Equal Load Carrying Capacity Design of Butt Joints Based on Plastic Limit Loads

Junli Guo, Zhibo Dong* and Hongyuan Fang
State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China
Email: iamgjl@163.com; `dongzhb@hit.edu.cn; hyfang@hit.edu.cn

Abstract. In order to reduce the weld size of weld joints designed based on equal load carrying capacity (ELCC) further, the shape of under-matching butt joints is designed with the parameter of plastic limit loads. The realization condition of ELCC is that the plastic limit loads of the weld equals to that of the base metal. Through analyzing the tensile/bending load carrying capacity of weld zone, the weld shape was determined, and the method of tensile/bending ELCC design for butt joints is given. The ELCC joints are designed and their elastoplastic finite element analyses are carried out to verify their load carrying capacities. The tensile ELCC joint fractures at the base metal in the mode of overall yield fracture and its load carrying capacity reaches the tensile strength of the base metal. The load carrying capacity, deformability and stiffness of the bending ELCC joint are better than that of the base metal. The results indicate that the joints with acceptable size meet the requirements of ELCC, which is of great significance to the application of ELCC joints.

Keywords. Equal load carrying capacity, plastic limit load, butt joints, design method.

1. Introduction
High strength steel has been widely used in various industrial products due to its good performance, but the load carrying capacity of its welded joints, especially the fatigue property, is lower than that of the parent material, which severely limits the application of high strength steel.

The traditional design concept, methods, and the current standard cannot solve this problem, thus the thought of equal load carrying capacity (ELCC), making the load carrying capacity of under-matching joints \( P^d \) equal to that of the base metal \( P^B \), is put forward. Zhili [1-2] established the ELCC theory of butt joints under tensile through linear elastic finite element analysis. The ELCC theory of butt joints with crack was studied from the perspective of stress intensity factor [3-5]. The ELCC butt joints under bending were designed based on the mechanics of materials [6-7]. The fatigue ELCC theory of butt joints was studied based on nominal stress and fracture mechanics [6-7]. Experimental results showed that all designed joints met the requirement of ELCC, that is, their bearing capacities were equal to that of smooth base material.

The core of ELCC is to increase the weld size to make up for the lack of strength. However, the increase of weld size leads to the increase of welding workload, and blindly increasing weld size may bring other adverse effects. This study, designing ELCC butt joint under tensile/bending based on the plastic limit load, can further reduce the weld size, which will promote the application of ELCC theory and high strength steel in welded structures.
2. The Theory of ELCC
According to the thought of ELCC, the load carrying capacity of the weld seam \( P^W \) should be no lower than \( P^B \): 
\[
P^W \geq P^B
\]  
(1)
When the failure mode of weld joint is static fracture, the load carrying capacity should be calculated by elastic-plastic analysis. But ELCC joints are heterogenic joints with weld reinforcement, the elastic-plastic analysis is very complicated. Instead plastic limit load, widely used in engineering, is far more simple and convenient.

2.1. Realization Condition of Tensile ELCC
If the weld seam and the base metal yield simultaneously, \( P^l \) is not less than the yield strength of the base metal \( (\sigma_s^B) \), and the yielding-to-tensile ratio of weld metal is lower than that of the base metal, \( P^l \) can reach the tensile strength of the base metal \( (\sigma_s^B) \). Thus realization condition of ELCC is that the plastic limit load of weld seam equal to that of base metal.

2.2. Realization Condition of Bending ELCC
According to the elastic-plastic bending theory, the elastic-plastic limit bending moment is 
\[
M = \frac{1}{3} \sigma_s b l^2 \left[ 3 - k^2 + \frac{E_t}{E} (k^2 - 3 + \frac{2}{k}) \right]
\]  
(2)
where \( \sigma_s \) is the yield strength; \( b \) is the width; \( l \) is half of the thickness; \( k \) is the ratio of yield strain to fracture strain; \( E_t \) is hardening modulus; \( E \) is elasticity modulus.
If \( E_t = 0 \) and \( k = 0 \), equation (2) is reduced to the plastic ultimate bending moment:
\[
M_p = \sigma_s b l^2
\]  
(3)
Rewrite equation (2) with equation (3):
\[
M = M_p \left[ 1 - \frac{1}{3} k^2 + \frac{1}{3} \frac{E_t}{E} (k^2 - 3 + \frac{2}{k}) \right]
\]  
(4)
According to the property of the derivative of (4), \( M \) decreases as \( k \) increases. At a certain \( M_p \), the \( M \) of weld metal, with better plasticity, is higher than that of base metal. Thus \( M_p \) can be used in ELCC design, and the realization condition is that the \( M_p \) of weld seam equal to that of base metal.

3. Calculation of Load Carrying Capacity
3.1. Under Tensile Load
Under tensile load, the yield in the weld seam of under-matching butt joints may occur on normal section (the normal stress reaches the yield strength), or on oblique section (the shear stress reaches the shear yield strength).

The plastic limit load of weld seam on normal section is 
\[
P^W = 2 l r^W / \sigma_s^W + 2 l r^B / \sigma_s^B
\]  
(5)
where \( r^W \) is half of thickness of the weld metal on the section; \( l \) is the length; \( \sigma_s^W \) is the yield strength of weld metal; \( r^B \) is half of the base metal’s thickness on the section; \( \sigma_s^B \) is the yield strength of base metal.

The plastic limit load of weld seam on oblique section is 
\[
P^W = 2 l^W / t^W \sin 2\theta / \sigma_s^W
\]  
(6)
where \( t^W \) is the shear yield strength of weld metal; \( \theta \) is the angle between oblique section and normal section.

The plastic limit load of base metal is
3.2. Under Bending Load
Under bending load, the $M_p$ of weld seam is

$$M_p^B = \sigma_s W_l (t_l^W)^2 + (\sigma_s^B - \sigma_s W) l_l^B$$

(8)

The $M_p$ of base metal is

$$M_p^B = \sigma_s^B l_l^2$$

(9)

4. Shape Design of ELCC

4.1. Tensile ELCC
Substituting equations (5)/(6) and (7) into (1), the weld metal’s thickness on the normal/oblique section is determined:

$$t^W \geq (1-\mu^B) \frac{\sigma_s^B}{\sigma_s^W}$$

(10)

$$t^W \geq t \sin 2\theta^* \frac{\sigma_s^B}{\sigma_s^W}$$

(11)

As shown in figure 1, for a double Y butt-welded joint, the weld profile is curve 1+2 according to equation (10), or curve 3 according to equation (11). Both equations (10) and (11) must be satisfied, the final profile must be the envelope curve of curve 1+2 and curve 3, for example, curve 4. The geometric optimization of weld toe is also needed to eliminate stress concentration, for example, curve 5, an arc with a radius more than 16t. Thus, the shape scheme of tensile ELCC is curve 4+5, the geometric parameters include the thickness of weld reinforcement ($h$), half of the width of $h(w)$, the radius of arc in weld toe.

$$h = t \left(1 - \mu^W \right)$$

(12)

$$w = \frac{t}{\mu} \tan \theta_0$$

(13)

$$r = 8t$$

(14)

where $\mu = \frac{\sigma_s^W}{\sigma_s^B}$; $\theta_0$ is half of $\angle AOB$.

4.2. Bending ELCC
Substituting equations (8) and (9) into (1), the weld metal’s thickness is determined:

$$t^W \geq \sqrt{\frac{1}{\mu^2} \frac{1-\mu}{\mu-1} \left(l_l^B\right)^2}$$

(15)

According to equation (15), the weld profile of a double Y butt-welded joint is curve 6+7, as shown in figure 2, where curve 7 is an arc. Thus, the geometric parameters are calculated by the following equation:

$$h = r \left(\sqrt{\frac{1}{\mu^2} - 1}\right)$$

(16)

$$w = c$$

(17)

where $c$ is the groove gap.
5. Elastoplastic Finite Element Analysis

The mechanical properties of the materials are shown in table 1, \( \theta_0 = 45^\circ \), \( c = 1 \text{ mm} \), \( t = 5 \text{ mm} \), the root face is 2 mm. For tensile ELCC joint, \( h = 5 \text{ mm} \), \( w = 10 \text{ mm} \), \( r = 80 \text{ mm} \). For bending ELCC joint, \( h = 4.15 \text{ mm} \), \( w = 1 \text{ mm} \), \( r = 80 \text{ mm} \), and the indenter diameter is 10 mm, the roller diameter is 30 mm, the roller spacing is 50 mm.

| Materials    | Yield strength (MPa) | Tensile strength (MPa) | Elongation |
|--------------|----------------------|------------------------|------------|
| Base metal   | 755                  | 810                    | 14%        |
| Weld metal   | 378                  | 484                    | 35%        |

Table 1. The mechanical properties of the materials.

The elastic-plastic finite element models are established to analyse the tensile/bending behaviours of ELCC joints. The material properties are defined based on true stress-strain relationship when modelling as well as in cloud diagram, while based on engineering stress-strain relationship in line diagram.

5.1. Tensile ELCC Joint

The stress change in weld root of tensile ELCC joint with the increase of applied load is shown in figure 3. The tensile process can be divided into three stages according to whether the weld root and base metal yield.

On stage 1, both the weld root and the base metal have not yielded. The distribution of Equivalent Von Mises stress of tensile ELCC joint is shown in figure 4, while the applied load is 200 MPa. The theoretical stress concentration coefficient at the weld toe is about 1.

On stage 2, before the applied load reaches the yield strength of base metal, the weld root gradually yields, but the base metal does not. The increase in Equivalent Von Mises stress of the weld root has slowed down because of yielding, but the Maximum Principal stress still increases rapidly because the plastic deformation is restricted by the surrounding unyielding base metal. In order to observe the damage degree of two different materials visually, the ratio of Equivalent Von Mises stress to yield strength \((R)\), but not stress, is used in figure 5, while the applied load is 700 MPa.

On stage 3, before the applied load reaches the tensile strength of base metal, both the weld root and the base metal have yielded. The stresses increase more rapidly because the base metal far away from the weld has yielded and the weld root is still restricted by the surrounding unyielding base metal. However, the weld root will not fracture before the base metal, because its Maximum Principal stress will not reach the tensile strength. The distribution of \( R \), with a 200 MPa load, is shown in figure 6. The \( R \) of weld toe increases slower and is finally smaller than that of weld root, because the weld toe is protected by nearby base metal.

Tensile ELCC joint fractures at the base metal in overall yield mode, its load carrying capacity equals to that of the base metal.
5.2. Bending ELCC Joint

Similarly, the bending process can be divided into three stages.

On stage 1, as shown in figure 7, the maximum X direction stress occurs at the bottom of the groove section, instead of the central section with the maximum bending moment. This is mainly because the elastic ultimate bending moment of the central section is larger than that of the groove section, even though their plastic ultimate bending moments are the same.

On stage 2, as shown in figure 8, the high stress area transfers to the adjacent base material.

On stage 3, as shown in figures 9a and 9b, the position of the high stress area is almost unchanged. The weld metal near the root face is the dangerous position of the joint, because its $R$ is higher than that of the base metal and the weld toe.

The bending process of base material is also simulated numerically. As shown in figure 10, the maximum applied load and maximum deflection of bending ELCC joint are bigger than that of base metal. At bending force that makes the base metal material yields or fractures, the deflection of the joint is smaller. All these indicate that the load carrying capacity, deformability and stiffness of bending ELCC joint are better.
6. Conclusions
The realization condition of ELCC is that the plastic limit loads of the weld equals to that of the base metal. The method of tensile/bending ELCC design for butt joints is given. The elastoplastic finite element analyses of tensile and bending process indicate that the designed joints with acceptable size meet the requirements of ELCC. The weld root and toe of the tensile ELCC joint will not fail before the base metal fails. The joint fractures at the base metal in the mode of overall yield fracture and its load carrying capacity reaches the tensile strength of the base metal. The load carrying capacity, deformability and stiffness of the bending ELCC joint are better than that of the base metal.
Acknowledgments
The authors thank the Natural Science Foundation of China (No. 51875131).

Reference
[1] Zhili Z, Jianguo Y, Hongyuan F and Fangbin W 2008 Transactions of the China Welding Institution 29 (10) 93-96
[2] Zhili Z, Hongyuan F, Jianguo Y and Jichao H 2008 Journal of Mechanical Engineering 46 1075-80
[3] Tao W, Jianguo Y, Xuesong L, Zhibo D and Hongyuan F 2012 Science and Technology of Welding & Joining 17 (3) 191-195
[4] Tao W, Jianguo Y, Xuesong L, Zhibo D and Hongyuan F 2012 Materials and Design 35 72-79
[5] Tao W, Jianguo Y, Xuesong L, Zhibo D and Hongyuan F 2012 Materials and Design 36 748-756
[6] Jiajie W, Zhibo D, Xuesong L, Hongyuan F and Tie G 2012 Transactions of the China Welding Institution 33 (8) 37-40
[7] Jiajie W, Hongyuan F, Jingqiang Z, Zhibo D and Xuesong L 2012 Transactions of the China Welding Institution 37 (7) 53-56
[8] Xue W, Ping W, Zhibo D, Yong Land Hongyuan F 2018 Metals 8 11
[9] Xue W, Ping W, Zhibo D, Yong Land Hongyuan F 2019 Applied Sciences 9 17