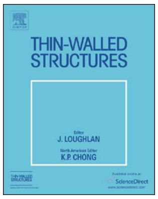
Thin-Walled Structures 121 (2017) 57–66

Contents lists available at ScienceDirect

Thin-Walled Structures

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



Full length article

Failure capacities of cold-formed steel roof trusses end-connections

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ARTICLE INFO

Keywords:
Cold-formed steel
Roof trusses
Failure capacity
Numerical simulation
TEK screw modeling

ABSTRACT

The response of cold-formed steel roof trusses undergoing large deformations resulting from unconventional loading is not totally known. Roof truss end-connections are one structural component that can cause premature failure. This paper investigates the failure capacities and the energy absorption capabilities of roof truss end-connections. Experimental tests were performed to obtain the capacities of these connections under quasi-static vertical and horizontal (tension and shear) loadings. Numerical simulations were developed to predict the connection response to failure for any configuration. Implicit and explicit dynamic procedures were used in the analysis of the numerical simulations. A deformable screw behavior with failure criterion was used in the numerical modeling to predict the progressive failure of the connection. The paper includes four verifications that validate the deformable behavior of #10 TEK screw used in the simulations. Results showed that the toughness (energy absorbed to failure) of the end-connection is greatly affected by the screw configuration and the direction of loading.

1. Introduction

CFS roof trusses are one of the structural elements that are versatile. Variable cross-section shapes and installation techniques have grown with the use of CFS trusses. Due to the uncertainty in the design, truss connections are generally overdesigned [1]. In 1995, the American Iron and Steel Institute (AISI) with the assistance of the Light Gauge Steel Engineers Association published a document entitled “Design Guide for Cold-Formed Steel Trusses” as an effort to eliminate confusion about CFS trusses design. This document helped with the design and promoted the development of CFS roof and floor trusses where the minimum strength and serviceability requirements for the design are determined [2]. However, information about trusses’ ultimate strength, modes of failures, end-connections capacities are very limited.

The response of these truss systems under high strain rate loading such as blast loading is totally unknown. Truss systems response will include highly nonlinear behavior past the linear elastic response under conventional loads. Since a truss system is only as strong as its weakest component, it is important to check if its connections meet the performance required. Truss end-connections are one important element that can cause premature failure if not designed properly. To enhance the energy absorption capability of CFS roof trusses under blast loads, it is recommended to design the end-connections to allow the CFS trusses to develop tension membrane resistance [3], which would lead to horizontal dynamic reactions (shear forces) during the blast loading phase and vertical downward reactions during elastic rebound. Bearing connections normally must also be designed for tension from reaction forces occurring during component elastic rebound [3]. This paper focused on evaluating the failure capacities of the end-connections for CFS roof trusses under horizontal (shear) and vertical (tension) loads.

Cold-formed steel (CFS) connections can be classified into fixed connections (no movement is allowed) and slip connections (partial movement is allowed in a specific direction). Fixed connections are normally used in axial-load bearing walls, curtain walls, trusses, roofs, and floors. The primary method to fasten CFS connections is using self-drilling screws. Other methods include bolts and weld. The first set of design equations for screw connections under shear, pull out and pull over, was formulated by Peköz [4] using the data of more than 3500 tests. Different failure modes for steel-to-steel connection can be calculated from the American Iron and Steel Institute [5]. Section E4.3.1 provides limit states for tilting and bearing of screws while Section E4.4.1 provides limit states for screw pullout. Pullover can be calculated using Section E4.4.2. The shear and tension in screws can be determined using Sections E4.3.3 and E4.4.3, respectively.

Many design recommendations for CFS connections found in the literature are empirical expressions developed based on experimental testing of specific ranges of material properties and specific geometrical dimensions [6]. These design rules are primarily developed for simple connections under conventional loads where the performance of the connected members is not limited by connection deformation [6].

Daudet and LaBoube [7] conducted 264 shear tests to investigate the shear behavior of self-drilling screws and to compare their

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http://dx.doi.org/10.1016/j.tws.2017.09.026
Received 2 May 2017; Received in revised form 14 August 2017; Accepted 26 September 2017

performance in low ductility steel as opposed to normal ductility steel. LaBoube and Sokol [8] focused on the behavior of screw connections and their strength. Two hundred single lap screw connections that varied in fastener patterns, screw spacing, and the number of screws were tested to determine their strength. This study concluded that the screw pattern did not significantly affect the strength of the connection, while the connection strength decreased with the decrease of the distance between screws. Another major finding of this study is that increasing the number of screws results in a decrease in strength per screw [8]. Reynaud and Dean [9] examined the relationship between the strength of screw connections computed based on the connected components and the strength of the screws. Screw strength test data from three independent manufacturers showed that the shear strength of screw fasteners can be significantly lower than the strength of the connected components. To avoid any mixed results, it was recommended that a plate of sufficient thickness be used to restrain screw tilting in the shear strength test [9].

Francka and LaBoube [10] aimed to understand the behavior of screw connections subjected to combined tension pull-out and shear forces. Four key parameters were investigated: screw size, the thickness of the steel sheet 'Ply 2' (Ply 2 is the sheet not in direct contact with the screw head), and the tensile strength and the ductility of the steel sheet. Based on the results of eighty-four tests, two interaction equations were proposed to calculate the design capacity of a screw connection subject to combined pull-out and shear forces [10].

Recent experiments on CFS screw connections by Corner [11] showed that screw tilting has a major effect on the limit states of the connection. Screw tilting was predicted as a function of ply thickness and fastener pitch as it was found that these parameters control the connection failure mechanism. The analysis of the experimental data indicated inaccuracy in predicting limit states provided in AISI. It was suggested to consider ply thickness over fastener pitch instead of the ratio Ply 2 over Ply 1 [11]. Another recent research performed by Haus [12] evaluated the performance of different types of screws in CFS connections. The research study included testing of single screw connections subjected to tension under monotonic and cyclic loading conditions. Three connection pairs with two different orientations and different types of screws commonly used in construction were examined. The typical load-displacement relationship included different failure modes of the screw. Tilting was observed at the early stage of the relationship, followed by tearing and bearing, then screw pullout, and finally breaking of the screw [12].

Recent studies on CFS connections [11,12] focused on investigating the capacities and the failure mechanisms of single screw connections. This paper focusses on investigating the failure capacities (energy absorption capacities) of CFS trusses end-connections under shear and tension forces. The experimental program includes testing symmetric and non-symmetric connections with different screw configurations under vertical and horizontal loads, and the performance of these connections is analyzed and discussed. In addition, this paper presents numerical models that were developed and verified using implicit and explicit dynamic procedures. The numerical models were able to predict the connection behavior including the failure point of the simulated test.

Typically, the roof system consists of multiple trusses connected together using horizontal bridging and the roof deck, which causes the connection to respond relatively closer to a symmetric case. To identify the capacity bounds of the end-connections, this paper evaluates the performance under both symmetric and non-symmetric conditions. The experimental program is described next.

2. Experimental study

CFS roof trusses are normally connected to the supporting system using hold down clips (HD-clip). A schematic profile showing details of the bearing connection that will be investigated is shown in Fig. 1.

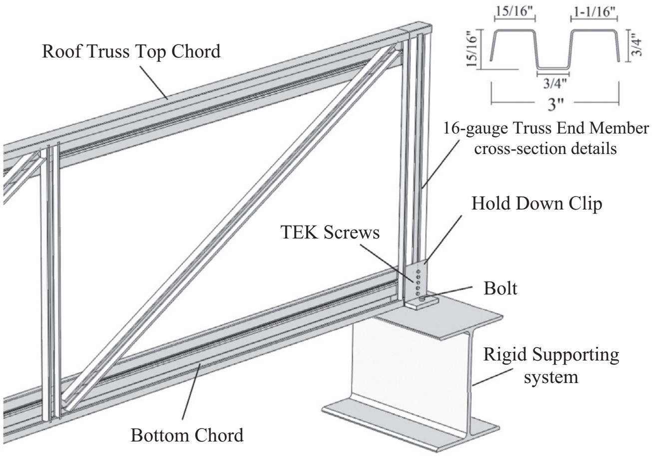

Fig. 1. Schematic profile of the end-connection of roof truss system.

Different configurations of #10 self-drilling screws are used to connect the HD-clip to the truss end member (TEM). Fig. 2 shows the screw configurations used in vertical and horizontal testing. A rigid steel plate of 19 mm (0.75-in.) is used to simulate rigid supporting condition. The HD-clip is connected to the rigid steel plate using different sizes of bolts. The thickness of the truss end member, as well as the thickness of HD-clip, are fixed parameters for all specimens. The truss end member is 16-gauge W-shape CFS section. For connections with a large number of screws double web truss end member is used. Two types of HD-clips were used; 76 mm and 152 mm (3-in. and 6-in.) wide clips of 12-gauge thickness. Small steel plates, 38 mm × 76 mm × 12.7 mm and 38 mm × 152 mm × 12.7 mm (1.5-in. × 3-in. × ½ -in. and 1.5-in. × 6-in. × ½ -in.), are used with the 76 mm and 152 mm (3-in. and 6-in.) clips on the side where bolts are used as connecting elements.

An MTS machine of 490-kN (110-kip) capacity is used to perform the experimental tests. Table 1 summarizes the test matrix, specifications, and the number of trials conducted for each test. The test specimens are designated with a prefix letter; V refers to vertical setup, while H refers to horizontal setup. Also, test specimens are designated with suffix letter; A for the first trial, B for the second trial of the same test, etc. The number between the two letters represents the test number. In case the test is a non-symmetric case, the designation ends with "-UN". Additional details about each of the vertical and horizontal setups are given next.

2.1. Vertical test setup

The TEMs are attached to the MTS machine using a 12.7 mm (0.5-in.) sandwich steel plate and high strength bolts. Holes were cut through the TEMs prior testing to prevent any contribution from the bearing around the high strength bolts. The connection clips are bolted to the thick steel plate that is attached to the machine hydraulics. The MTS machine upper crosshead is held stationary while the hydraulics move downwards at a rate of 6.35 mm/min (0.25 in./min) to apply a vertical load to the connection of the tested specimen. The non-symmetric setup includes testing one connection while the symmetric setup includes testing two connections bolted back-to-back. Fig. 3(a) and (b) show a front and a side view of a typical vertical symmetric test setup in the MTS machine. Fig. 3(c) illustrates a typical vertical non-symmetric test setup. The load and the connection displacement are monitored using a data acquisition system. The data are collected at a rate of 1 sample/second using a ram displacement rate of 0.1 mm/s (0.004 in./s).

2.2. Horizontal test setup

The typical horizontal test setup in the MTS machine is shown in