional buckling is much more complicated and its critical stress is dependent on the dimensions of not only the buckled flange and lip but also other parts of the section [2–5].

In contrast to the local and distortional buckling, the lateral-torsional buckling generally occurs when a beam which is bent about its major axis develops a tendency to twist and/or displace laterally. Since roof purlins and sheeting rails, in most cases, are restrained against lateral movement by roof or wall cladding, such restraints reduce the potentiality of the lateral buckling of the whole section, but do not necessarily eliminate the problem completely [6]. For example, roof purlins are generally restrained against lateral displacement by the cladding, but under wind uplift which induces compression in the unrestrained flange, lateral-torsional buckling is still a common cause of failure [7]. This occurs due to the flexibility of the restraining cladding and to the distortional flexibility of the section itself which permits lateral movement to occur in the compression flange even if the other flange is restrained. However, there is a case where the lateral-torsional buckling may be prevented, which is that the cladding can also provide a rotational restraint to the purlin. In this case the rotational restraint turns the lateral-torsional buckling mode to a

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web-flange distortional mode. Note that the web-flange distortional buckling is different from the flange-lip distortional buckling. The former is characterized by the translation and rotation of a system consisting of the compression flange and lip plus part of the web, whereas the latter is characterized by the rotation of the compression flange and lip system about the lower flange-web junction. In addition, the wavelength of the web-flange distortional buckling mode is much longer than that of the flange-lip distortional mode. In this paper, investigation will be focused on the web-flange distortional buckling, particularly on the calculation of the critical stress of the web-flange distortional buckling of zed-section purlins with different restraints applied at the upper flange-web junction when subjected to a pure bending about its major axis.

Web-flange distortional buckling of CFS sections has been discussed by several researchers [7–9] by using numerical methods. Hancock defined the web-flange distortional buckling as the lateral-distortional buckling in order to distinguish it from the flange-lip distortional buckling [7]. Early attempt was made to apply the analytical model proposed for the flange-lip distortional buckling to the web-flange distortional buckling but without success [10]. An analytical model was also developed by Svensson [11] and Sokol [12] in which the web-flange distortional buckling was modeled by using an elastically supported column subjected to an axial compression force. The cross-section of the column was assumed to consist of the compression flange and lip plus part of the web. However, the model was not properly validated.

In this paper an analytical model is presented to describe the web-flange distortional buckling behavior of partially restrained CFS section beams when subjected to uplift pure bending. Formula used to calculate the critical stress of the web-flange distortional buckling is derived. Comparisons of the predicted critical stresses with those obtained using finite strip and finite element methods are provided to demonstrate the appropriateness of the model proposed.

2. Web-flange distortional buckling model

Web-flange distortional buckling occurs in a purlin when its lateral-torsional buckling is partially or fully prevented. Fig. 1 shows the typical buckling curves of a zed-section purlin with different restraints applied at the upper flange-web junction when subjected to a pure bending about its major axis. The results were obtained using the finite strip method. It is evident from the figure that the rotational restraint has significant influence on the lateral-torsional buckling of the purlin. When the rotational restraint is strong enough, it can turn the lateral-torsional buckling mode to a web-flange distortional mode.

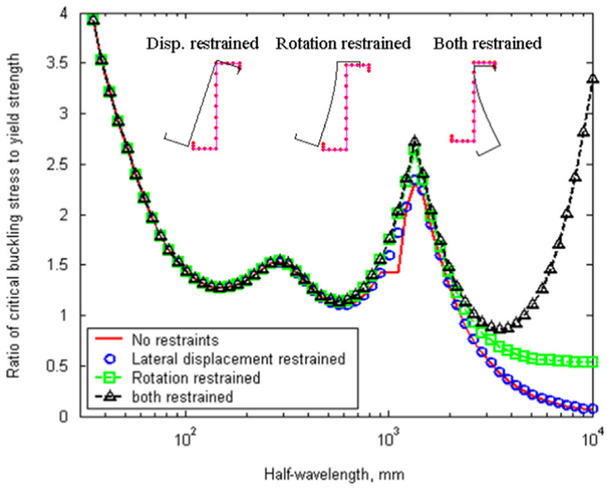

Fig. 1. Buckling curves and lateral-torsional buckling/web-flange distortional buckling modes of a zed-section purlin with different restraints applied at the upper flange-web junction (tension zone) when subjected to a pure bending (h=270 mm, b=70 mm, c=20 mm, t=2.5 mm, σ_y=390 MPa).

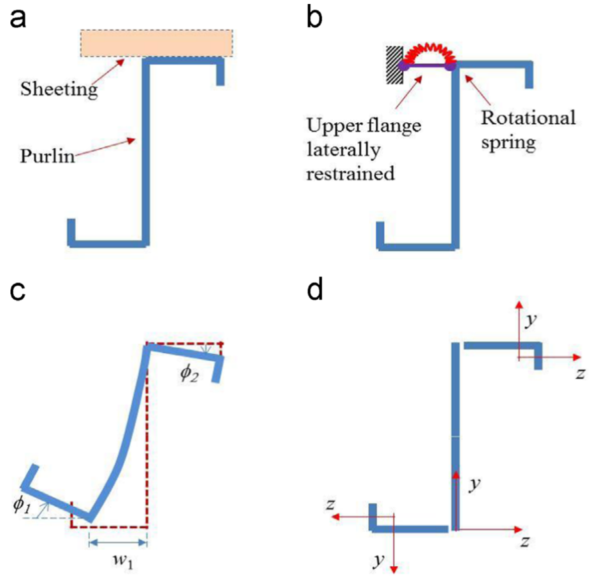

Fig. 2. (a) Purlin-sheeting system. (b) Analysis mode. (c) Displacements representing web-flange distortional buckling. (d) Coordinate systems used in individual components.

Consider a zed-section purlin-sheeting system shown in Fig. 2a. The load on the sheeting is transferred to the purlin through the self-drilling screws and/or the contact between the sheeting and upper flange. The sheeting provides lateral restraints to the purlin in both the translational and rotational directions. The translational restraint is due to the membrane stiffness of the sheeting, whereas the rotational restraint is provided because of a resisting couple produced by the contact stresses. For most types of sheeting, the translational restraint is much strong and therefore the lateral displacement at the fixing point may be assumed to be fully restrained. The rotational restraint, however, is dependent on several factors. These include the dimensions of sheeting and purlin, number, type and positions of the screws. If the stiffness of the rotational restraint provided by the sheeting is known, then the purlin-sheeting system may be idealized as a purlin with lateral displacement fully restrained and rotation partially restrained at the flange-web junction [13,14], as shown in Fig. 2b.

When the purlin has lateral-torsional buckling and/or web-flange distortional buckling due to uplift loading, the restrained flange and lip system, which is in tension, rotates about its web-flange junction and the free flange and lip system, which is in compression, not only moves laterally but also rotates about its web-flange junction (see Fig. 2c). The main difference of the model presented in Fig. 2c from that proposed by Svensson [11] and Sokol [12] is that the web and the free flange and lip system can buckle in a combined torsional and flexural buckling mode, whereas in Svensson and Sokol model the system consisting of free flange and lip plus part of the web can buckle only in a flexural mode about the axis parallel to web line [15]. To determine the critical load which can generate such buckling displacements shown in Fig. 2c, the change of the total potential energy of the system due to the buckling displacements is to be examined. For simplicity of the presentation, the zed section is split into three components, the restrained flange and lip system, the free flange and lip system, and the web. It is assumed that during the lateral-torsional buckling and/or web-flange distortional buckling both the restrained and