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Welded Connections in Structural Engineering: A Comparative Study of Design Standards

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Abstract

This paper comprehensively reviews analytical approaches for designing welded connections based on established design standards, including European, US, and Indian standards. The study emphasizes the behaviour of fillet welds under various load directions, demonstrating that their strength depends significantly on the orientation of the applied forces. Through detailed analysis of design guidelines and independent research, this review highlights the directional and mean stress methods in European standards, the Load and Resistance Factor Design (LRFD) and Allowable Stress Design (ASD) in US standards and Indian standards. The findings offer a comparative perspective on welded connections' load-bearing capacity and resistance factors, providing valuable insights such as guidance on selecting standards based on loading conditions and material strength considerations for safer and cost-effective welded connections.

Keywords: *Fillet welds, Filler metal, Base metal, Load bearing capacity, weld direction*

1. Introduction

Welding is the process of assembling two or more metallic parts by fusing them and filling them in with molten metal from the electrode (Bernuzzi and Cordova, 2016). Structural integrity is one of the important aspects in many industrial sectors where welding is a primary technique for connection (Ghimire *et al.*, 2024; Ghimire *et al*., 2024). Many steel industries are working to develop light and slender constructions of steel structures having good welding characteristics and high ductility (Spiegler, 2018). Weld materials are referred to as the material which is added to the joint in its liquid state while necessary to connect the base material during the welding process. There are two types of welding process, autogenous process (base metal participates in the formation of the joint by fusion or crystallization with the weld metal if present) and heterogeneous process (only the base material is the weld material used at a temperature lower than the melting temperature of the base material) (Bernuzzi and Cordova, 2016). It is essential to ensure the strength, ductility, and toughness of welded connections to allow for the redistribution of stresses and internal forces when using steel (Günther *et al*., 2012). Failures in welded connections can lead to catastrophic structural collapses, causing financial losses and endangering lives.

In construction, various types of welded connections are used, including fillet welds, all-around fillet welds, butt welds, plug welds, and flare groove welds. The selection of each type depends on its specific properties (European Committee for Standardization (CEN), 2005). Fillet welds and partial penetration connections are widely utilized in building construction due to their practicality and versatility. Design engineers often prefer fillet welds over other connection types, primarily because of compliance with standards, technical constraints, and the economic efficiency of welding materials. Consequently, the design of fillet welds must not only meet the strength requirements specified in design codes but also ensure cost-effectiveness (Taheri *et al.*, 2024). Extensive experimental and analytical research has been conducted to examine the behaviour of fillet welds and accurately predict their strength and ductility (Kanvinde *et al.*, 2009).

Designing welded connections requires adherence to stringent standards and guidelines established by various international codes. Eurocode, American Welding Society (AWS), and Indian standards were chosen for their global usage and varying design philosophies, providing a comprehensive basis for comparison. However, significant variations exist in the methodologies prescribed by these standards, particularly regarding the evaluation of fillet weld strength and the effects of directional loading.

This paper aims to provide a detailed comparative analysis of the approaches recommended by these codes. It focuses on critical aspects such as the influence of weld orientation on strength, the role of filler and base metals in resisting loads, and the design philosophies underpinning methods like directional and mean stress analysis, Load and Resistance Factor Design (LRFD), and Allowable Stress Design (ASD). By synthesizing insights from diverse design standards, this review seeks to guide engineers in selecting optimal design strategies for welded connections that balance safety, efficiency, and material economy.

2. Standards for Fillet Welded Connections

2.1 European Standards

The structural performance of the welded connection depends on the joint type and the corresponding load situation. According to Eurocode EN 1993-1-8 (European Committee for Standardization (CEN), 2005) and EN 1993-1-12 (European Committee for Standardization (CEN), 2011), the design strength of fillet welded connection is calculated from two different methods; the directional method and the mean stress method.

2.1.1 Directional Method

For a more accurate directional method, the forces transmitted by the weld are resolved into stress components $\sigma_{\perp}$, $\tau_{\perp}$, and $\tau_{\parallel}$ within the area of the throat section because it is assumed to form the resisting and failing section (Kuhlmann *et al.*, 2008). The design resistance of the fillet welded connection is expressed in equation 1 as a function of the tensile strength of the base material along with the correlation factor β_w. However, the strength of the filler metal is not considered. According to EN 1993-1-8 (European Committee for Standardization (CEN), 2005), the normal stress parallel to the weld axis is not considered when verifying the design resistance of the weld. The resolved stress components $\sigma_{\perp}$, $\tau_{\perp}$, and $\tau_{\parallel}$ helps to optimize weld design are shown in Figure 1 are calculated from design loads with the assumption of uniform stress distribution in the weld throat. The methodology is based on the description of an ultimate strength surface expressed by the Huber-Hencky-von-Mises criterion resulting in an equivalent stress $\sigma_{w,Ed}$ (Kuhlmann *et al.*, 2008).

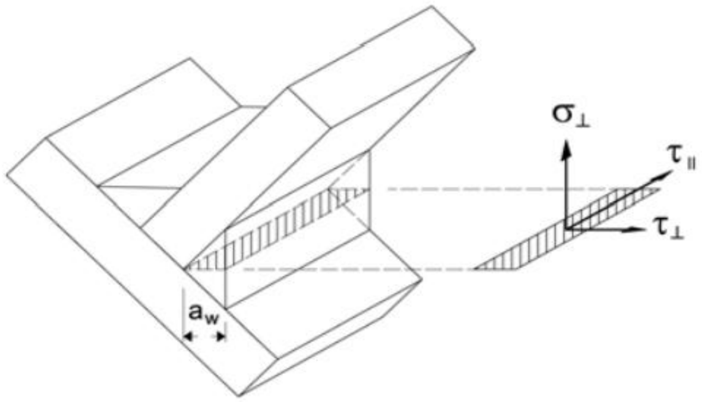


Figure 1: Stress Components longitudinal and perpendicular to the weld throat (Günther *et al.*, 2009).

$$\sigma_{w,Ed} = \sqrt{\sigma_{\perp}^2 + 3\tau_{\perp}^2 + 3\tau_{\parallel}^2} \leq \frac{f_u}{\beta_w \, x \, \gamma_{M2}} \text{ and } \sigma_{\perp} \leq \frac{0.9 \, x \, f_u}{\gamma_{M2}} \quad (1)$$

where $\sigma_{\perp}$ is the normal stress perpendicular to the throat, $\tau_{\perp}$ is the shear stress perpendicular to the axis of the weld, $\tau_{\parallel}$ is the shear stress parallel to the axis of the weld, f_u is the tensile strength of the base metal (Weaker part of the joined base metals), γ_{M2}=1.25 is the partial safety factor for the resistance of welds, and β_w is the correlation factor depends on the grade of steel which is increased from 0.8 for mild steel to 1.0 for high strength steel see in Table 1 (European Committee for Standardization (CEN), 2005) and (European Committee for Standardization (CEN), 2011).

Table 1: Correlation factor β_w depending on standard and steel grade (European Committee for Standardization (CEN), 2005).

Standard and steel grade			Correlation factor β_w
EN 10025	EN 10210	EN 10219	
S235	S235 H	S235 H	0.8
S235 W			
S275	S275 H	S275 H	0.85
S275 N/NL	S275 NH/NLH	S275 NH/NLH	
S275 M/ML		S275 MH/MLH	
S355		S355 H	0.9
S355 N/NL	S355 H	S355 NH/NLH	
S355 M/ML	S355 NH/NLH	S355 MH/MLH	
S355 W			
S420 N/NL		S420 MH/MLH	1.0
S420 M/ML			
S460 N/NL			1.0
S460 M/ML	S460 NH/NLH	S460 NH/NLH	
S460 Q/QL/QL1		S460 MH/MLH	

2.1.2 Simplified Method

The mean stress method is a simplification of the directional method. The design resistance of a fillet weld may be assumed to be adequate if, at every point along its length the resultant of all forces per unit length transmitted by the weld $F_{w,Ed}$ satisfy the following criteria:

$$F_{w,Ed} \leq F_{W,Rd}$$

Where $F_{W,Ed}$ is the design value of the weld force per unit length and $F_{W,Rd}$ is the design weld resistance per unit length.

The design weld resistance per unit of weld should be determined using equation 2, regardless of the orientation of the weld throat plane to its applied force (European Committee for Standardization (CEN), 2005).

$$F_{w,Rd} = f_{vw,d} \; x \; a \qquad (2)$$

$$f_{vw,d} = \frac{f_u}{\sqrt{3}\,\beta_w \gamma_{M2}}$$

Where $f_{vw,d}$ is the design shear strength of the weld and a is the effective throat thickness of the fillet weld which should be taken as the height of the largest triangle (with equal or unequal legs) that can be inscribed within the fusion faces and the weld surface, measured perpendicular to the outer side of this triangle and should not be less than 3 mm as per clause 4.5.2 (1) and (2) (European Committee for Standardization (CEN), 2005).

Table 2: Values for the design weld resistance according to EN 1993 in case of fillet welds, $t \leq 40$ mm (Günther *et al.*, 2009).

Steel grade		**S235**	**S355**	**S460**	**S690**
f_y	[MPa]	235	355	460	690
f_u	[MPa]	360	510	540	770
β_w		0.8	0.9	1.0	1.0
$\frac{f_u/\sqrt{3}}{\beta_w \gamma_{M2}}$	[MPa]	360	453	432	616

The design weld resistance for welds is outlined in the standards EN 1993-1-1 (European Committee for Standardization, 2010), EN 1993-1-8 (European Committee for Standardization (CEN), 2005), and EN 1993-1-12 (European Committee for Standardization (CEN), 2011). This resistance varies based on structural steel grades as specified in EN 10025-2 (European Committee for Standardization, 2004), EN 10025-3 (British Standards, 2004), and EN 10025-6 (European Committee for Standardization, 2004). For fillet welds with a thickness of $t \leq 40$ mm, the information is summarized in Table 2. The table illustrates that the design resistance of the higher-strength steel grade S460 is somewhat lower than that of the steel grade S355.

Example calculations for welds perpendicular and parallel to the direction of an applied force, along with the design resistance of fillet welds according to European Standards, are presented in Tables 3 and 4.

Table 3: Design resistance of welds perpendicular and parallel to the direction of action of force according to Eurocode (European Committee for Standardization (CEN), 2005).

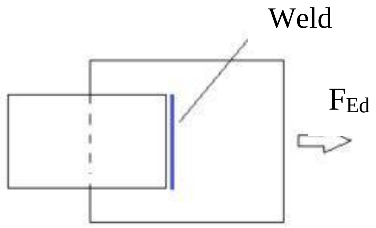
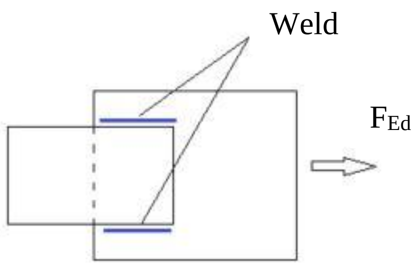
Sample	Description	Details
	Normal and Shear stress perpendicular to the direction of force:	$\sigma_{\perp} = \tau_{\perp} = \frac{F_{Ed}}{\sqrt{2}\,A_w}$
	Directional Method	$\sqrt{\sigma_{\perp}^2 + 3\tau_{\perp}^2} \leq \frac{f_u}{\beta_w \gamma_{M2}}$ $\frac{F_{Ed}}{A_w} \leq \frac{f_u}{\sqrt{2}.\beta_w \gamma_{M2}}$
	Simplified Method	$\frac{F_{Ed}}{A_w} \leq \frac{f_u}{\sqrt{3}.\beta_w \gamma_{M2}}$
	Comparison	Directional Method gives 22% more durable results than that of simplified method.
	Shear stress parallel to the direction of force:	$\tau_{\parallel} = \frac{F_{Ed}}{A_w}$
	Directional Method	$\sqrt{3\tau_{\parallel}^2} \leq \frac{f_u}{\beta_w \gamma_{M2}}$ $\frac{F_{Ed}}{A_w} \leq \frac{f_u}{\sqrt{3}.\beta_w \gamma_{M2}}$
	Simplified Method	$\frac{F_{Ed}}{A_w} \leq \frac{f_u}{\sqrt{3}.\beta_w \gamma_{M2}}$
	Comparison	Same strength from both method

Table 4: Design resistance of fillet welds according to EN 1993-1-8 (European Committee for Standardization (CEN), 2005).

	Combination of base metal & filler metal	
	S690Q-G42	S690-G46
Base Metal (f_y) [N/mm2]	690	690
Base Metal (f_u) [N/mm2]	770	770
Filler Metal (f_y) [N/mm2]	420	460
Filler Metal (f_u) [N/mm2]	500	530
β_w	1	1
γ_{M2}	1.25	1.25
$f_{vw,d} = \frac{f_u/\sqrt{3}}{\beta_w \gamma_{M2}}$	230.94	244.80

2.2 US Standards

In the US, load and resistance factor design (LRFD) and allowable strength design (ASD) methods are considered for the design strength of weld according to ANSI/AISC 360-16 (American Institute of Steel Construction, 2016). Fillet welds are often considered the weakest component due to their geometry, which concentrates stresses at critical points, leading to potential failures under high loads. The design strength of the fillet weld is determined using section J2.4 in ANSI/AISC 360-16 (American Institute of Steel Construction, 2016). According to ANSI/AISC 360-16 (American Institute of Steel Construction, 2016), the directional strength of fillet welds loaded perpendicular to the weld axis is increased by 50%.

The design strength ϕR_n of welded joints shall be the lower of the base material strength and the weld metal strength. The weld metal strength is determined according to the limit state of rupture, and base material strength is determined according to the limit states of tensile rupture and shear rupture as follows:

For the base metal. However, the base metal check is not required for matching electrodes.

$$\phi x R_n = \phi x F_{nBM} x A_{BM} \quad (3)$$

For the filler metal

$$\phi x R_n = \phi x F_{nw} x A_{we} \quad (4)$$

Where A_{BM} is the base metal's cross-sectional area, A_{we} is the weld's effective area, F_{nBM} is the nominal stress of the base metal, and F_{nw} is the nominal stress of the weld metal. The values of ϕ, Ω, and F_w and limitations thereon, are given in Table J2.5 of ANSI/AISC 360-16 (American Institute of Steel Construction, 2016).

The design strength for a linear weld group through the centre of gravity having a uniform leg size is determined as follows:

$$\phi x\ R_n = \phi x 0.60 F_{EXX} x \left(1.0 + 0.50 x \sin^{1.5}(\theta)\right) x A_{we} \quad (5)$$

Where F_{EXX} is the filler metal classification strength, and θ is the angle between the direction of the force and the weld axis.

The load-bearing capacity of a welded connection is determined based on the type of filler metal used. Specifying the steels associated with the filler metals is important to make effective comparisons with other standards. Table 5.3 of AWS D1.1/D1.1M:2020 (American Welding Society, 1980) provides a selection of potential steel and welding consumables combinations. Some strengths of steels and their associated welding consumables are listed in Table 5, along with the design weld strength presented in Table 6.

Table 5: Strength of steels with associated welding consumables according to AISC 360-16 (American Institute of Steel Construction, 2016)(AWS D1.1/D1.1M:2020) (American Welding Society, 1980).

Steel	f_y **[N/mm2]**	f_u**[N/mm2]**	F_{EXX}
A36 (≤ 20 mm)	250	400-550	60 ksi/70 ksi (414/483 N/mm2)
A913 (Size 50)	345	Min. 455	70 ksi (483 N/mm2)
A913 (Size 60)	415	Min. 520	80 ksi (552 N/mm2)
A913 (Size 65)	450	Min. 550	80 ksi (552 N/mm2)
A852	485	620-760	90 ksi (621 N/mm2)

Table 6: Design strength of fillet welds according to AISC 360-16 (American Institute of Steel Construction, 2016), [AWS D1.1, 2020] (American Welding Society, 1980).

	Welding Consumables material		
	60 ksi	70 ksi	80 ksi
f_y [ksi/ N/mm2]	48/331	57/393	67/462
f_u [ksi/ N/mm2]	60/414	70/483	80/552
F_{EXX}[N/mm2]	414	483	552
Ø [-]		0.75	
Ø $* \mathbf{0.60}\ x\ F_{EXX}$	186.3	217.35	248.4
Ø $* \mathbf{0.60}\ x\ F_{EXX}\ (\mathbf{1.0} + \mathbf{0.50}\ x\ Sin^{1.5}(\theta))$			
$\theta = 0^{\circ}$ (welds parallel to the direction of force)	186.3	217.35	248.4
$\theta = 90^{\circ}$(welds perpendicular to the direction of force)	279.45	326.03	372.6

2.3 Indian Standards

The design shear strength of the fillet welded connection as per Indian standards IS 800-2007 (BIS (Bureau of Indian Sandards), 2007) is given in the equation (6).

$$V_{dw} = \frac{f_u}{\sqrt{3}\gamma_{mw}} x\ L_W x\ t_e \qquad (6)$$

Where f_u is the ultimate strength of the weld or parent metal, whichever is minimum, L_W is the effective length of the weld, t_e is the effective throat thickness of the weld, and γ_{mw} is the partial safety factor. Table 7 illustrates the design of resistance welds with different welding combinations.

According to IS 800-2007 (BIS (Bureau of Indian Sandards), 2007), the size of fillet welds must not be less than 3 mm. To prevent the risk of cracking without preheating, the minimum size of the first run or a single-run fillet weld is specified in Table 21 of IS 800-2007 (BIS (Bureau of Indian Sandards), 2007). In practice, the actual length of the weld should be the effective length plus two times the size of the weld, but it must not be less than four times the size of the weld. Additionally, the effective throat thickness of a fillet weld should be no less than 3 mm and, generally, should not exceed 0.7t or 1.0t under exceptional circumstances, where 't' is the thickness of the thinner plate being welded.

Table 7: Design resistance of fillet welds according to IS 800-2007 (BIS (Bureau of Indian Sandards), 2007).

	Welding combination		
	Combination-I	Combination-II	Combination-III
Base Plate (f_u) [N/mm2]	410	360	490
Filler Metal (f_u) [N/mm2]	490	490	490
γ_{mw}	1.25	1.25	1.25
$V_{dw} = \frac{f_u/\sqrt{3}}{\gamma_{mw}}$	189.37	166.27	226.32

3. Comparison of strength for fillet welded connection

Using a specific example, this section compares the design strength for fillet welded connections based on the aforementioned standards. The parent and filler materials are assumed to have an ultimate tensile strength of 360 MPa. This example considers a weld with a throat thickness of 3 mm and a length of 100 mm. The strength of the fillet welded connection is evaluated for two loading directions: parallel and perpendicular to the weld. The comparative design resistances, calculated according to European, US, and Indian standards, are presented in Table 9.

Table 9: A comparison of the design strength of fillet welded connections based on different standards.

Standards	**The direction of the line of action**		
	Parallel to the weld	Perpendicular to the weld	Perpendicular/Parallel
European Standard	62.35 kN	76.37 kN	1.22
US Standard	48.60 kN	72.9 kN	1.50
Indian Standard	49.88 kN	61.01 kN	1.22

The results presented in Table 9 reveal significant variations in the predicted design strength of fillet welded connections based on different international standards. These differences can be attributed to each standard's distinct methodologies, safety factors, and material strength considerations. In addition to this, Variations in predicted design strength across standards influence material selection, construction costs, and safety. For instance, a more conservative standard might require additional material, impacting cost but enhancing safety margins.

a) European Standard: The design resistance predicted by the European Standard is higher when the load is perpendicular to the weld (76.37 kN) compared to parallel loading (62.35 kN). This indicates a more conservative approach in estimating resistance for parallel loading, with a perpendicular-to-parallel strength ratio of 1.22.
b) US Standard: The US Standard shows a relatively balanced prediction, with a higher resistance under perpendicular loading (72.90 kN) and a lower resistance under parallel loading (48.60 kN). Notably, the perpendicular-to-parallel ratio of 1.50 is the highest among the standards, suggesting a more pronounced difference in strength predictions between the two loading directions.
c) Indian Standard: The Indian Standard also reflects higher resistance under perpendicular loading (61.01 kN) compared to parallel loading (49.88 kN), with a perpendicular-to-parallel ratio of 1.22, similar to the European Standard. This suggests alignment in their design philosophy regarding directional strength variations.

The comparison highlights that all three standards consistently predict higher strength for perpendicular loading than for parallel loading. This aligns with the physical behavior of fillet welds, where the weld's capacity is generally greater under perpendicular loading due to the orientation of stress distribution and weld geometry.

However, the US Standard predicts a much more significant disparity between the two loading directions than the European and Indian Standards. This could indicate a more conservative approach in accounting for uncertainties in parallel loading scenarios or differing assumptions about stress transfer mechanisms. The conservative nature of the US standard prioritizes safety but may lead to overdesign in certain scenarios.

These differences underscore the importance of understanding the underlying assumptions and safety margins of each standard. For design engineers, this comparison emphasizes the need to select appropriate standards based on the specific application, ensuring that the design aligns with both safety and performance requirements.

4. Summary

This study has reviewed and compared analytical methods for designing welded connections across various international standards, highlighting similarities and differences in approaches. The study reveals Eurocode's directional method yields higher resistance for perpendicular loading, while the US standard adopts a more conservative approach, leading to safer but potentially overdesigned connections. Highlighting these differences provides clear guidance for material and method selection in structural applications.

Overall, the analysis underscores the importance of selecting appropriate design methodologies based on project-specific requirements, material properties, and local standards. Insights from this study can enhance engineering education by integrating cross-standard comparisons into curricula and assist practitioners in adapting codes for local construction challenges, ensuring optimal performance and safety.

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