# Strength Coefficients for Eccentrically Loaded Weld Groups

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## ABSTRACT

When AISC *Manual* Tables 8-4 through 8-11 are used to calculate the strength of eccentrically loaded weld groups with $F_{EXX} \neq 70$ ksi, the values are multiplied by an electrode strength coefficient, $C_1$. The $C_1$ values are dependent on the filler metal classification strength; however, they are not proportional to the filler metal classification strength ratio when $F_{EXX} \geq 80$ ksi. To consider the potential effect of reduced ductility, the $C_1$ values include reduction factors of 0.85 and 0.90 for higher-strength welds.

To investigate the accuracy of the electrode strength coefficients, the ductility of high-strength welds was evaluated using the data from 93 experimental tests from three existing research projects with $F_{EXX} > 70$ ksi. The data was used to plot the weld metal tensile strength versus the normalized rupture deformation of both longitudinal and transverse fillet welds. The analysis showed that, when $F_{EXX} \leq 120$ ksi, the $C_1$ values can be based solely on the filler metal classification strength ratio, $F_{EXX}$/70 ksi, without the reduction factors of 0.85 and 0.90 for higher-strength welds.

**Keywords:** eccentrically loaded weld groups, electrode strength coefficient, weld ductility.

## INTRODUCTION

AISC *Steel Construction Manual* (2023) Tables 8-4 through 8-11 are used to calculate the strength of eccentrically loaded weld groups. The tables were developed using the instantaneous center of rotation (ICR) method with a filler metal classification strength, $F_{EXX}$, of 70 ksi. For other filler metal strengths, Table 8-3 provides electrode strength coefficients, $C_1$, that are used with Tables 8-4 through 8-11. The $C_1$ values are dependent on the filler metal classification strength; however, they are not proportional to the filler metal classification strength ratio when $F_{EXX} \geq 80$ ksi. This results in a significant strength reduction for higher-strength welds, which is not required in either the AISC *Specification* (2022) or AWS D1.1 (2020a). Based on experimental tests, the accuracy of the electrode strength coefficients will be determined and revised values will be proposed.

## AISC *MANUAL*

Part 8 of the AISC *Manual* discusses three methods to analyze eccentrically loaded weld groups: The ICR method, the elastic method and the plastic method. Both the elastic and plastic methods were developed theoretically. The ICR method was developed using a semi-empirical approach, with an empirical load-deformation curve for short segments within the weld group.

Because the ICR method is iterative, considerable design effort is required to calculate the strength of a weld group using this method. AISC *Manual* Tables 8-4 through 8-11 provide a simpler, noniterative design method by listing the appropriate coefficients for several different weld group geometries. The tables were developed using the equations in AWS D1.1 Subclause 4.6.4.3. These equations are also shown on AISC *Manual* pages 8-13 and 8-14. AWS D1.1 is based solely on ASD. The AISC *Manual* provides the nominal strength equations, which can be used with ASD and LRFD. The weld group strength is the sum of the strengths of each element within the group. The nominal stress in Element *i* is calculated with AISC *Manual* Equation 8-3.

$$F_{nwi} = 0.60F_{EXX}\left(1.0+0.50\sin^{1.5}\theta_i\right)\left[p_i\left(1.9-0.9p_i\right)\right]^{0.3} \qquad (\textit{Manual}\ \text{Eq. 8-3})$$

where $0.60F_{EXX}$ is the nominal stress for concentrically loaded fillet welds from AISC *Specification* Table J2.5. The first term in parentheses is the directional strength increase factor, which is identical to AISC *Specification* Equation J2-5 if $\theta_i$ is replaced with $\theta$. The second bracketed term is a strain compatibility factor, which is dependent on the deformation ratio, $p_i$. The ratio of Element *i* deformation to its deformation at maximum stress is

$$p_i = \frac{\Delta_i}{\Delta_{mi}} \qquad (\textit{Manual}\ \text{Eq. 8-4})$$

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The deformation of Element $i$ at maximum stress is

$$\Delta_{mi} = 0.209w(\theta_i + 2)^{-0.32}$$

(*Manual* Eq. 8-6)

The deformation of Element $i$ at an intermediate stress level is

$$\Delta_i = \Delta_{ucr}\frac{r_i}{r_{cr}} \qquad (\textit{Manual}\ \text{Eq. 8-5})$$

where $\Delta_{ucr}$ is the deformation of the weld element with the minimum $\Delta_{ui}/r_i$ ratio at ultimate (rupture) stress. The deformation of Element $i$ at ultimate (rupture) stress is

$$\Delta_{ui} = 1.087w(\theta_i + 6)^{-0.65} < 0.17w$$

(*Manual* Eq. 8-7)

where

$F_{EXX}$ = filler metal classification strength, ksi

$r_{cr}$ = distance from the instantaneous center of rotation to the element with the minimum $\Delta_{ui}/r_i$ ratio, in.

$r_i$ = distance from the instantaneous center of rotation to Element $i$, in.

$w$ = weld leg size, in.

$\theta_i$ = angle between the longitudinal axis of weld element $i$ and the direction of the resultant force acting on the element, degrees

## BACKGROUND

This section of the paper will document background information related to the electrode strength coefficients. The ICR method will be briefly reviewed, followed by the implementation history of the electrode strength coefficients in the AISC *Manual*.

### Instantaneous Center of Rotation Method

Butler et al. (1972) developed the ICR method based on the empirical load-deformation curves from Butler and Kulak (1971), who tested concentrically loaded fillet welds at angles of 0°, 30°, 60°, and 90° from the loading direction. The tests by Butler and Kulak as well as the tests on eccentrically loaded weld groups by Butler et al. used 60 ksi electrodes and ¼ in. fillet welds.

The ICR equations in both AWS D1.1 Subclause 4.6.4.3 and the AISC *Manual* were primarily developed by Lesik and Kennedy (1990). Lesik and Kennedy used linear regression to formulate the load-deformation curves with the data from Miazga and Kennedy (1989), who tested concentrically loaded 70 ksi fillet welds with varying load angles, θ, from 0 to 90° in 15° increments. These equations were used to plot the strength ratio, $F_{nw}/(0.6F_{EXX})$, versus normalized deformation, $\Delta/w$, curves for θ = 0°, 30°, 60°, and 90° in Figure 1. An increase in θ results in a nonlinear strength increase based on the directional strength increase factor and a decrease in ductility based on AISC *Manual* Equation 8-7.

Lesik and Kennedy (1990) originally developed the strain compatibility factor as a polynomial function; however, their equation was replaced by the simpler empirical approximation in AISC *Manual* Equation 8-3. Also, an upper limit of 0.17$w$ was added to their original equation for $\Delta_{ut}$, resulting in AISC *Manual* Equation 8-7.

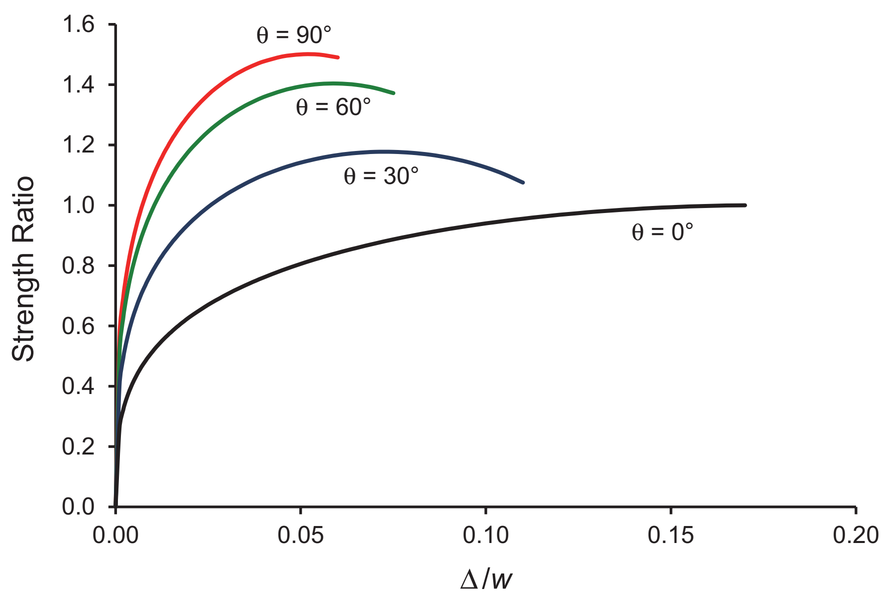


*Fig. 1. Fillet weld strength ratio versus normalized deformation as a function of load angle,* θ.

| Table 1. Electrode Strength Coefficient, $C_1$ | | | | | | |
|---|---|---|---|---|---|---|
| $F_{EXX}$ | 60 | 70 | 80 | 90 | 100 | 110 |
| $C_1$ | 0.857 | 1.00 | 1.03 | 1.16 | 1.21 | 1.34 |
| $\dfrac{F_{EXX}}{70 \text{ ksi}}$ | 0.857 | 1.00 | 1.14 | 1.29 | 1.43 | 1.57 |
| $\dfrac{C_1}{\left(\dfrac{F_{EXX}}{70 \text{ ksi}}\right)}$ | 1.00 | 1.00 | 0.90 | 0.90 | 0.85 | 0.85 |

**Electrode Strength Coefficient**

The values in AISC *Manual* Tables 8-4 through 8-11 were calculated using $F_{EXX} = 70$ ksi. The strength of weld groups with other weld metal strengths can be calculated by adjusting the tabulated values by the electrode strength coefficient, $C_1$ in *Manual* Table 8-1.

The 6th Edition AISC *Manual* (1967) was the first to provide information on eccentrically loaded weld groups. The elastic method was used to develop design tables with $F_{EXX} = 60$ ksi. The weld group strengths for other filler metal classification strengths were calculated with the filler metal classification strength ratio, $F_{EXX}/60$ ksi. The 7th Edition *Manual* (AISC, 1973) used elastic design with $F_{EXX} = 70$ ksi; therefore, the weld group strength for other filler metal classification strengths was calculated with the filler metal classification strength ratio, $F_{EXX}/70$ ksi.

The 8th Edition *Manual* (AISC, 1980) was the first to publish design tables that were based on the ICR method. The development of these tables, which were also published in the 9th Edition *Manual* (AISC, 1989), was discussed by Tide (1980). The table coefficients were calculated with $F_{EXX} = 70$ ksi, and $C_1$ was used to calculate the weld group strength for other filler metal classification strengths, where $C_1 = F_{EXX}/70$ ksi.

For the 1st Edition LRFD *Manual* (AISC, 1986) and the 13th Edition combined ASD/LRFD *Manual* (AISC, 1992), as well as all later editions, the tables were based on the ICR method with $F_{EXX} = 70$ ksi. However, the value of $C_1$ included a reduction factor equal to either 0.90 (for 80 and 90 ksi welds) or 0.85 (for 100 and 110 ksi welds). These values are shown in Table 1.

The background of these reduction factors is ambiguous, and communication with members of past AISC *Manual* Committees (Thornton, 2020; Tide, 2020) revealed no further information. According to Butler et al. (1972), who originally developed the ICR method based on $F_{EXX} = 60$ ksi, "Because E60 and E70 electrodes have specified ultimate elongations nearly the same, it is felt that these results could be applied to connections made using E70 electrodes by proper consideration of the increase in electrode strength. The method could be used for fillet welds made from electrodes other than E60 and E70 by ascertaining the load-deformation response for these welds."

An accurate solution relies on sufficient ductility of the critical segment for load redistribution without rupture. The reduction factors were likely implemented in the AISC *Manual* because higher-strength welds are less ductile than E60 and E70 welds. However, in 1986 when these reduction factors were first published, experimental strength versus deformation data was unavailable for welds with $F_{EXX}$ greater than 70 ksi.

## DUCTILITY OF HIGH-STRENGTH WELDS

To investigate the accuracy of the electrode strength coefficients, the ductility of high-strength welds will be evaluated. After the modified coefficients were first published in 1986, a significant amount of experimental strength-versus-deformation data has become available for welds with $F_{EXX}$ greater than 70 ksi.

Because transverse fillet welds have significantly less deformation capacity than longitudinal fillet welds, the ductility of transverse high-strength welds are the primary concern. In weld groups with both longitudinal and transverse welds, the longitudinal weld strength will be limited by the ductility of the transverse weld. According to the AWS D1.1 equation for rupture deformation (which is identical to AISC *Manual* Equation 8-7), the normalized rupture deformations for longitudinal and transverse welds are $\Delta_{ui}/w = 0.17$ and $\Delta_{ui}/w = 0.056$, respectively.

Figure 2 shows a plot of the weld metal tensile strength versus the normalized rupture deformation, $\Delta_u/w$, of fillet welds. The data are from the 93 experimental tests on high-strength longitudinally and transversely loaded fillet welds by Collin and Johansson (2005), Bjork et al. (2012), and Sun et al. (2019). The red × data points represent transverse welds, and the blue hollow circles represent longitudinal welds. The red and blue vertical dashed lines represent the AWS normalized rupture deformations for longitudinal and transverse welds, respectively. It can be observed that, for tensile strengths less than 120 ksi, the AWS D1.1 equation for rupture deformation (which is identical to AISC

*Manual* Equation 8-7) generally provides conservative estimates of the normalized rupture deformation.

The average normalized deformations from this data are listed in Table 2. The data for 60 ksi welds from Butler and Kulak (1971) are also listed. A comparison of the rupture deformations shows that, for longitudinal welds, the rupture deformation of high-strength welds is 68% of that of 60 ksi welds; however, the rupture deformation of transverse welds is independent of strength. Because the shape of the load-deformation curves for high-strength welds is similar to that of 60 ksi welds, high-strength longitudinal welds in weld groups will reach a higher proportion of their rupture load compared to 60 ksi welds. The average transverse-to-longitudinal normalized deformation ratio for lap joints is $0.103/0.284 = 0.363$, which is similar to the value calculated with AISC *Manual* Equation 8-7: $0.056/0.17 = 0.33$.

## Load-Deformation Curves

An evaluation of the load-deformation curves can provide further information on the behavior of high-strength fillet welds. The equations developed by Neis (1985) explicitly compensate for the effect of reduced weld metal ductility on the behavior. Neis used plasticity theory to derive the ultimate strength and maximum displacement of fillet welds. Although several simplifying assumptions were required, limited comparisons with experimental results showed "an acceptable fit." The ultimate (rupture) force and normalized deformation are calculated with Equations 1 and 2, respectively.

$$R_u = \sigma_{tu} w L \sqrt{\frac{1+15\sin^2\alpha_d}{6(1+7\sin^2\alpha_d)}} \tag{1}$$

$$\delta_u = \varepsilon_u \sqrt{\frac{3}{2(1+7\sin^2\alpha_d)}} \tag{2}$$

The load-deformation curve can be plotted with Equations 3 through 5.

$$R_i = R_u \frac{f_i}{f_u} \tag{3}$$

$$f_i = 1 - \frac{e^{-25\delta_i} + e^{-75\delta_i}}{2} \tag{4}$$

$$f_u = 1 - \frac{e^{-25\delta} + e^{-75\delta_u}}{2} \tag{5}$$

As a conservative estimate, the authors noted that the true tensile rupture stress can be calculated with Equation 6.

$$\sigma_{tu} = \sigma_u(1+0.75\varepsilon_u) \tag{6}$$

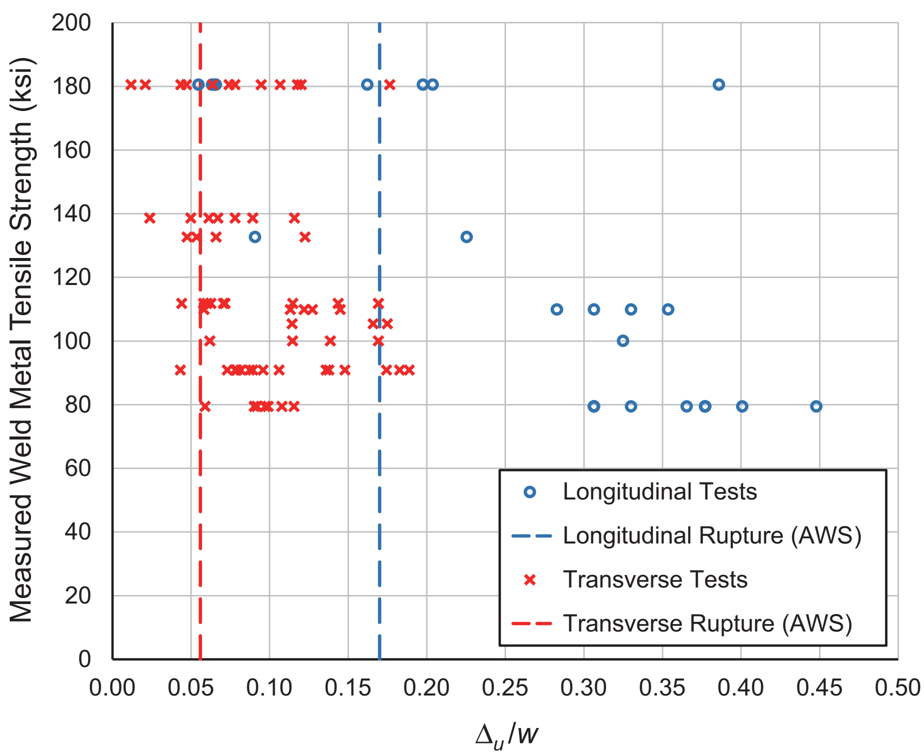


*Fig. 2. Weld metal tensile strength versus normalized rupture deformation.*

| Table 2. Average Normalized Deformation | | | |
|---|---|---|---|
| Joint Type | $F_{EXX}$ = 60 ksi (Butler and Kulak, 1971) | High Strength ($F_{EXX} \approx$ 80 to 180 ksi) | |
| | Average $\Delta_u/w$ | Number of Specimens | Average $\Delta_u/w$ |
| Longitudinal | 0.420 | 26 | 0.284 |
| Transverse (total) | — | 67 | 0.0966 |
| Transverse lap joints | 0.104 | 36 | 0.103 |
| Transverse T-joints | — | 31 | 0.0889 |

| Table 3. Minimum Elongation for All-Weld-Metal Tension Tests (%) | | | | |
|---|---|---|---|---|
| $F_{EXX}$ ksi | Welding Process | | | |
| | SMAW | GMAW | FCAW | SAW |
| 60 | 17 to 22 | — | 22 | 22 |
| 70 | 17 to 25 | 19 to 24 | 20 to 22 | 22 |
| 80 | 17 to 24 | 17 to 24 | 19 | 20 |
| 90 | 17 to 24 | 16 to 18 | 16 to 17 | 17 |
| 100 | 16 to 20 | 16 | 15 to 18 | 16 |
| 110 | 15 to 20 | 15 | 15 | 15 |
| 120 | 11 to 18 | 14 to 15 | 14 | 14 |

Equation 7 provides an approximate value of the angle between the weld longitudinal axis and the weld displacement direction.

$$\tan \alpha_d = \frac{\tan \theta}{4} \tag{7}$$

where

$R_i$ = strength at deformation $\Delta_i$, kips

$L$ = weld length, in.

$\alpha_d$ = angle between the weld longitudinal axis and the weld displacement direction

$\Delta_i$ = deformation at an intermediate strength level, in.

$\Delta_u$ = ultimate (rupture) deformation, in.

$\delta_i$ = $\Delta_i/w$

$\delta_u$ = $\Delta_u/w$

$\varepsilon_u$ = uniaxial engineering tensile rupture strain

$\sigma_{tu}$ = true tensile rupture stress, ksi

$\sigma_u$ = uniaxial engineering tensile rupture stress, ksi

The elongation requirements for carbon and low-alloy steels for shielded metal arc welding (SMAW), gas metal arc welding (GMAW), flux cored arc welding (FCAW) and submerged arc welding (SAW) welding processes from AWS A5.1 (2012), A5.5 (2014), A5.17 (2019), A5.18 (2017), A5.20 (2015), A5.23 (2011), A5.28 (2020b) and A5.29 (1998) are summarized in Table 3. Generally, weld metals exceed these requirements. For example, the average elongation measurements in Dowswell et al. (2021) Table 3.7 are 40 to 50% higher than the required minimum values in Table 3. These measurements are from all-weld-metal tensile tests with $F_{EXX}$ = 70, 80 and 100 ksi.

The values in Table 4 are appropriate lower bounds for analyses with the Neis (1985) equations. The strength ratios, $\sigma_{tu}/\sigma_u$, in Table 4 are between 1.11 and 1.17. These values are similar to the constraint factor by Miazga and Kennedy (1989), which is 1.14 when $\theta = 90°$.

The Butler and Kulak (1971) curves were scaled up from 60 ksi to 70 ksi and plotted in Figures 3 and 4 for longitudinal and transverse welds, respectively. These normalized load versus normalized deformation curves are for 70 ksi electrodes. The figures also include the AWS D1.1 and Neis (1985) equations. The figures show that the Neis curves provide a close approximation of the shape of the empirical curves of Butler and Kulak, while also resulting in rupture loads that are similar to the AWS D1.1 equations. Also, the Neis equations explicitly compensate for the effect of reduced weld metal ductility on the behavior. Therefore, the Neis curves can be used as a baseline to project the behavior of higher-strength weld metals.

| Table 4. Variables for Neis (1985) Equations | | | |
|---|---|---|---|
| $F_{EXX}$ ksi | $\varepsilon_u$ | $\sigma_{tu}$ ksi | $\sigma_{tu}/\sigma_u$ |
| 70 | 0.22 | 81.6 | 1.17 |
| 80 | 0.19 | 91.4 | 1.14 |
| 90 | 0.17 | 101 | 1.12 |
| 100 | 0.16 | 112 | 1.12 |
| 110 | 0.15 | 122 | 1.11 |
| 120 | 0.14 | 133 | 1.11 |

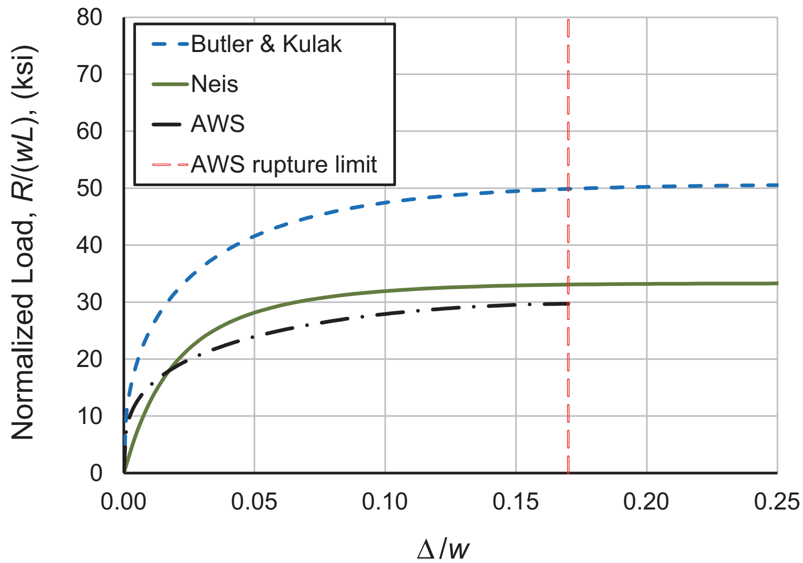


*Fig. 3. Normalized load versus normalized deformation for 70 ksi longitudinal fillet welds.*

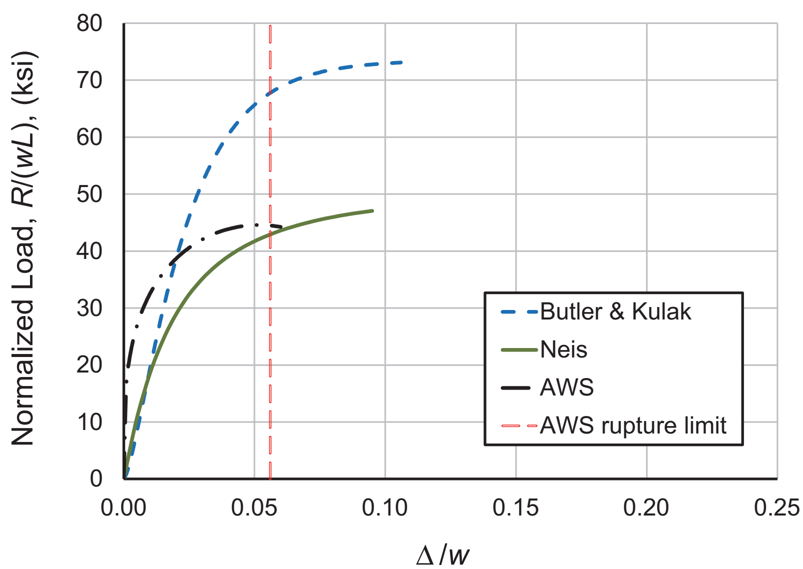


*Fig. 4. Normalized load versus normalized deformation for 70 ksi transverse fillet welds.*

For both the AWS D1.1 and Neis (1985) equations, the normalized load versus normalized deformation curves are plotted in Figures 5 and 6 for 70 ksi and 120 ksi electrodes, respectively. Generally, the AWS D1.1 curves are higher than the curves for transverse welds and lower than the Neis curves for longitudinal welds. Because the AWS D1.1 equations predict a similar, but more conservative, proportion of the longitudinal strength at the transverse rupture load, it can be concluded that the AWS D1.1 curves are conservative for both 70 ksi and 120 ksi electrodes.

## SUMMARY AND CONCLUSIONS

When AISC *Manual* Tables 8-4 through 8-11 are used to calculate the strength of eccentrically loaded weld groups with $F_{EXX} \neq 70$ ksi, the values are multiplied by an electrode strength coefficient, $C_1$. The $C_1$ values are dependent on the filler metal classification strength; however, they are not proportional to the weld metal tensile strength ratio when $F_{EXX} \geq 80$ ksi.

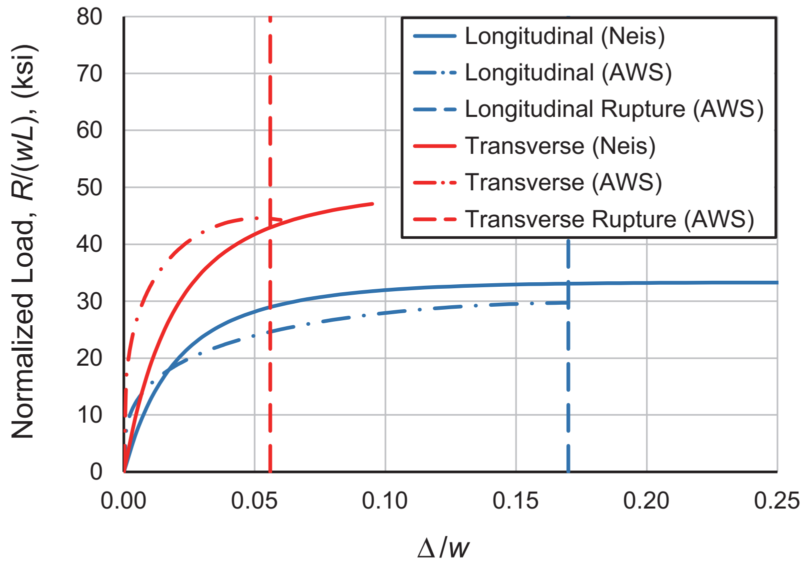


*Fig. 5. Normalized load versus normalized deformation for 70 ksi fillet welds.*

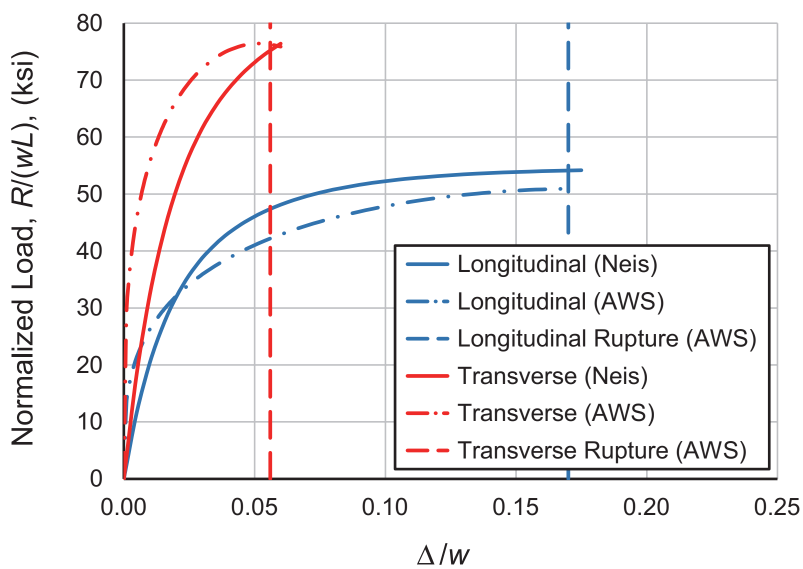


*Fig. 6. Normalized load versus normalized deformation for 120 ksi fillet welds.*

| Table 5. Current and Proposed Values for the Electrode Strength Coefficient | | | | | | |
|---|---|---|---|---|---|---|
| $F_{EXX}$ | 60 | 70 | 80 | 90 | 100 | 110 |
| Current | 0.857 | 1.00 | 1.03 | 1.16 | 1.21 | 1.34 |
| Proposed | 0.857 | 1.00 | 1.14 | 1.29 | 1.43 | 1.57 |
| $\dfrac{\text{Current}}{\text{Proposed}}$ | 1.00 | 1.00 | 0.90 | 0.90 | 0.85 | 0.85 |

An accurate solution relies on sufficient ductility of the critical segment for load redistribution without rupture. In 1986, when these modified electrode strength coefficients were first published, experimental strength-versus-deformation data were unavailable for welds with $F_{EXX} >$ 70 ksi. To consider the potential effect of reduced ductility, the $C_1$ values included reduction factors of 0.85 and 0.90 for higher-strength welds.

To investigate the accuracy of the electrode strength coefficients, the ductility of high-strength welds was evaluated. A significant amount of experimental strength-versus-deformation data is now available for welds with $F_{EXX} >$ 70 ksi. The data from the 93 experimental tests from three existing research projects were analyzed. The data were used to plot the weld metal tensile strength versus the normalized rupture deformation of both longitudinal and transverse fillet welds. The analysis showed that when $F_{EXX} \leq$ 120 ksi, the $C_1$ values can be based solely on the filler metal classification strength ratio, $F_{EXX}/70$ ksi, without the reduction factors of 0.85 and 0.90 for higher-strength welds. Both the current and proposed values for the electrode strength coefficient are listed in Table 5.

## REFERENCES


AISC (1967), *Manual of Steel Construction*, 6th Ed., American Institute of Steel Construction, Chicago, Ill.

AISC (1973), *Manual of Steel Construction*, 7th Ed., American Institute of Steel Construction, Chicago, Ill.

AISC (1980), *Manual of Steel Construction*, 8th Ed., American Institute of Steel Construction, Chicago, Ill.

AISC (1986), *Manual of Steel Construction—Load and Resistance Factor Design*, 1st Ed., American Institute of Steel Construction, Chicago, Ill.

AISC (1989), *Manual of Steel Construction—Allowable Stress Design*, 9th Ed., American Institute of Steel Construction, Chicago, Ill.

AISC (1992), *Manual of Steel Construction—Volume II Connections*, ASD 9th Ed./LRFD 1st Ed., American Institute of Steel Construction, Chicago, Ill.

AISC (2022), *Specification for Structural Steel Buildings*, ANSI/AISC 360-22, American Institute of Steel Construction, Chicago, Ill.

AISC (2023), *Steel Construction Manual*, 16th Ed., American Institute of Steel Construction, Chicago, Ill.

AWS (1998), *Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding*, AWS A5.29/A5.29M, American Welding Society, Miami, Fla.

AWS (2011), *Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding*, AWS A5.23/A5.23M, American Welding Society, Miami, Fla.

AWS (2012), *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*, AWS A5.1/A5.1M, American Welding Society, Miami, Fla.

AWS (2014), *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*, AWS A5.5/A5.5M, American Welding Society, Miami, Fla.

AWS (2015), *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*, AWS A5.20/A5.20M, American Welding Society, Miami, Fla.

AWS (2017), *Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding*, AWS A5.18/A5.18M, American Welding Society, Miami, Fla.

AWS (2019), *Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding*, AWS A5.17/A5.17M, American Welding Society, Miami, Fla.

AWS (2020a), *Structural Welding Code—Steel*, AWS D1.1, American Welding Society, Miami, Fla.

AWS (2020b), *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*, AWS A5.28/A5.28M, American Welding Society, Miami, Fla.

Bjork, T., Toivonen, J., and Nykanen, T. (2012), "Capacity of Fillet Welded Joints Made of Ultra High-Strength Steel," *Welding in the World*, Vol. 56.

Butler, L.J. and Kulak, G.L. (1971), "Strength of Fillet Welds as a Function of Direction of Load," *Welding Research Supplement*, pp. 231–234.

Butler, L.J., Pal, S., and Kulak, G.L. (1972), "Eccentrically Loaded Welded Connections," *Journal of the Structural Division*, ASCE, Vol. 98, No. ST5.

Collin, P.P. and Johansson, P.B. (2005), "Design of Welds in High Strength Steel," *Proceedings of the Fourth European Conference on Steel and Composite Structures.*

Dowswell, B., Cox, C., Gallow, M.S., and Fouad, F.H. (2021), *Fillet and PJP Welds*, Final Report, American Institute of Steel Construction, Chicago, Ill.

Lesik D.F. and Kennedy, D.J.L. (1990), "Ultimate Strength of Fillet Welded Connections Loaded in Plane," *Canadian Journal of Civil Engineering*, Vol. 17, No. 1, pp. 55–67.

Miazga, G.S. and Kennedy, D.J.L. (1989), "Behavior of Fillet Welds as a Function of the Angle of Loading," *Canadian Journal of Civil Engineering*, Vol. 16, No. 4, pp. 583–599.

Neis, V.V. (1985), "New Constitutive Law for Equal Leg Fillet Welds," *Journal of Structural Engineering*, Vol. 111, No. 8.

Sun, F.F., Ran, M.M., and Wang, Y.B. (2019), "Mechanical Behavior of Transverse Fillet Welded Joints of High Strength Steel Using Digital Image Correlation Techniques," *Journal of Constructional Steel Research*, Vol. 162.

Thornton, W.A. (2020), Personal Communication.

Tide, R.H.R. (2020), Personal Communication.

Tide, R.H.R. (1980), "Eccentrically Loaded Weld Groups—AISC Design Tables," *Engineering Journal*, AISC, Vol. 17, No. 4, pp. 90–95.