Journal of Constructional Steel Research 145 (2018) 300–314

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Shear lag effect on ultimate tensile capacity of high strength steel angles

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ARTICLE INFO

Article history:
Received 5 December 2017
Received in revised form 1 February 2018
Accepted 16 February 2018
Available online xxxx

Keywords:
Shear lag
High strength steel
Tension angle
Experiment
Design method

ABSTRACT

This research investigates the shear lag effect on the behaviour and ultimate tensile capacity of high strength steel (HSS) tension angles with bolted and welded connections. Eighteen full-scale tests were conducted, including fourteen specimens with HSS tension angles and four specimens with normal steel (NS) tension angles. For these specimens, single tension angles were connected to the gusset plates either by bolted or welded connections. The main test parameters included steel grade, connection length and out-of-plane eccentricity. In general, the test observations showed that the shear lag effect was significant for the bolted HSS angle specimens connected by the short leg. The effectiveness of the design equation in the current design specifications for quantifying the shear lag ($1-\bar{x}/L$ rule, where $\bar{x}$ = out-of-plane eccentricity and L = connection length) was evaluated using the test results. The comparison of the test results and the predictions by the design equations showed that the latter gave un-conservative estimates of the ultimate tensile capacity of the specimens with bolted HSS angles connected by the short leg. Based on the finite element models validated by the test results, a parametric study was carried out, and the results also indicated that the current design equation would lead to unsafe estimates of the ultimate tensile capacities of bolted HSS angles connected by the short leg. Finally, a modified design guideline was proposed based on the results of the numerical study.

1. Introduction

In steel construction, hot-rolled or welded sections such as I-sections, angles, and tees are often utilised as tension or compression members to resist axial forces. These steel members are usually connected to other structural components such as gusset plates using bolted or welded connections. Since it is common to connect only part of the section of a tension member (e.g. one leg of a single angle) to the connecting elements at the connection, therefore the unconnected part of the section near the connection may not be effectively mobilised to carry the applied tension force. Consequently, the tensile strength of the section cannot be fully developed in the vicinity of the connection, and this phenomenon is commonly known as "shear lag". Taking a single angle with welded connection shown in Fig. 1 as an example, the applied tension load is transferred from the connected leg to the outstanding leg by shear, leading to stress lagging behind from the heel to the outstanding toe of the section. Thus, the unconnected leg is not completely effective in carrying the load. In addition, the applied axial load is generally transferred by bolts (for bolted connections) or welds (for welded connections), and hence the load transfer path which is in line with the bolt line or the weld plane may not align with the centroid of the cross-section. In this context, secondary bending produced by the loading eccentricity would also be expected. In general, the cascading effect of shear lag, secondary bending and stress concentration at the connection would compromise the ultimate tensile resistance of a tension member. In practical cases, since it is difficult to decouple the interdependence between the effect of shear lag and secondary bending, a modification factor is usually utilised to consider both.

The research efforts dedicated to the shear lag effect on the behaviour and ultimate tensile capacity of tension members were initiated in the last century. For instance, Davis and Boomsliter [1] carried out an investigation to quantify the ultimate tensile strength of tension angles with welded or riveted connections. Gibson and Wake [2] conducted a series of tests of angles subjected to tension, and the influence of the weld detail on the ultimate tensile resistance of the specimens was studied. To provide a comprehensive insight into the behaviour and ultimate tensile strength of tension members of bolted or

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https://doi.org/10.1016/j.jcsr.2018.02.015
0143-974X/

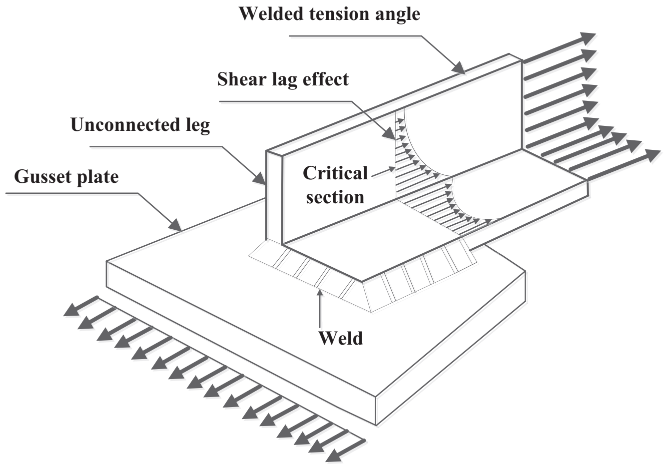

Fig. 1. Stress distributions in welded single angle due to shear lag effect.

riveted connections, Chesson and Munse [3,4] conducted experimental works on specimens covering a wide spectrum of parameters, and they proposed a strength reduction coefficient to quantify the shear lag effect of tension members, as reproduced in Eq. (1):

$$U_{Rule} = 1 - \bar{x}/L \tag{1}$$

where U_{Rule} = design section efficiency, $\bar{x}$ = out-of-plane eccentricity and L = connection length as illustrated in Fig. 2. Eq. (1) has been included in various design specifications [5–7] to account for the effect of shear lag in tension members. Regan and Salter [8] conducted an experimental study on single angles of welded connections with varied welding details. Utilising the test results of seventeen specimens, they proposed design equations for quantifying the ultimate tensile strength of tension angles with welded connections. In addition, Easterling and Gonzalez [9] investigated the behaviour of double members under tension, and the effect of the presence of the transverse welds on the shear lag effect was evaluated. Later, Kulak and Wu [10] initiated an experimental programme including twenty-four single and double angle tension members with bolted connections and developed a set of design recommendations for quantifying the shear lag effect of bolted tension angles. Abi-Saad and Bauer [11] developed an analytical model for predicting the ultimate tensile capacity of tension members using assumed stress distribution in the vicinity of the connection. Subsequently, more test data were provided by Zhu et al. [12] to characterise the behaviour of single tension angles with welded connections. More recently, Fang et al. [13] studied the effect of the shear lag on the behaviour and the ultimate tensile capacity of tension angles and tees with welded connections. Nonetheless, all of the research works described above and the corresponding research findings are limited to tension members made of normal steels (NSs) with a nominal yield stress lower than 460 MPa.

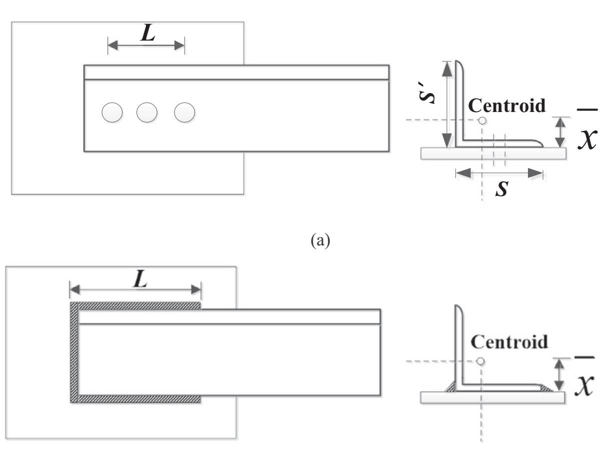

Fig. 2. Definition of connection length and out-of-plane eccentricity: (a) specimens with bolted connections and (b) specimens with welded connections.

Recently, developments and technological advances in metallurgical industry have improved the availability and economic viability of high strength steels (HSSs) with a specified minimum yield stresses equal to or higher than 460 MPa [14]. Research communities have also initiated explorations in behaviour of HSS material [15,16], HSS connections [17–20], components [21] and HSS structures [22,23]. In engineering practice, utilising HSS can achieve significant reductions in cross-section dimensions of components and overall weight of a structure because HSS possesses significantly higher yield and ultimate strengths compared with those of NS, and hence producing more economical and sustainable structures.

In this respect, steel tension members, which are generally controlled by strength criteria, may be fabricated using HSS to satisfy the required load resistance with more efficient section sizes. On the other hand, recent research findings also indicate that HSSs generally possess limited ductility, and the characteristics of the stress-strain curves of HSSs are quite different from those of NSs that show adequate post-yielding strength hardening and deformability, e.g. S275 steel and S355 steel. Typically for S690 steel, although its nominal yield strength could reach 690 MPa, the ultimate strength to yield strength ratio is close to unity, and the ultimate strain is only around 6–8% along with the fracture strain close to 15%. In this context, when using HSS in bolted or welded tension members, premature fracture of the material may occur in the vicinity of the connection before sufficient stress redistribution is achieved in the cross-section. This effect is particularly aggravated if only part of the section is connected in a connection such as a single angle tension member connected to a gusset plate. Hence, due to the reduced ductility of HSS, the shear lag effect on HSS angle tension members is expected to be more significant than that of the counterparts made of NS. Since the existing design rules for quantifying the shear lag effect were developed primarily based on the test results of NS tension members, therefore they may not be adequate for predicting the structural behaviour of HSS tension members. Hence, more experimental and analytical studies are needed to examine the influence of the shear lag on the behaviour and the ultimate tensile capacity of HSS tension members with bolted and welded connections.

Based on the above, an experimental investigation consisted of fourteen HSS and four NS single angles with bolted and welded connections was carried out to examine the shear lag effects on the ultimate tensile capacity of HSS angle tension members. The main parameters were steel grade, connection length and out-of-plane eccentricity. The test results were compared with the predictions by the classical $1-\bar{x}/L$ rule proposed by Munse and Chesson [3,4] to examine its applicability for quantifying the shear lag effect of HSS single angle. Subsequently, detailed finite element (FE) models simulating the structural behaviour of the specimens were established and verified by the test results, and a parametric study was conducted utilising the validated FE models covering a wide range of parameters. Finally, based on the experimental and numerical results, design considerations for quantifying the shear lag effect on the ultimate tensile capacity of HSS tension members were proposed.

2. Test programme

2.1. Test specimens

Eighteen full-scale specimens with bolted and welded single angles of varied steel grades, connection lengths and out-of-plane eccentricities were examined in the test programme. Out of the eighteen