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Technical and economic aspects of load-bearing welded joints in reinforcing steel

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Abstract: Reinforcing bars are usually produced with a length of 12 m (max. 18 m). In some reinforced concrete structures, it is necessary to use full-length continuous bars. However, it is more convenient to work with shorter rods. For these reasons, it is often necessary to connect the bars on site, e.g. when repairing RC beams or columns. This article presents welded joints that connect rebars in the longitudinal direction to ensure force transmission: joints with fillet welds and butt welds. The advantages and disadvantages of the various types of reinforcement bar welded connections are shown, allowing a decision to be made on which type of connection to use in a particular case. Analyzing the different types of connections and their technical aspects makes it easier to determine which one is more economical. Alternative butt joints and mechanical splices were also presented.

Keywords: welded joint, reinforcing steel, butt weld, fillet weld

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Introduction

The joining of reinforcing bars for joints in concrete elements is usually carried out with tie wire (Dabiri et al., 2022; Issa & Nasr, 2006; Zhou el al., 2022). Sometimes, there is a need for welded joints in order to increase the stiffness of the reinforcement cage or to make a load-bearing joint. The guidelines for welding reinforcing steel for load-bearing joints are contained in (PN-EN ISO 17660-1:2008), while for non-load-bearing joints they are contained in (PN-EN ISO 17660-2:2008). These standards apply to welding both in the production workshop and on site.

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They specify requirements for the design and execution of welded joints, materials, welding personnel, quality, inspection and testing.

The most common load-bearing welded joints of reinforcing bars are made as longitudinal joints, which extend the bars and transfer normal forces. These joints can be made as lap, strap or butt joints (Dabiri et al., 2022; Moustafa et al., 2016; Rodrigues et al., 2018). These joints are the subject of this study. Cross-welded joints (single or double-weld) and joints between reinforcing steel bars and other steel elements are also made (Caprili et al., 2021; Wang et al., 2022a). The latter group of joints includes side-lap weld joints and transverse end-plate joints.

General technical requirements for welding steel structures are included in the standard (PN-EN 1090-2:2018-09), types of joint preparation are presented in the standard (PN-EN ISO 9692-1:2014-02) and principles of safe and economical design and assembly of welded joints can be found in many articles, including: (Kubicki, 2021; 2022; Kubicki & Wojsyk, 2022; Lienert et al., 2011; Mazur et al., 2014; Radkovic et al., 2017).

An alternative to welded joints are mechanical connections. There are many types of bar connectors, including: swaged, threaded, headed bar and shear screw couplers (Bompa & Elghazouli, 2018; 2019; Dabiri et al., 2022; Kheyroddin & Dabiri, 2020; Tazarv & Saiidi, 2016; Tazarv et al., 2023). A special type of mechanical connection is grouted sleeve couplers (Hua et al., 2014; Lu et al., 2019; Wang et al., 2022; Zheng et al., 2023).

1. Load-bearing welded joints of reinforcing steel

Reinforcing bars can be joined in the longitudinal direction with fillet or butt welds. Joints using welding processes 111, 114, 135 or 136 were analyzed (processes 24, 25, 42 and 47 were also mentioned). The choice of joint type and welding process depends on many factors. Each type of joint has certain advantages and disadvantages.

1.1. Joints with fillet welds

Traditional lap joints have certain advantages, e.g. they can be used to connect bars made of different materials (Zhou el al., 2022), but they are increasingly being replaced by welded lap joints. According to (Issa & Nasr, 2006), the cost of lap joints is lower than that of welded joints of reinforcing bars with a diameter $d \leq 12$ mm. Fillet welds are the easiest type of weld to perform and do not require special skills from the welder. They are used in the two types of rebar connections recommended in the standard (PN-EN ISO 17660-1:2008).

The simplest to make is a single-sided lap joint with intermittent welds (Fig. 1). The effective throat thickness of these welds must be $a \geq 0.3d$ and can be taken as $a \approx 0.5w$. For double-sided welds, the joint length can be reduced from $4d$ to $2.5d$. Recommended joint lengths and thicknesses ensure the full load-bearing capacity of the bar.

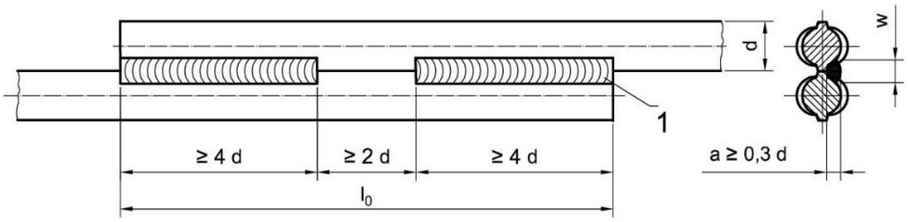

Fig. 1. Lap joint proposed by the standard PN-EN ISO 17660-1:2008 (Key: 1 – weld, a – throat thickness, d – nominal diameter of the thinner of the two welded bars, l_0 – overall lap length, w – weld width)

Non-European standards may recommend other solutions. For example, the standard (IS 9417:2018) reduces the throat thickness of the weld to $a \approx 0.2d$ at the same time extending it on each side of the joint to at least $5d$, regardless of whether the weld is single or double-sided. At the same time, the standard (IS 456:2000) allows the use of lap joints for larger diameters than recommended in the standard (PN-EN ISO 17660-1:2008) and also mechanical connections of reinforcement bars. In contrast, the standard (AWS D1.4/D1.4M:2011) leaves the throat thickness of the weld but shortens it on each side of the joint to at least $2d$.

Unfortunately, the lap joint transmits force eccentrically and this is its main disadvantage. While in reinforced concrete slabs the lap joint is not a problem because of the large bar spacing, in beams and columns it can make it difficult or in extreme cases even impossible to form a proper concrete cover. The joint itself will always be non-axial (asymmetric force flow). In order to maintain the alignment of the connected bars outside the joint, one of the bars must be deflected accordingly. With significant tensile forces the bar will tend to straighten. With compression bars connected in this way, buckling may occur at lower forces. Compacted stirrups must be used in the area of this joint to prevent damage to the concrete cover of the bars.

Another disadvantage of such a joint is that the cross-sectional area of the bars at the joint is doubled. In column or beam elements with densely spaced reinforcing bars, it may not be possible to concrete them correctly. In addition, such a joint requires more steel due to the overlap length l_0. The more joints, e.g. in the columns of multi-storey buildings, the greater the steel consumption (increase in material, electricity demand and transport costs).

Lack of axial connection can be eliminated by using a strap joint (Fig. 2).

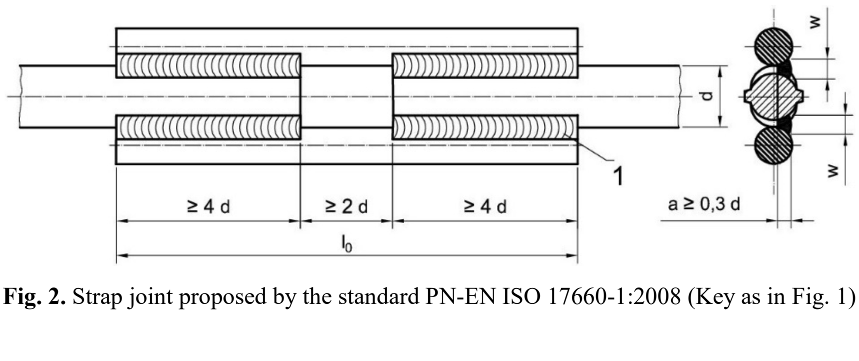

Fig. 2. Strap joint proposed by the standard PN-EN ISO 17660-1:2008 (Key as in Fig. 1)

It is beneficial when the bars and the straps have the same mechanical properties, then the cross-sectional area of the two straps is equal to or greater than the cross--sectional area of the bars to be joined. However, when the mechanical properties of the materials of the bars and the straps are not the same, the cross-sectional area of the straps is adapted on the basis of the ratio of their individual nominal yield stresses. Unfortunately, in this case, the amount of material is also increased, although by using straps with a higher yield strength than the joined bars, the cross--sectional area of the reinforcement in the joint can be slightly reduced.

Significant lengths of fillet welds in lap and strap joints also increase the need for electricity and introduce a great deal of heat into the work pieces, which can lead to adverse changes in the properties of the materials being joined.

1.2. Butt joints

The use of butt joints eliminates most of the disadvantages of lap and strap joints. It is assumed that a properly made butt joint transfers the full load between the connected bars.

The implementation of butt joints requires higher level of expertise from the welding personnel. This is due to the need to properly prepare the ends of the joined bars and the more difficult formation of the weld beads. Examples of the butt joints recommended in (PN-EN ISO 17660-1) are shown in Figure 3. In addition, a single V butt weld (Fig. 3b) can be made with a backing, allowing the groove angle to be reduced to 45° and resulting in less weld metal. For vertical bars, the joint shown in Figure 3c is suitable, with the top bar being beveled. A 3D view of the beveled ends of the bar is shown in Figure 5.

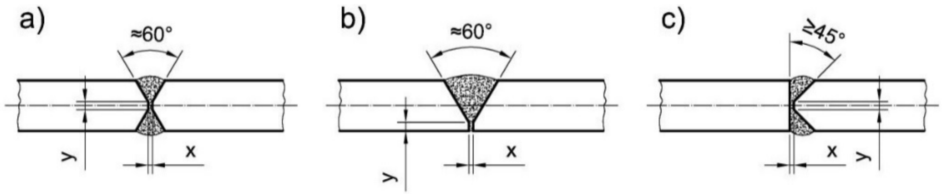

Fig. 3. Examples of butt joints proposed by the standard PN-EN ISO 17660-1:2008: a) double V butt weld; b) single V butt weld; c) double bevel butt weld (Key: x – root gap, y – depth of root face)

Standard (PN-EN ISO 17660-1) allows for other joint configurations. Examples of joints are shown in Figure 4.

The butt joints shown in Figure 4a and 4c, which require the preparation of a beveled joint in the form of frustum of cone (Fig. 5c), are difficult to realize and do not offer significant advantages. Only forming a frustum of cone by a surfacing process can be justified. However, you then get a square butt joint. In this case, the advantage is that there is no need to bevel the ends of the bars, but more weld metal is needed.

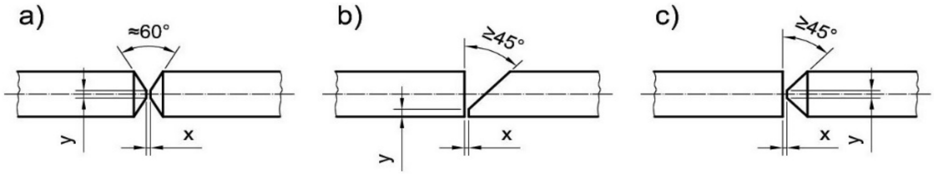

Fig. 4. Examples for preparation of butt joints other than those proposed by the standard PN- EN ISO 17660-1:2008: a) double *V* butt weld – frustum of cone; b) single ½*V* butt weld; c) double bevel butt weld – frustum of cone (Key as in Fig. 3)

This type of joint can also be obtained by using the hot extrusion gas pressure welding method (Dabiri & Kheyroddin, 2021; Kheyroddin & Dabiri, 2020), whereby this type of welding does not require additional filler material to join two bars together. A rebar gas pressure welding device is used to make such a joint (*Rebar Gas*, 2023; *Gas Pressure*, 2023). This type of weld can also be achieved by other methods such as: upset welding or flash welding (Matteson, 2011; Singh & Arora, 2013) or friction welding (the last method only in the workshop). Upset welding has many advantages compared to typical fusion welding processes, including: high speed, basic equipment, only three primary control variables (current, force and time), fewer welding defects and less heat-input zone.

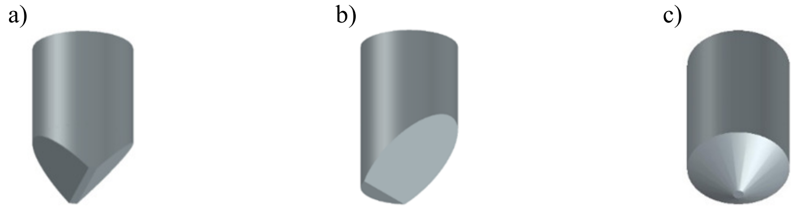

Fig. 5. Beveling of butt joints (*own research*)

In other cases, the prepared joint is beveled. The joint preparation should be carried out by grinding or flame cutting. If access to the connected bars of the RC column is only on one side, the joint shown in Figures 4b and 5b is convenient. Special attention should be paid to proper design and execution of depth of root face.

2. Economic analysis of welded joints

The use of butt joints for reinforcing bars is more economical because longer bars are used in lap joints and additional bar lengths are used in strap joints, particularly in projects with large-diameter bars (Dabiri et al., 2022; Moustafa et al., 2016).

The analysis of welded joints was carried out in terms of weld-metal consumption. It was noticed that in the types of welded joints adopted in the standard (PN-EN ISO 17660-1) the minimum volume of weld metal in lap and strap joints depends on the smaller diameter of the joined rods. The volume of weld metal in butt joints also depends on the diameter of the rods. This makes it easy to determine how much more weld metal is needed to make a fillet-weld joint compared to a butt-weld joint. A significant gain with butt welds is the reduced consumption of weld metal, which involves a reduction in the cost of material. Table 1 shows the percentage increase in the amount of weld metal in lap and strap joints compared to butt joints. The calculations assumed the minimum theoretical weld thicknesses for both butt and fillet welds.

The actual cross-section of the butt weld is slightly larger due to the reinforcement of the weld bead. When welding rods with fillet welds, any reinforcement of the weld bead is compensated by the shape of the groove.

Table 1. Increasing the amount of weld metal needed to make a lap and strap joint compared to different types of butt joints (*own research*)

Butt welds \ Fillet welds		Lap joints		Strap joints	
		single-sided weld	double-sided weld	single-sided weld	double-sided weld
	Volume of weld	$0.72\,d^3$	$0.9\,d^3$	$1.8\,d^3$	$2.25\,d^3$
Double V butt weld Fig. 3a	$0.19245\,d^3$	374%	467%	935%	1169%
Single V butt weld Fig. 3b	$\frac{\pi\sqrt{3}}{12}d^3$	158%	198%	397%	496%
Double bevel butt weld Fig. 3c	$\frac{1}{6}d^3$	432%	540%	1080%	1350%
Double V butt weld (frustum of cone) Fig. 4a	$\frac{\pi\sqrt{3}}{18}d^3$	238%	297%	595%	744%
Double bevel butt weld (frustum of cone) Fig. 4c	$\frac{\pi}{12}d^3$	275%	343%	687%	859%
Single bevel butt weld Fig. 4b	$\frac{\pi}{8}d^3$	183%	229%	458%	573%

The least economical, due to the amount of weld metal required, are double-sided strap joints, despite of the shorter weld lengths than in lap joints. Replacing these joints with butt joints shown in Figures 3a or 3c would provide the greatest benefits. On the other hand, the smallest material gains are with single V butt welds (Fig. 3b), even though their processing is the easiest.

Conclusions

Lap and strap joints bearing reinforcing steel are easier to do and are therefore more often made on site than butt joints. However, the cost of making them is higher due to the greater consumption of both base material (lap or strap) and weld metal. An additional disadvantage of the lap joint is the non-axial transfer of forces between the connected bars. Moreover, such joints cannot always be used due to the lack of sufficient space to properly cover the reinforcing bars with concrete.

Butt joints are more difficult to make and therefore require more skill from the welder than joints using fillet welds. However, they have many advantages. Such connections take up less space, require much less materials, have a load-bearing capacity at least as high as the weaker of the connected bars and forces are transmitted axially. The need to prepare a butt joint can be eliminated by using a square butt joint made using a hot extrusion gas pressure welding process, upset welding process or flash welding process.

Determining the exact economic benefits of replacing lap or strap joints with butt welds is only possible for a specific project. These benefits depend on the size of the project, the number of connections, rod diameters, the adopted welding method, the price of steel rods, welding materials, as well as the costs of preparing butt joints, transport and electricity. The adopted criterion for comparing the volume of weld metal for various joints shows the percentage gains for different cases.

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