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Tensile capacity of self-piercing rivet connections in thin-walled steel structures

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ABSTRACT

The paper presents an experimental investigation on the tensile behavior and strength of self-piercing rivet (SPR) connections used in cold-formed thin-walled steel structures. The sheet thickness ratio, the sheet combination type, and the rivet length were analyzed for their effects on the tensile performance of SPR connections. The research also studied the feasibility of the existing calculation method of SPR connections and the other design methods of self-tapping screw connections for the SPRs investigated herein. Based on the test results and analyses, a new design method for the tensile capacity was proposed. The test results showed that the sheet thickness ratio, the sheet combination type, and the rivet length were the key factors controlling the failure mode and the tensile capacity of SPR connections. The proposed design method for the tensile capacity of SPR connections considers those primary factors as well as the different failure modes.

1. Introduction

In recent years, prefabricated cold-formed thin-walled steel structural systems have become a popular choice for low-rise buildings due to their advantage in modular design, industrial production, mechanized assembly and others [1,2]. The components of cold-formed thin-walled steel structures are commonly connected by self-drilling screws, blind rivets and other traditional connections in today's projects. However, the conventional connection methods may not provide the desired efficiency for mass production [3]. This paper presents an attempt to improve the efficiency of connections in prefabricated cold-formed thin-walled steel structures by using self-piercing rivet (SPR) technique which was originally used in the automotive industry.

SPR joining is not only suitable for an automated production line, but also offers higher strength, stiffness and efficiency in connecting steel sheets than screw connections and blind rivet connections [4,5]. The process of forming SPR joining involves: (1) clamping the sheets in advance, (2) exerting pressure to top molds, (3) the rivet through piercing the top sheet, (4) deformation of rivet in the bottom sheet under the action of bottom molds, (5) forming of joint. The prototyping mechanism of self-piercing riveted joint is illustrated in Fig. 1 [6].

Han et al. [7] investigated the mechanical properties of three-layer aluminum plates connected by SPR joints. It was found that shear and tensile capacity mainly depended on shearing between rivet tail and sheets (mechanical interlock). Iyer and Mucha et al. [8,9] studied the effect of rivet numbers on the mechanical properties of SPR connections. They concluded that the strength of a double riveted joint was not higher than a similar single-rivet joint in terms of strength per rivet. The highest strength was exhibited when the rivet head pulled out the top sheet. The influence of die parameters on interlock length and rivet opening in different joints comprising steel and aluminum composite panels were reported by Pickin et al. [10], and their results showed that the rivet opening and interlock length increased as the die diameter increased and height of internal die tip decreased. Porcaro et al. [11] presented the forming process of SPR connections using numerical simulation, and drew a conclusion that the accuracy of the calculated result was determined by the properties of the rivet material. Bouchard et al. [12] proposed a two-dimensional simulation method of the forming process and a three-dimensional joint analysis method for SPR joints. The effect of sheet thickness on fatigue performance of SPR aluminum joints was examined by Su and Zhao et al. [13,14]. Wan et al. [15] presented the technical parameters and the method of quality assessment of SPR joints. For the shear strength of SPR joints, a method of finite element analysis was developed by Yi Zhong et al. [16]. For the shear strength of self-piercing rivet connections, a design method based on the numerical model of transmission dynamics of infectious diseases was proposed by Yan et al. [17], and the strength reduction due to the effect of group rivets was considered in this method.

In summary, the research on SPR joints of automobile and mechanical fields has been primarily concentrated on the forming mechanism and fatigue behavior for aluminum sheets with lower hardness, strength and higher ductility. There have been minimum studies on SPR connections made of cold-formed thin-walled steel sheets with high strength,

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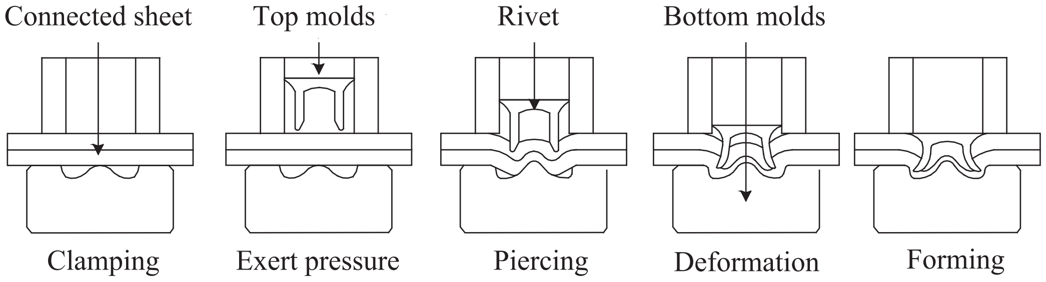

Fig. 1. Prototyping mechanism of self-piercing riveted joint [6].

hardness and lower ductility, and the study of tension performance was also very rare. No calculation formula for tensile capacity has been developed for the applications in the field of Civil Engineering.

In order to introduce the SPR technique to the cold-formed thin-walled steel structural field, 84 SPR specimens with common steel thicknesses were designed to test the tensile properties. Based on the effects of the sheet thickness ratio, the sheet combination type and the rivet length on tension properties of SPR connections, an empirical formula of the relationship between thickness and rivet length was established. The application of the existing calculation method for the tensile capacity of SPR connections and the current design method for the tensile capacity of self-tapping screw connections to the SPRs tested in this research was analyzed. Based on different failure modes, a set of formula of the tensile capacity for SPR connections applied to the Civil Engineering field was developed. This research will provide a theoretical guidance and additional experimental data for supporting the application of SPR technique in the field of Civil Engineering.

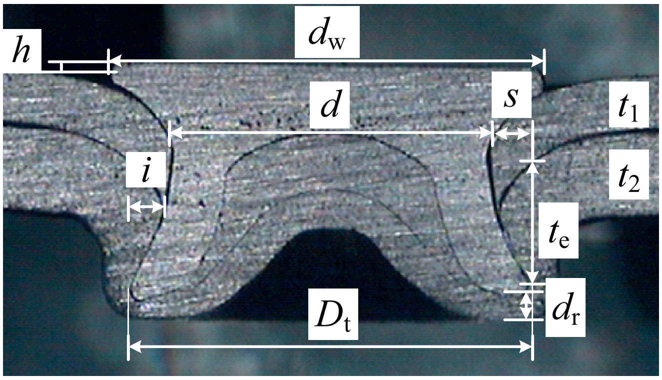

Fig. 2. Definition of geometric parameters of the cross section of SPR joint.

2. Analysis of the existing design method of the tensile capacity

2.1. The tensile design calculation method of blind rivet joints in Eurocode

According to Eurocode 9 (prEN1999-1-4), the design of SPR connection is mostly based on the design method of blind rivets as follows [18]:

$$F_p = 1.5 f_{u1} \sqrt{d{t_1}^3} / \gamma_M \tag{1}$$

where F_p is the pull-out resistance for cross-tension loading (N); f_{u1} is minimum ultimate tensile strength of parent sheets (N/mm^2); d is rivet diameter (mm); t_1 is the thickness of the thinner connected sheet (mm); γ_M is the partial factor for resistance of the connection ($\gamma_M = 1.25$).

It should be noted that the above design equation is only concerned with the failure modes of blind rivet connections. However, the mechanism of SPR connections is different from blind rivets, so its application needs to be further investigated.

2.2. Prediction method of the tensile capacity proposed by sun and Haque

Based on the geometric parameters of the cross section of SPR, Sun et al. [19] suggested an empirical equation of SPR connections as follows:

$$F_{ST} = 0.7 \eta_t \beta_t t_e \pi D_t \sigma_t \tag{2}$$

where F_{ST} is the joint strength for tail pull-out failure (N); $\eta_t$is the reduced

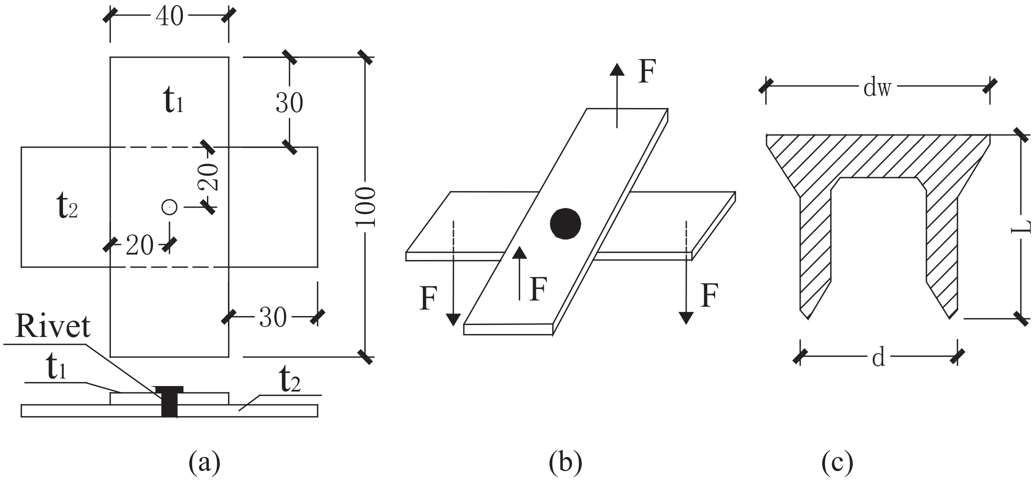

Fig. 3. Diagram of cross-tension SPR joint: a) connection specimen, b) loading direction, c) rivet cross-section.