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# Buckling behaviour of partially restrained cold-formed steel zed purlins subjected to transverse distributed uplift loading

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ABSTRACT

This paper presents a numerical investigation into the buckling behaviour of cold-formed steel zed purlins when subjected to transverse distributed uplift loading. The study uses both linear and non-linear finite element methods (ABAQUS shell Finite Element analyses) to investigate the pre-buckling, buckling and post-buckling behaviour of zed-section purlins in purlin-sheeting systems. The numerical modelling strategy is carefully validated using the results of available experimental data. Influences of boundary conditions and restraints from sheeting on web shear buckling, local, distortional and lateral-torsional buckling behaviour, and the buckling interactions of the purlins are discussed. Furthermore, the strengths and failure modes of the purlins obtained from numerical results are compared with the design strengths predicted using the direct strength method (DSM) specified in the 'North American Specification' (AISI S100). The comparisons show that the ultimate strengths of buckling interactions are generally underestimated. Hence, the DSM is modified to cover the partially restrained zed-sections in purlin-sheeting systems.



## 1. Introduction

Cold-formed steel sections are commonly used in a variety of ways such as for purlins, rails, sheeting, decking, mezzanine floor beams, lattice beams, wall studs, storage racking and shelving. Among these products, purlins and rails are the most common members, widely used in buildings as the secondary members supporting corrugated roof or wall sheeting, and transmitting forces to the main structural frame. The most common sections are the zed, channel and sigma profiles, which may be plain or have stiffened lips. The lips are small additional elements at the free edges in a cross section, and are added to provide structural efficiency under compressive load.

Local, distortional and lateral-torsional buckling are the three different types of buckling which a cold-formed steel member may experience [1]. Since the 1970s there has been substantial research activity in the field of cold-formed steel structures which has led to numerous published works on the local, distortional and lateral-torsional buckling of cold-formed steel sections (see [2–7], for example). The outcome of this has also led to the new design specifications developed recently in Europe [8], the USA [9] and Australia [10]. However, for the post-buckling, ultimate strength and failure modes are likely to be strongly affected by the buckling interactions between these three buckling modes, in which the ultimate strength may be eroded significantly and may be unacceptable for safe design when the member experiences buckling interaction phenomena. These buckling interactions have attracted the attention of several researchers and have been the subject of a number of journal articles published in recent years [11–20]. However, most of these studies were limited to cases where the cold-formed steel sections are subjected to pure compression and/or pure bending.

In most existing design specifications and published work, the critical stress is calculated based on a model in which the member is subjected to pure compression or pure bending. In either case the pre-buckling stress is independent of the member length. For purlins and rails, however, the loading case is usually the transverse distribution load, for which the pre-buckling stress distribution is largely dependent upon the member length. The influence of the longitudinal stress gradient on the buckling behaviour of cold-formed steel members has been discussed by several researchers. Yu and Schafer analysed the effect of the longitudinal stress gradient on the ultimate strength of thin plates with different support conditions on four edges to illustrate the influence of the longitudinal stress gradient on stiffened and unstiffened elements of cold-formed steel sections, respectively [21]. Rousch and Hancock

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presented a vacuum test to simulate a uniformly distributed load using wind uplift loading for simply supported channel and zed-section purlins with screw fastened sheeting [22]. Bebiano et al. investigated the buckling behaviour of channel sections under uniformly distributed loads [23]. They found that for short members the dominant buckling is the web shear buckling. Vieira et al. provided simplified models that can be used to predict the longitudinal stresses developed in C-section purlins in uplift loading [24].

Trapezoidal sheeting is usually fixed to the purlins in order to enclose the building, and these members together are thus commonly treated as purlin-sheeting systems, in which the beams are either fully or partially restrained in their lateral and rotational directions by sheeting. If the member is partially restrained by the sheeting, the pre-buckling stress distribution will be even more complicated as the member is not only under bending and shear but is also in torsion. Chu et al. investigated the influence of non-uniform bending stress distribution on the local and distortional buckling behaviour of channel and zed-sections [25,26]. The results showed that the critical stresses of local and distortional buckling decrease with an increase in the member length. The reduction in the critical stress continues until the member reaches a certain length. Ye et al. investigated the influence of the lateral restraint of the sheeting on the pre-buckling stress distribution and on the corresponding buckling behaviour of the channel and zed section purlins [27,28]. The results showed that the lateral restraints of the sheeting have a considerable influence on both the pre-buckling stress and the critical stresses of local and distortional buckling. Ren et al. proposed an analytical model for calculating the linear bending stresses in roof purlins, from which the influence of sheeting on the bending performance of the roof-purlin can be evaluated [29,30]. Ren presented a numerical investigation into the effect of rotational stiffness of cold-formed steel zed- and channel-section purlins when subjected to uplift loading in purlin-sheeting systems [31]. The conclusion of this study demonstrated that the rotational spring stiffness has significant influence not only on performance but also on failure type.

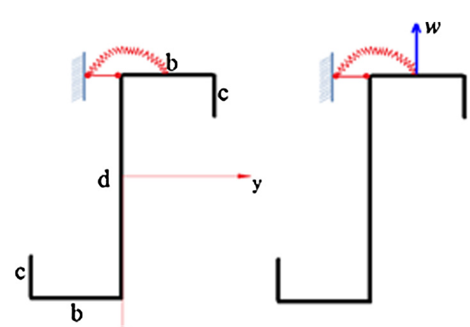
In this paper a numerical (ABAQUS [32]) investigation is presented on the buckling behaviour of partially restrained cold-formed steel zed-purlins in purlin-sheeting systems when subjected to transverse distributed uplift loading. This study uses both linear and non-linear finite element methods to investigate the pre-buckling, buckling and post-buckling behaviour of zed-sections in purlin-sheeting systems. The influence of the boundary conditions, lateral and rotational restraints caused by the sheeting on the web shear buckling, and local, distortional and lateral-torsional buckling behaviour are examined. The buckling interactions of the purlins in purlin-sheeting systems are also discussed. The modified DSM curves for buckling interactions are presented. To validate the present finite element model, the pre-buckling stress distribution, load–displacement curve and ultimate moment obtained from the present finite element model are compared with those obtained from the available experimental data.

## 2. Finite element analysis models and validations

Consider a cold-formed steel member of length $L$, having a zed-shape cross section of web depth $d$, flange width $b$, lip length $c$ and thickness $t$. The material properties of the member are assumed as: Young's modulus, $E = 210$ GPa and Poisson's ratio, $\nu = 0.3$. The stress–strain curve is assumed to follow that of an elastic-perfectly plastic material with yield stress $\sigma_y = 390$ MPa. Two steps of analyses are performed. One is the elastic, linear buckling analysis, which is to determine the pre-buckling stress and the buckling critical load. The other is the material and geometric non-linear analysis, which is to determine the load–displacement response curve of the member. The latter uses the modified Riks method built in ABAQUS. The member is subjected to a transverse uplift distributed loading, as shown in Fig. 1. Two boundary conditions are considered here (see Fig. 2). One is where the normal and tangential displacements of the web at the end of the member are zero. The other is where all normal displacements of lips, flanges and web at end of the member are zero. In both cases, only half of the length of the beam is modelled in which a symmetric boundary is used on one of the ends of the beam. The model is simplified to be laterally and rigidly restrained at the web-flange junction to represent the lateral restraint of the sheeting. A rotational spring restraint is applied at the middle of the upper flange where the sheeting is screw connected, and the rotational stiffness is assumed to be $k_\phi = 791$ N/rad, which is taken from experimental results gained by Zhao et al. [33], to represent the rotational restraint of the sheeting. It should be noted that $k_\phi$ is the per-unit length stiffness constant of the rotational spring which is determined from a single skinned trapezoidal cold-formed steel sheeting (each sheeting size is 1060 mm × 1000 mm × 0.7 mm, for cross sectional dimensions see Fig. 3). Trapezoidal sheeting is usually fixed to these members in order to enclose the building, and this type of sheeting is widely used as the corrugated roof or wall sheeting in farming and industrial buildings. In addition, self-drilling screws are normally used to connect purlin and roof sheeting, thus the screw type, the number of screws per unit length and the screwed positions have influence on the lateral and rotational restraints of purlin-sheeting systems.

The four-node shell element of reduced integration scheme built into ABAQUS is employed to carry out the analyses. The element used is a thin, shear flexible, isometric quadrilateral shell element. In order for the results obtained from the finite element analyses to be sufficiently accurate, the element size used in the finite element mesh is kept at 10 mm. Fig. 4 shows a typical mesh used in the analysis. The tests of numerical models with different size meshes show that this kind of mesh is accurate enough, since any further reduction in element size (i.e. 5 mm) has negligible influence on the obtained results (see Table 1).

The present linear and nonlinear finite element models are validated by using available experimental data. Fig. 5 shows the comparisons of the numerical results with the test results of Rousch and Hancock [22], including pre-buckling stress distributions of the compression flange and load–displacement curves obtained from the present linear and non-linear finite element models and the experimental data. Table 2 provides the cross-sectional dimensions of specimens and yield stresses taken from LaBoube's test [34]. Table 3 compares the ultimate moments of the tested specimens and the corresponding finite element predictions. It is found that the ultimate moments obtained from finite element analyses




(a) Sectional dimensions (b) Uplift loading

**Fig. 1.** The finite element models used for a purlin-sheeting system ($d = 200$ mm, $b = 70$ mm, $c = 20$ mm, $t = 2.0$ mm).