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The rational use of welds in steel structures

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Abstract: The incorrect design or execution of joints contributes to higher costs through material, time and/or energy losses. Choosing the right type of joint, type of weld or manufacturing technology may not only significantly reduce the expenditure, but also considerably increase the design resistance of the joint itself. The paper shows how to use butt and fillet welds more economically.

Keywords: fillet weld, butt weld, deep-penetration welding process

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Introduction

The rules for shaping welded structures are included in many textbooks and articles, e.g. (Kudła & Wojsyk, 2019; Skarbiński & Skarbiński, 1982). Welding techniques are constantly developing and new welding methods are introduced. This includes low-energy and deep-penetrating methods (Srinivasan et al., 2022) or laser methods (Katayama, 2013).

Welded joints in steel structures usually include butt or fillet welds. Edge flanged, edge joints or plug and slot welds in building structures are used very rarely.

The dominant share of fillet welds results from the ease of their execution, which consists of:

– no need to bevel the parts to be joined,
– predominant share of profiles and sheets mutually perpendicular,
– possible lower qualifications of welders (PN-EN ISO 9606-1).

Unfortunately, fillet welds in steel structures are often oversized. When looking at the solutions for welded structures, one can get the impression that the fillet welds

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used are too thick and are not designed individually to take into account the actual needs of the project.

Designers do not differentiate between the load-bearing and joint functions of the welds, often assuming their thicknesses with the maximum permissible value. They usually ignore the recommendation that the loads should be transfer by construction materials and not by the welds themselves. In this way, they introduce an unnecessary additional amount of filler metal, while increasing the stress and deformation state in the structure.

Due to the quality of the joint, it is increasingly recommended to use butt welds. The benefits of replacing fillet welds with butt welds or butt-fillet welds can be deduced from analyzing the features of these welds (Kudła et al., 2020).

Butt welds almost always have the thickness of the joined materials or, except for butt welds with incomplete penetration allowed by Eurocode 3 (PN-EN 1993-1-8). Their cross-section is defined by the thickness of the parts to be joined. Its reduction is possible through the use of a high-density arc welding methods. The length of the butt weld is always equal to the length of the joined elements. As a result, they do not increase the volume of the structure.

In a fillet weld (Fig. 1a), there is always the root notch. Cracks usually start at the root of the weld (Fig. 2a). Therefore, fillet welds are intended rather for joining elements that are less loaded and not subjected to vibration loads. Both in the case of single- and double-sided welds, there is a limited possibility of controlling the existence and quality of penetration with the use of non-destructive methods. These problems do not occur in butt welds (or butt-fillet welds) with full penetration (Fig. 1b) – a root of the weld with high mechanical parameters can be obtained in this case. Moreover, the quality of butt welds can be easily inspected using radiographic or ultrasonic methods.

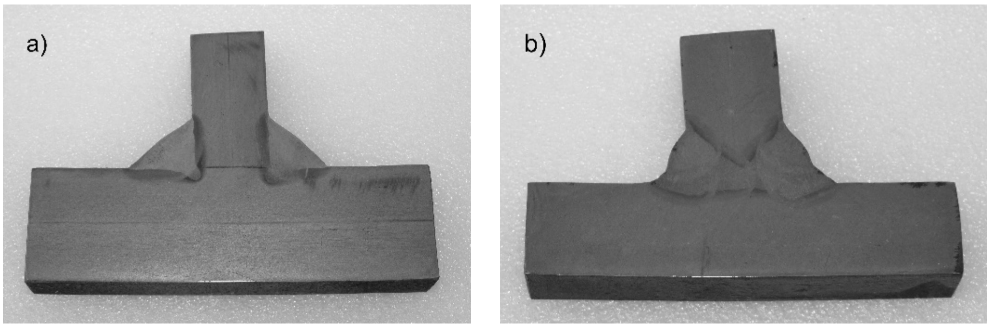

Fig. 1. T-joint: a) fillet welds, b) double-bevel butt welds **K** (*own research*)

Tensile tests of cross joints made with butt welds always result in breaking the parent material (Fig. 2b) without damaging the weld itself.

Therefore, butt welds should be used wherever it is possible and the welds are load-bearing. They are designed to carry the main loads and their load capacity is proportional to the cross-section of the connected elements.

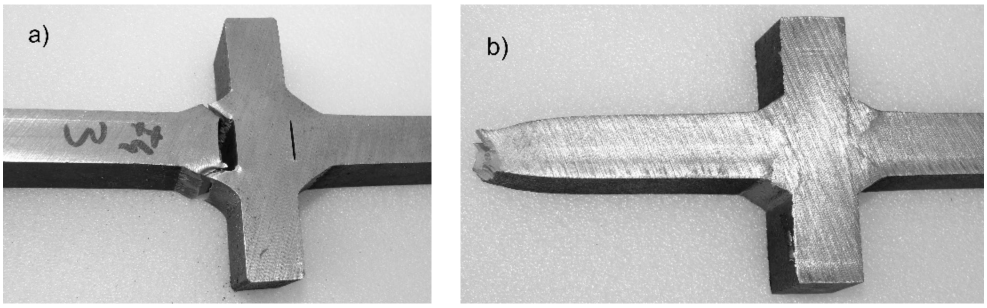

Fig. 2. Tensile test of cross joints: a) with fillet welds, b) with butt welds (*own research*)

1. Shaping butt welds

Butt welds, despite their many advantages, also have some disadvantages. Correct execution of butt welds, especially those with large thicknesses, is not an easy task. Above a certain thickness, characteristic of a particular welding method, the joints are assembled from bevelled materials. The necessity to bevel the welded edges increases the cost of making the weld. It is a time-consuming operation and simultaneously increases the amount of weld metal necessary to fill the joint groove. Currently, the edge preparation process is easier, especially when using automatic cutting devices, e.g. laser or plasma devices. Thanks to them, bevelling the edges is quick and in many cases allows the reduction of material waste.

Butt welds can have different cross-sectional shapes, but should have a flat or slightly convex face. Double-sided welds are the most advantageous (Fig. 3a), as it is easier to obtain the correct root fusion and the volume of the weld is smaller than in the case of single-sided welds. Correct penetration can also be obtained for single-sided welds with backroot (Ferenc & Ferenc, 2022). However, this requires access from both sides of the weld, as in the case of double-sided welds.

Fig. 3. Butt welds: a) double-**V** (**X**), b) **V**, c) single-**U** (*own research*)

The shape of the butt weld groove affects its volume. Among the welds presented in Figure 3, the double-**V** weld requires the least amount of weld metal deposit to make (Fig. 3a) and the most is needed for the **V** weld (Fig. 3b). The ratio of the weld volume **X** : **U** : **V** is 1 : 1.44 : 1:55. The smallest volume of the weld can be obtained for welds without edge bevelling, i.e. plain butt welds (type **I**).

2. Shaping fillet welds

Contrary to butt welds, fillet welds increase the volume of the structure, but do not require bevelling of the welded materials. Properly designed and made fillet welds are not as thick as the joined materials. Their thickness *a* is in the range:

$$a > 0.2\, t_{max}$$
$$a \leq 0.7\, t_{min} \text{ – for single-sided welds}$$
$$a \leq 0.5\, t_{min} \text{ – for double-sided welds}$$

where:
a – the theoretical throat thickness,
t_{max}/t_{min} – maximum/minimum thickness of joined materials.

The effective length of the weld is not strictly related to the length of the joined elements. Intermittent welds can also be made. The length of single sections of fillet welds is between 6*a* and 150*a*, but not less than 30 mm. Above 150*a* or 1.7 m, the welds have lower effective strength.

From the economic point of view, the use of fillet welds should be limited to those with a joint function and of small thickness. As the strength of a fillet weld increases in proportion to the thickness *a*, and its volume $V = a^2 \cdot l$ is proportional to the square of the thickness (Fig. 4), it is pointless to use thick welds. In Figure 4, the symbol $A = a \cdot l$ denotes the area of the longitudinal section of the weld, where l is its effective length.

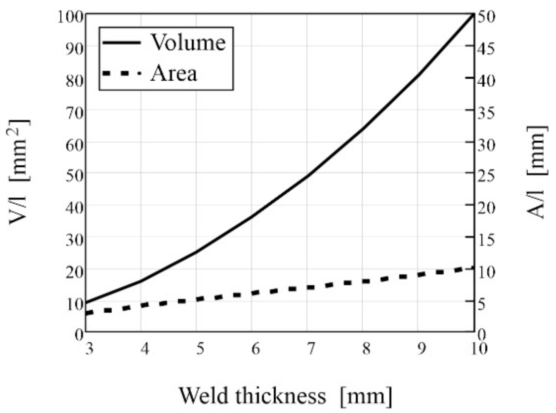

Fig. 4. Differentiated increase in the strength (---) and the volume (–) of a symmetrical flat-faced fillet weld (*own research*)

Additionally, increasing the thickness of fillet welds contributes to introducing stress concentration, and at the same time, by moving the centre of gravity of the weld metal away from the neutral axis of the joint, it increases the welding deformation of the joined elements. The convex face of the weld is always disadvantageous for reasons of both strength and economy.

2.1. Material losses due to the convexity of the face of a fillet weld

The most economical fillet weld is a weld with a flat face (Fig. 5a). A weld with a concave face has a slightly larger cross-sectional area for the same thickness (Fig. 5c). However, the use of such welds is justified, especially in joints subjected to variable loads, as there is a smooth transition from the face to the base material. In practice, fillet welds with a convex face are the most common (Fig. 5b), and are the easiest to make, but they are not recommended for two reasons. Firstly, a geometric notch is formed along the edge of the face, which significantly reduces the fatigue strength of the weld.

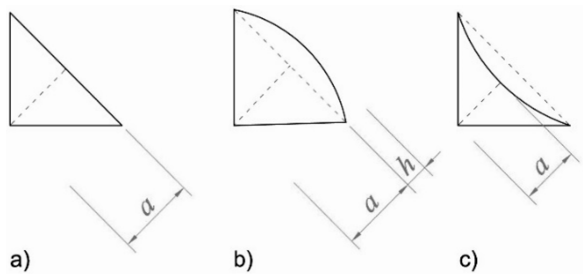

Fig. 5. Cross-section of a symmetrical fillet weld: a) with a flat face, b) with a convex face, c) with a concave face (*own research*)

The second reason is the loss of material on the useless part of the weld, which depends on the height of convexity of the weld h (Fig. 5b). The method of determining the thickness of an asymmetric weld ($\alpha \neq 45°$) is shown in Figure 6. When the angle $\alpha = 45°$, the weld is symmetrical ($a_{as} = a$). The graph (Fig. 8) shows material losses depending on the h/a_{as} ratio. For a symmetrical weld ($\alpha = 45°$) with the ratio $h/a_{as} = h/a = 0.5$, the useless volume of the weld is almost 70%.

2.2. Material losses due to asymmetry of a fillet weld

Although Eurocode 3 (PN-EN 1993-1-8) allows for the production of asymmetric fillet welds (Fig. 6), their use is not cost-effective.

Maintaining the same thickness of the asymmetrical joint as the symmetrical joint $a_{as} = a$ increases its volume (Fig. 7a). The greater the asymmetry of the weld (smaller angle α), the lower its load capacity compared to the symmetrical weld ($\alpha = 45°$). On the other hand, in order to keep the material consumption at the level of the symmetrical weld, the thickness of the asymmetric weld decreases with increasing asymmetry (Fig. 7b).

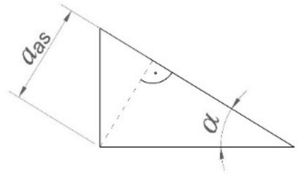

Fig. 6. Cross-section of an asymmetrical fillet weld (*own research*)

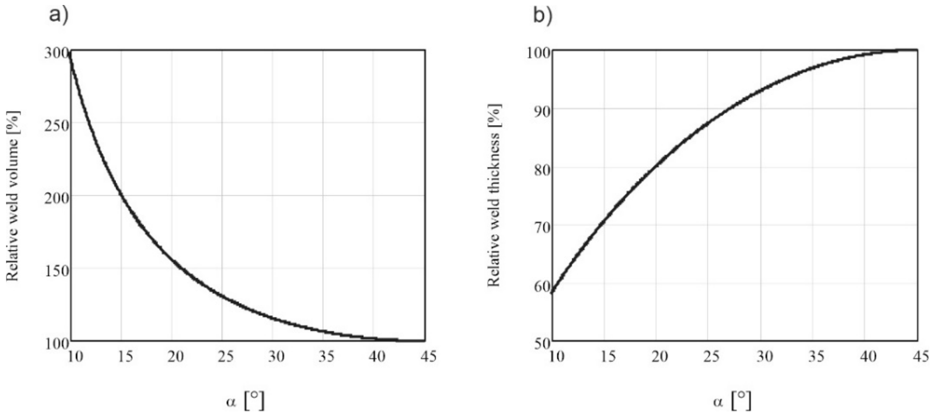

Fig. 7. The effect of asymmetry of a fillet weld with a flat face on: a) the volume of the weld while maintaining its thickness, b) the thickness of the weld while maintaining its volume (*own research*)

Even greater material losses occur in the case of asymmetric welds with a convexity. The diagram (Fig. 8) shows for the selected angles *α* what is the relative useless volume of the weld in comparison to the volume of a symmetric weld with a flat face. In the extreme case presented in this diagram ($\alpha = 15°$ at the ratio $h/a_{as} = 0.5$), the useless volume of the weld is $V_{useless} = 235\%$.

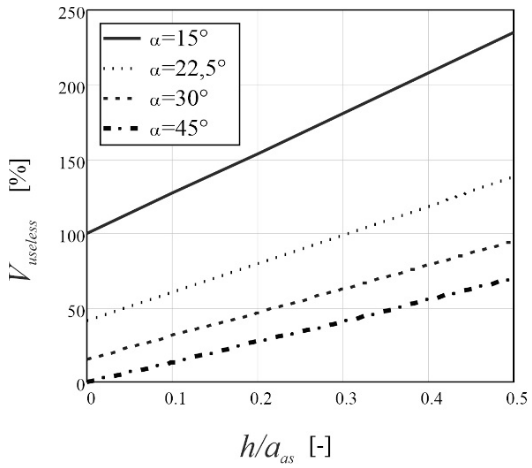

Fig. 8. Useless volume ($V_{useless}$) of an asymmetrical fillet weld depending on the ratio h/a_{as} and the angle *α* (*own research*)

Even for slight asymmetry ($\alpha = 30°$), the average riser ($h/a_{as} = 0.4$) increases the useless volume of the weld from 15.5% (flat weld) to 78.5%.

2.3. The use of deep-penetrating welding methods

Fillet welds can be enlarged inwards. The standard (PN-EN 1993-1-8) allows for the taking into account of increased penetration, provided that this fact is documented and ongoing technological supervision is conducted. Figure 9a shows a cross joint made with fillet welds using a deep-penetrating welding method – Lincoln Electric RapidArc. With a repeatable, controlled depth of penetration, instead of theoretical thickness a, the thickness of the fillet weld can be assumed, taking into account the deep penetration a_{DP} (Fig. 9b).

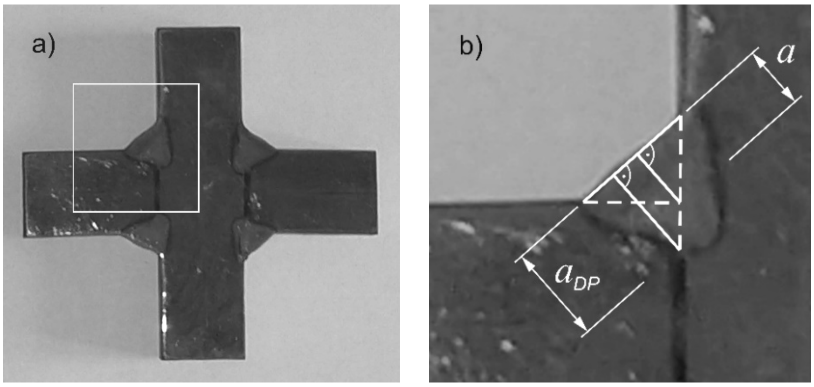

Fig. 9. Cross joint: a) view, b) detail; a – fillet weld thickness; a_{DP} – fillet weld thickness taking into account deep penetration (*own research*)

The increase in the thickness of a fillet weld by using deep penetration usually amounts to 30-40%. For the selected weld presented in Figure 9, the design thickness of the weld may be assumed to be about 50% greater than the theoretical one ($a_{DP} \cong 1,5 \cdot a$).

Conclusions

Proper shaping of welds not only contributes to saving welding materials, but also to increasing the quality of welded joints. This leads to the reduction of residual stresses, stress concentration, welding deformations, increasing the load-bearing capacity of the welds, and especially the fatigue strength of the structure. Using the correct welding method results in welds of the desired shape and minimum volume. This is especially important in the case of fillet welds, as any unintentional deviation from the symmetry of the weld and the flat face adversely affects their quality.

Obtaining a good weld is facilitated by the automation and robotization of the welding process, including the preparation of materials for welding. Some welding methods, such as LE RapidArc, are dedicated to automatic welding. They not only ensure a higher quality of welds and greater economy, but also high welding speed. Laser welding is particularly effective.

In addition, the use of low-energy welding methods, such as ColdArc, Cold Metal Transfer or Surface Tension Transfer, especially for joining sheets of small thickness, result in high-quality welds and reduce energy consumption for their production.

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