Thin-Walled Structures 131 (2018) 1–15

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Experimental investigation of cold-formed steel shear walls with self-piercing riveted connections

Zhiqiang Xie[a], Weiming Yan[a], Cheng Yu[b,*], Tingting Mu[a], Linlin Song[a]

[a] Beijing Key Laboratory of Earthquake Engineering and Structural Retrofit, Beijing University of Technology, Beijing, China
[b] Department of Engineering Technology, University of North Texas, Denton, TX, United States

ARTICLE INFO

Keywords:
CFS shear wall
Self-piercing riveted connection
Monotonic loading
Reversed cyclic loading
Mechanical behavior

ABSTRACT

With the purpose of introducing a new connection to cold-formed steel structure, this paper presents an experimental investigation of cold-formed steel (CFS) shear walls with self-piercing riveted (SPR) connections under monotonic and reversed cyclic loading. The effects of loading type (Monotonic and Cyclic), rivet spacing at the steel sheet edges, rivet number at CFS framing joints, axial compression ratio, and the steel sheathing types (steel sheet sheathing and corrugated steel sheathing) on mechanical behavior and failure modes of CFS shear walls were investigated. The shear strength, initial stiffness, and ductility of CFS shear walls with SPR connections were evaluated by comparing to the results of CFS shear walls with self-drilling screw connections under the same condition. Lateral loading, safety factor, and resistance factor under the wind and seismic loads were determined in accordance with test results of CFS shear wall with SPR connections. The research indicated that the rivet spacing at the sheet edges was a key factor affecting failure modes and mechanical properties of CFS shear walls. The relationship of shear strength and ultimate deformation decreased linearly with the increase of the rivet spacing. Compared to CFS shear walls with self-drilling screw, CFS shear walls with SPR have significantly improved shear strength and stiffness. Safety factor and resistance factor recommended by AISI Seismic Design Standard are conservative for the wind and seismic design of CFS shear wall using SPR connections.

1. Introduction

Cold-formed steel (CFS) structure has obtained wide attention and promotion in low- and mid-rise buildings because it is suitable for modular design, industrial production, fast transportation and assembly, high strength, and good fire resistance. CFS shear walls is composed of CFS frame and sheathing as a lateral force resisting system for CFS structures. There are many types of sheathing material, such as steel sheet [1,2], corrugated steel sheet [3], oriented strand board (OSB) panels [4,5], gypsum board [6], calcium silicate panel [7] and cement based panels [8]. Yu [1] conducted monotonic and cyclic tests on CFS framed walls with single sided steel sheet sheathing, and the study indicated that the primary failure modes for sheet steel CFS shear walls were the buckling of the steel sheathing and pullout of sheathing screws. Additionally, dynamic testing of single- and double-story steel-sheathed cold-formed steel-framed shear walls had been carried out by Shamim et al. [2]. It was shown that the load-versus-displacement hysteretic behavior, as well as failure modes, did not differ significantly from that observed for shear walls tested using cyclic loading protocols. Experimental research were employed by Fülöp et al. [3] to explore failure mechanism for CFS shear walls with corrugated steel sheet sheathing. The experimental results showed that failure of the specimens occurred in the two horizontal seams and in their vicinity, which was shown as pullout and tilting of screw. Landolfo [4] and Liu [5] conducted experimental study on seismic behavior of OSB sheathed CFS shear walls. Seismic response of CFS shear walls sheathed with gypsum panels and calcium silicate board were studied by Macillo [6] and Lin [7], respectively. They found the limit states in the tested shear walls were fastener pull-through, edge tear out, and fastener bearing, and the hysteresis curve was obvious pinched as a result of the fastener pull-through and bearing mechanism. Experiments on seismic behavior of steel sheathed cold-formed steel shear walls cladded by gypsum and fiber cement boards were investigated by Mohebbi et al. [8]. Their experimental studies showed that on the use of claddings connected to the CFS walls their effects on the shear strength cannot be ignored. Overall, for CFS shear walls with steel sheet sheathing or corrugated steel sheet sheathing, the seismic energy dissipation mechanism were buckling of the steel sheathing as well as slip of screw at the steel sheet edges. For CFS shear walls sheathed with OSB or gypsum panels, the primary energy dissipation mechanism occurs at the fastener-to-

* Corresponding author.
E-mail addresses: xzq198898@163.com (Z. Xie), Yanwm@bjut.edu.cn (W. Yan), cheng.yu@unt.edu (C. Yu), 1045768585@qq.com (T. Mu), 577070636@qq.com (L. Song).

https://doi.org/10.1016/j.tws.2018.06.028
Received 15 October 2017; Received in revised form 4 May 2018; Accepted 21 June 2018

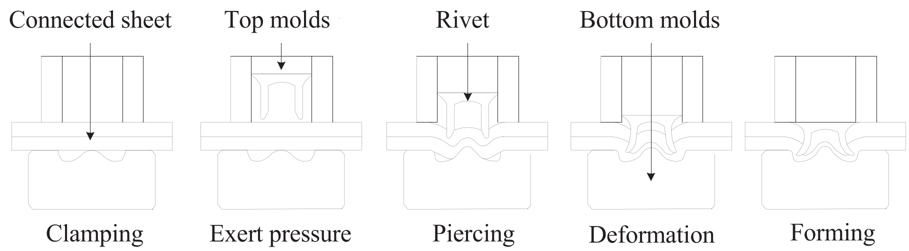

Fig. 1. Forming mechanism of self-piercing rivet connection [10].

sheathing connection and involves fastener tilting and bearing as well as pull-through.

Because of flexible construction operation and low price, the self-drilling screw is typical and common type of fasteners, which is widely used in the cold-formed thin-walled steel structure. However, a large number of experimental studies found that the damage of cold-formed thin-walled steel members is mainly caused by the tilting, shearing and pulled-out of screws [9]. Furthermore, positioning, drilling, nailing, and other processes will reduce the efficiency of production and result in longer production term and higher cost. Therefore, the type of connection used in cold-formed thin-walled steel structure needs to be further improved.

Self-piercing riveted connection is commonly used in the fields of automobile and mechanical engineering. The forming mechanism of SPR joint (see Fig. 1) involves driving a separate rivet component into the layer of the parent metal sheet, piercing, clinching, and forming of the interlocked mechanism under the action of bottom molds [10]. This connection type has many significant advantages including: (1) SPR joints with high strength, stiffness, and fatigue resistance [11]; (2) High connection efficiency and easy to mechanize connection in production line; (3) joints with smooth appearance and good anti-corrosion performance [12]. However, the key factors that affect the feasibility of self-piercing riveting are the operation space and the combination thickness of the steel sheet. In general, whether the self-piercing riveted connection can be realized, the key is whether the connected area can have enough operation space. According to current equipment capability, the self-piercing riveted connection technique is only to the perimeter connections in CFS shear walls. While for field connections between the interior and the steel sheet, it can be realized by improving the self-piercing riveted device in which increasing net space between the upper mold and the bottom mold, the inside diameter of the clamp, and the height of bottom die. Due to limitations of the rivet hardness, the mold size, the ability of the device and so on, the combination thickness of the steel sheet shall not exceed 4 mm [13].

Abundant research had presented the forming mechanism and mechanical behavior of SPR connection. Xu et al. [14] investigated the influence of rivet length, sheet thickness on the interlocked mechanism of aluminum alloy joints. It was found that the rivet flaring increased with the increase of rivet length and sheet thickness. Fu and Xu et al. [15,16] presented the great effect of rivet hardness, length, and diameter on formed quality and shear strength of SPR joints of aluminum alloy. The shear strength of SPR joints of aluminum alloy increased with the increase of rivet length was indicated by Sun et al. [17]. They found that shear strength showed 3.7 kN and 5.3 kN respectively when 6 mm and 6.5 mm long rivets were used to join sheets (1.6 + 2.0 mm). Zhao and Calabrese et al. [18,19] described the major effect of sheet thickness on static property and fatigue performance. The types of failure and shear strength were controlled by the thinner top sheet. Li et al. [20] studied the influence of end distance on quality and strength of 4 mm thick steel connected by SPR. They discovered that end distance over 11.5 mm had minimal effect on joints. Yan et al. [10] did a pilot study on the shear strength of SPR connections used in cold-formed steel sheets. They proposed the shear constitutive model of SPR connections based on the model of transmission dynamics of infectious diseases, and then the formula of predicting shear strength was further developed. The shear and tensile design method for SPR joints using a central section measurement method were reported by Haque et al. [21]. They summarized joint strength was determined by the length of interlock, the effective thickness of bottom sheet, and the diameter of deformed rivet.

At present, the researches of CFS shear wall with self-drilling screw are considerably mature in the aspect of mechanical performance. Serrette et al. [22,23] conducted a series of monotonic and cyclic loading test for 1.22 m wide × 2.44 m high, 0.61 m wide × 2.44 m high CFS shear wall. The results showed that failure modes of all test walls mainly were sheet buckling, and the shear walls with smaller screw spacing occurred stud buckling as well, and peak load and deformability of walls under the monotonic loading were similar with that of cyclic loading. Based on the experimental investigation of 1.83 m wide × 2.44 m high CFS shear wall with steel sheathing under the monotonic and cyclic loading, Yu et al. [24] proposed a set of detailing recommendations for CFS shear walls (3:2 aspect ratio) with steel sheathing. Yu et al. [1,25] also carried out the monotonic and cyclic loading test of CFS shear walls with 0.686 mm. 0.762 mm, 0.838 mm (0.027 in., 0.030 in., 0.033 in.) plain steel sheets. The provision of nominal shear strength in the AISI about this three types shear wall was improved [26,27]. The results indicated that failure mode of the walls was pull out of screws; nominal shear strength of walls was linear reduction with the increase of screw spacing; steel thickness has minimal effect on the shear capability of shear wall. Attari et al. [28] researched the CFS shear wall with single-sided or double-sided steel sheathing. They found that the shear wall with double-sided steel sheathing had two times more bearing capability than that of single-sided, and the shear behavior of walls was primarily determined by the ratio of steel sheathing thickness to the sheet thickness of frame. The results of numerical simulation showed the ratio of ultimate strength of walls to nominal thickness of frame elements was linear with steel sheathing thickness. Javaheri-Tafti et al. [29] provided a reasonable amendment factor of seismic response and lateral bearing capability for CFS walls. According to previous test results, North American Standard for Seismic Design [27] has made a comprehensive provision for screw-connected CFS shear wall with sheathing including steel sheet, wood panel, gypsum board, and calcium silicate panel.

In summary, researches on SPR joints have been primarily concentrated on the aluminum sheets with lower hardness, and higher ductility, but there were limited studies on mechanical properties of SPR connections using steel sheet with high hardness and lower ductility. The research on lateral and seismic performance of CFS shear wall with self-drilling screws is relatively mature, and the specifications [26,27,30,32] have a comprehensive provision for different types of the shear wall design. However, a knowledge gap existed in the application of SPR on CFS shear walls and there is no recommendations for nominal shear strength and deflection for such shear walls.

This paper presents a series of shear wall tests on 14 full-scale CFS shear wall specimens under monotonic and cyclic loading with a goal to study mechanical properties of CFS shear walls using SPR connections, and to further examine the applicability of SPR on CFS shear walls in terms of wind and seismic design. The effects of loading type, rivet