Thin-Walled Structures 94 (2015) 214–224

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Numerical study of purlin joints with sleeve connections

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ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form
18 March 2015
Accepted 14 April 2015
Available online 14 May 2015

Keywords:
Cold formed steel
Purlins design
Semi rigid joints
Finite elements
Bolted joint

ABSTRACT

The joint behaviour influences the stresses and deformations developed by the structure. Based on a predesign for the structural efficiency, a numerical study of cold formed purlins joints with sleeve connections has been performed, allowing for the actual joints structural behavior. The moment rotation curves of the joint configurations are obtained from the corresponding simulations. A simple method to consider the semi rigid nature of the sleeve joint is proposed, by including rotational springs, located on the bolts lines. It permits the characterization of the actual stiffness and strength of the sleeve joints.

1. Introduction

The multi span purlin design employing cold formed profiles is a topic of great interest in the building industry. As a structural system, a purlin is a continuous beam with multiple supports, but a correct design depends on the joints characteristics.

This work focuses on the sleeve connection. It is a kind of joint quite convenient when compared with other types of connection, because it facilitates the assembly process of the purlins.

A purlin can be assembled by linking several cold-formed Z section profiles. The present work deals with the problem of the purlin joints behavior. There are two main kinds of connection: The overlap connection and the sleeve connection. The first connection is formed overlapping the Z section profiles and bolting them through their webs. The sleeve connection consists of an inverted piece of Z section profile, which overlaps the two longitudinal elements on the joint. Their webs are linked by means of bolts.

The overlap and sleeve joint design presents similarities and differences. The transmission of forces in the overlap zones is based on two mechanisms, the embrace of the flanges (contact and friction) and the bolted webs. Both joints have a region where the elements are overlapped and the ratio between the lap length and the depth is a fundamental parameter of design [1–3]. Pham et al. have recently published a numerical research of high strength cold-formed lapped Z purlins under combined shear and bending. This kind of joint gives continuity and double properties on the support regions [4]. However, the design parameters proposed for overlap joints cannot be employed in the sleeve connections design, which is usually based on experimental campaigns.

In general, the stresses developed on a loaded structure depend on the joint behavior. There are numerous studies about it. Lim and Nethercot [5] study the stiffness of the bolted moment connections, where the main source of their flexibility is the holes elongation caused by bearing against the bolts. They employ spring elements to idealize the rotational flexibility of the bolt groups. The joints stiffness in bolted steel trusses is experimentally and numerically studied by Zaharia and Dubina in [6] aiming to evaluate their real behavior. They conclude that the response of the truss is influenced by the rotational stiffness and propose a formula to evaluate the initial flexural stiffness. This expression is employed for Dubina and Ungureneanu in [7] to establish a semi continuous model to study the overall buckling of multi span purlins, restraining solely the Z top flange due to sheeting.

Chung et al. summarized in [8] the research carried out by the authors on steel structures bolted connections, with emphasis on the structural efficiency. They affirm that for an efficient design it is desirable to understand and assess the connections behavior effects on the overall performance of the structural systems.

This paper is focused on the study of the sleeve joint behavior. Considering the stiffness, this kind of connection is more flexible than overlap connection. Considering the ultimate strength and the failure, the most challenged piece of the connection is the sleeve. Regarding purlin design with sleeve joints, it is necessary to include the semi rigid behavior in the modelling. Double properties at the lapped region cannot be considered. The actual simulation of the sleeve connection behavior is an important issue for a safety design.

Yang and Liu [9] study the sleeve joints of multi span purlins for sigma section profiles. They find that there are not design methods in any code or regulations. They make a complete experimental

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http://dx.doi.org/10.1016/j.tws.2015.04.014
0263-8231/

study of rotational stiffness and resistance developing engineering models for the joints design. Ye et al. [10] study experimentally and numerically the behavior of the sleeve joint through the curve force–displacement for modified Z section purlins. They analyze various configurations, highlighting its non-linear behavior and indicating that the lap length is a fundamental parameter in the joint stiffness.

The joint behaviour and their influence on the stresses and deformations developed in a structural system is a very interesting subject. Dubina et al. have published a book about cold forming steel design [11], what compiles the theoretical background and the rules of design developed in recent years in Europe. It is of great value to the interpretation and application of the European standard [12], indicating the liveliness of this subject and the research in this field. They say that the cold forming steel design is dominated by two specific problems, stability and technology of connections, which significantly influence the structural performance.

In other paper, authors have developed an advanced numerical model [13], validated against experimental studies, which is able to predict the structural behaviour of a sleeve connection. It includes the geometrical and material nonlinearity of the problem, and the contact problem between all parts of the joint, including the detailed geometry of the slotted holes. It employs continuum 3D solid elements including several elements through the thickness. This model considers the deformability and the resistance of all components.

The resistance mechanism of the sleeve joint, based on the friction and the embrace of flanges, and the stress concentration around holes and at folding area, make that the sleeve joint does not usually reaches the idealized stiffness and resistance of the continuous model. The sleeve joint has a semi rigid behavior. Thus, the behavior of multi-span purlins with sleeve joints may be quite different if continuity, as traditionally, is assumed.

In a previous work [14], a case study of the sleeve joint behaviour has been made. It is a joint between two Z section profiles with a depth of 300 mm and a thickness of 3.0 mm, varying the overlap length, where the joint stiffness and strength are estimated.

In this work a study of the sleeve joint is performed in order to simulate the realistic connection behavior. Based on the advance model developed in [13], several sleeve joint configurations are numerically studied. The developed models are detailed allowing for an actual joint behaviour simulation.

The numerical study is defined considering Z section profiles for multi span purlins used in practice to support the cladding in industrial buildings. It considers a predesign that improves the structural efficiency. The study range has been selected considering the mentioned predesign for a multi span purlin up to 10 spans. It is a range of profiles commonly used in the European construction market.

Considering the size, i.e., the Z section depths and thickness of the joint profiles and sleeves, two cases of practical use are considered: large and small joints, for multi span purlins of 11 and 6 m span respectively. Additionally, the numerical study takes into account different configurations, varying the lap length.

2. Numerical analysis

2.1. Predesign

The typical approach for a multi span purlin analysis consists of a continuous beam with multiple supports. Under gravity load, the continuous model produces the diagrams of shear forces and bending moments well established. The maximum positive bending moment occurs in the middle of the first span, and the maximum negative, on the second support.

The purlin is formed by linking several Z section profiles. The connections are located on the supports and connected to the rafter through the angle brackets. Besides, the upper flange is fixed to the sheeting, restraining the lateral movements of the purlin.

A multi span purlin can be built using identical Z section profiles for each span, but it can be more effective to consider a thicker profile for the first span, which is bearing the maximum positive bending moment.

Considering this purlin pre design, two kinds of joints are needed to form a continuous beam. The main joint, on the second support, involves profiles with equal depth but different thickness. The secondary joint, over the rest of supports, connects equal section profiles. The main joints require greater lap length than the secondary joints, to withstand the higher negative moment. The paper is focused on the structural behaviour of both types.

The parameters considered in this study are the section depth, varying between 200 and 300 mm, the thickness, varying between 2.0 and 3.0 mm and the lap length, chosen as a percentage of the span, as Table 1 indicates. With this approach, there are 12 different configurations, 6 corresponding to main joints and 6 to secondary joints, which are summarized in Table 2.

In order to study the cold formed profile sleeve connections, the virtual one point load test of each joint configuration is performed. In this test, the joints are withstanding actual working gravity load conditions. The span test should be equal to the distance between the points of zero bending moment of the continuous beam with multiple supports. The setup is shown in Fig. 1. It consists of a structural beam formed by two faced purlins. The Z section profiles of each purlin are linked by a sleeve joint located at the mid span, where the load is applied. The flanges of each purlin are not in contact. The faced purlins are connected at four points in longitudinal direction, by pieces that link the lower and the upper flanges, avoiding lateral buckling.

In the cold formed joint design, it is frequent addressing an intensive experimental campaign. Advanced numerical simulations can be a more effective and economic way of analysis [15].

Finite elements joint models of the scheme shown in Fig. 1 (the one point load test) are developed, and corresponding simulations are performed. The main joint simulations consider a single plane of symmetry. Each Z section profile involves two different connections, as the sleeve connects profiles of different thickness. The secondary joint simulations have two symmetry planes. Each model produces the structural behaviour of the connection, resulting the stiffness and strength of the joint.

The finite element models developed to simulate the joint behavior of the each sleeve connection are based on the experimentally calibrated model presented in [13]. Most influential issues on this studied sleeve joint structural behavior are the joint geometry, which determines the forces path and the stress concentration points, the lap lengths and the modeling of the slotted holes geometry, approximately twice the bolt diameter. Solid elements are employed (C3D8I, linear approximation with incompatible modes). Details of employed mesh can be seen at Figs. 4 and 5.

Each simulation is performed solving a dynamic problem, controlling the process to be quasi-static, to facilitate the solution of the contact problems. They are solved with the general algorithm of the Abaqus explicit package that includes all the outer surfaces of the involved instances. A pure master–slave surface formulation is used, with the tangential behavior forced by a penalty formulation, with a

Table 1
Lap length (% of the span) selected for the numerical study of the purlins.

Main joint lap length (%)	Secondary joint lap length (%)
14	7
19	9
22	16