Effect of Loading Angle on the Behavior of Fillet Welds

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The behavior of fillet welds is well known to be a function of the direction of the applied load with respect to the weld axis. Experimental studies have shown that as the angle of loading increases from 0° (longitudinal weld) to 90° (transverse weld), the strength of the fillet weld increases but the overall connection ductility decreases. The influence of the angle of loading on fillet weld strength and ductility is recognized by the most recent North American steel design standards, the *Specification for Structural Steel Buildings* (AISC, 2005), and CSA–S16–01 (CSA, 2001). The equation used in both standards is based on the expression proposed by Lesik and Kennedy (1990), which is a simplified version of the original relationship developed by Miazga and Kennedy (1989) using the results of their experimental program. The equation predicts that fillet weld strength increases by 50% as the angle of loading increases from 0° to 90°.

The test program of Miazga and Kennedy (1989) included lap-spliced fillet weld specimens fabricated using the shielded metal arc welding (SMAW) process with one electrode type that had no minimum toughness requirement. This welding process is not commonly used in industry for high-production welding. Because of heat input limitations with the SMAW process, it can produce welds with higher toughness levels than the more prevalent flux-cored arc welding (FCAW) process (Sakino, Horikawa, and Kamura, 2001). Moreover, the toughness of the filler metal used in Miazga and Kennedy's study was not measured so the impact of toughness is not quantifiable based on these tests alone. Therefore, as part of a comprehensive research program initiated by AISC on the behavior of fillet welds, research was carried out to reevaluate the effectiveness of the current method to account for the angle of loading and to assess the level of safety currently being provided by welds with different orientations. Additional tests on fillet welds of different measured toughness levels were conducted to determine the effect of toughness and filler metal classification on the strength and ductility of welds and to ensure that the strength improvements recognized by the design provisions are independent of weld toughness. An earlier phase of the research program, described in Ng, Deng, Grondin, and Driver (2004a) and Ng, Driver, and Grondin (2004b), investigated the effect of several parameters on the strength and ductility of transverse fillet welds. This paper draws on experimental results from that research.

The objectives of this phase of the research program were achieved through an experimental program consisting of 27 lap-spliced fillet weld specimens where electrode classification and weld orientation were the main variables, as detailed in Table 1. Nine specimens each were fabricated with transverse welds (Figure 1), with welds oriented at 45° to the line of action of the load (Figure 2), and with longitudinal welds (Figure 3). The specimens were prepared using the FCAW process with electrodes of three different classifications, namely, E70T-4, E70T-7, and E71T8-K6. The first two electrodes have no minimum toughness requirement, while the last one has a minimum toughness requirement of 27 J at –29 °C (20 ft-lbf at –20 °F) (AWS, 1998). All results were analyzed and compared with the data available from other studies. The applicability of the current design equation to fillet welds made with three different FCAW filler metal classifications was assessed by comparing the predicted strength and ductility with the experimental results and by evaluating the associated safety indices.

BACKGROUND

Several test programs conducted over the past five decades have investigated the strength of fillet welds oriented at various angles relative to the line of action of the load. A detailed review of these test programs is presented by Deng, Grondin, and Driver (2003) and a summary is presented by Ng et al.

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Table 1. Test Matrix									
Filler Metal Classification	E70T-4			E70T-7			E71T8-K6		
Weld Orientation	0°	45°	90° †	0°	45°	90°†	0°	45°	90° †
Number of Specimens	3	3	3	3	3	3	3	3	3
Number of Charpy Tests	3 × 2			3 × 2			3 × 2		
Number of Material Tension Tests	2			2			2		

† Specimens also reported by Ng et al. (2004a)

(2004a). In addition to the orientation of the weld axis, test parameters have included weld tensile strength, base metal strength, fillet weld size, and weld length. The strength of transverse fillet welds was found to be from 1.44 to 1.59 times that of equivalent longitudinal fillet welds.

Based on the results of tests on full-scale welded specimens, Miazga and Kennedy (1989) proposed a method to predict the strength of fillet welds based on the maximum shear stress failure criterion. The method was validated by a comparison with their own test results and tests from other researchers (Butler and Kulak, 1971; Clark, 1971). Lesik and Kennedy (1990) extended the work of Miazga and Kennedy and proposed a simplified equation for which the predicted weld tensile strength deviates from that predicted by Miazga and Kennedy by less than 1.5%. This equation is a function only of the angle, θ, between the axis of the weld and the line of action of the load and takes the following form:

$$V_\theta / V_0 = 1.0 + 0.50 \sin^{1.5} \theta \quad (1)$$

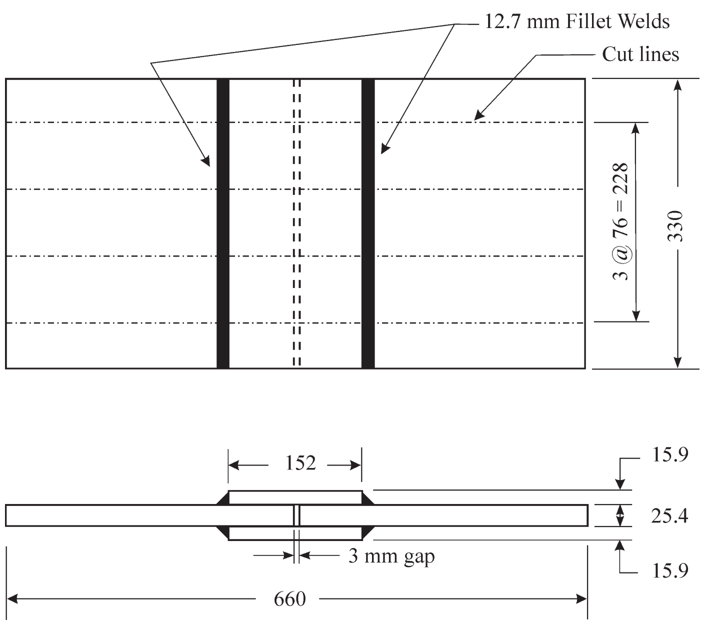


Fig. 1. Transverse fillet weld specimens.

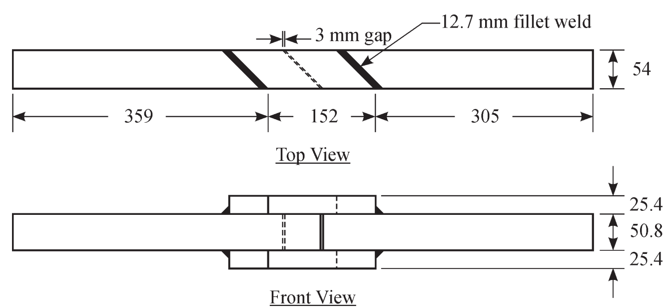


Fig. 2. 45° fillet weld specimens.

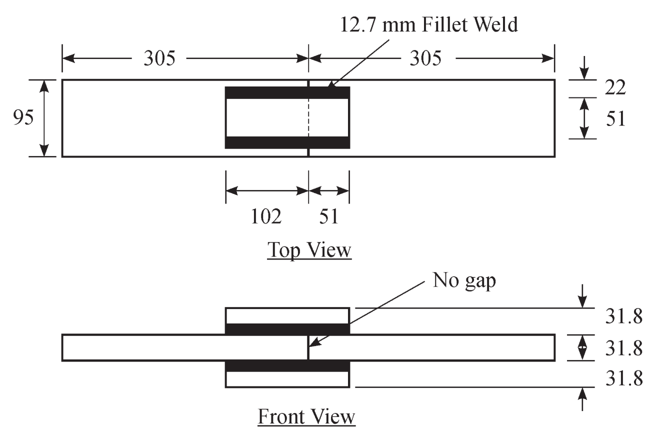


Fig. 3. Longitudinal fillet weld specimens.

Table 2. Welding Procedure Specification							
Classification	Wire Dia. (mm)	Polarity	Stick-Out (mm)	Wire Speed (mm/min)	Current (A)	Voltage (V)	Heat Input* (kJ/mm)
E70T-4	2.38	DC+	63.5	225	350	29	2.17
E70T-7	2.38	DC–	38.1	170	350	26	2.57
E71T8-K6	1.98	DC–	19.05	180	330	24	2.11

Note: All welds were nominally 12.7 mm and were deposited in three passes.
* Calculated using 80% efficiency for FCAW.

where V_θ / V_0 is the ratio of the strength of a fillet weld oriented at an angle θ to that of an equal size longitudinal fillet weld. This equation, which predicts that a transverse fillet weld has 50% more capacity than an equal size longitudinal fillet weld, has been adopted by both the Canadian structural steel design standard, CSA–S16–01 (CSA, 2001), and the American Institute of Steel Construction originally as part of Chapter J of the 1999 *Load and Resistance Factor Design Specification for Structural Steel Buildings* (AISC, 1999) and more recently in the 2005 *Specification for Structural Steel Buildings* (AISC, 2005), hereafter referred to as the AISC *Specification*. The broad applicability of this large increase in strength for transverse welds has recently been questioned since Miazga and Kennedy performed all their tests using one filler metal (E7014) and the SMAW process. E7014 electrodes have no specified toughness requirement; however, the level of toughness was not determined and may have been influential since SMAW generally produce welds with toughness levels that exceed 27 J (20 ft-lbf) at room temperature (Ng et al., 2004a).

TEST PROGRAM

Description of Test Specimens

The weld orientations studied are 0°, 45°, and 90°, measured relative to the line of action of the load. Filler metals both with and without a specified minimum toughness were selected and the fracture toughness, determined from Charpy tests, was measured for each classification. Three FCAW filler metals were selected for this study: two with no specified toughness (E70T-4 and E70T-7) and one with a toughness requirement of 27 J at –29 °C (20 ft-lbf at –20 °F) (E71T8-K6). As determined from a previous investigation (Ng et al., 2004b), the selected filler metals provide a wide range of weld metal toughness. All the filler metals used in this test program were produced by the same major manufacturer and were all of the self-shielding type. Filler metals of the same classification were obtained from the same spool for consistency.

All plates used for the transverse weld specimens met the requirements of ASTM A572 Grade 50 and CAN/CSA–G40.21–98 Grade 350W steel. All plates used for the longitudinal and 45° weld specimens conformed to the specifications of CAN/CSA–G40.21–98 Grade 300W steel. The plate thickness used for the longitudinal and 45° weld specimens was generally larger than for the transverse weld specimens (see Figures 1 to 3), which necessitated the use of a lower-grade steel for the thicker plates. All steel grades used for the preparation of the test specimens are widely used structural grades. Four different plate thicknesses were used in the fabrication of the specimens: 15.9 mm (⅝ in.), 25.4 mm (1 in.), 31.8 mm (1 ¼ in.), and 50.8 mm (2 in.). In order to minimize the sources of variation in the test results, plates of the same thickness were obtained from the same heat, except for the 25.4 mm (1 in.) plates. The 25.4 mm (1 in.) plate used for the fabrication of the transverse weld specimens and the one used for the fabrication of the longitudinal and 45° weld specimens came from different heats.

All specimens were fabricated as double lap-spliced joints, as depicted in Figures 1 to 3, with 12.7 mm (½ in.) fillet welds oriented at one of three angles with respect to the loading direction: 0°, 45°, and 90°. Because several studies (Higgins and Preece, 1969; Swannell and Skewes, 1979; Ng et al., 2004a) have shown that unit weld strength (strength per unit weld size) decreases with increasing weld size, the larger weld size used by Ng et al. (2004a) was selected in order to produce conservative results. For each weld orientation, three specimens were fabricated with each of the three flux-cored electrode classifications selected for this project. All plates were made sufficiently thick to allow fracture to occur in the welds, but they were not designed to prevent yielding before fracture. A summary of the test matrix is shown in Table 1, along with the ancillary tests conducted on the weld metal. The welding procedure specification adopted for the preparation of the test specimens is summarized in Table 2.

The welds at one end of each specimen were reinforced to force failure to occur at the other end, thus reducing the amount of instrumentation and number of pre-test measurements required. The transverse and 45° welds were reinforced by depositing three additional weld passes. The longitudinal welds were reinforced through the design of the specimens, as described below. The welds that were not reinforced are referred to in the following as the "test welds."

Three transverse fillet weld specimens of the same filler metal classification were fabricated in a single assembly. An extra 100 mm (4 in.) was added to the width of the assembly to avoid including the weld starts and stops within the test specimens. Three specimens, with weld lengths of 76 mm (3 in.), were then cut from the assembly using a water jet cutting process and the cut edges were then milled smooth. Figure 1 shows a typical assembly for the transverse weld specimens. The 45° specimens were fabricated individually with the aid of weld tabs that were removed with a precision grinding wheel prior to testing. The 54 mm (2⅛ in.) width was chosen to produce the same weld length as the transverse fillet welds (see Figure 2). The longitudinal weld specimens were also fabricated individually but, due to the specimen design, weld tabs were required at the test end of the specimen so that the weld would not be stopped in the test area. Unlike the other specimen types, the two main plates were placed against one another with no gap in between, an arrangement that allowed for continuous welds on each side of the splice plates, as shown in Figure 3. These fillets would later be separated into test welds and reinforced welds by cutting the weld at the junction of the main plates with a precision grinding wheel. The reinforced welds were of the same leg size as the test welds, but their length was twice that of the test weld to ensure that failure would occur at the test end.

Specimen Measurements and Test Procedure

Before testing, the weld leg size and weld profile were measured at 10 mm (7⁄16 in.) intervals along the weld length. The actual length of each weld was also recorded. Summaries of the mean weld dimensions are given in Tables 3 to 5 and the locations of the measurements on the weld profile are indicated in Figure 4. The complete data set and plots of the weld profiles are reported in Deng et al. (2003).

Four linear variable differential transformers (LVDTs)—two on each test weld—were used to measure weld deformations on the transverse and 45° welds. Six LVDTs were used to measure weld deformations on the longitudinal welds. The locations of the LVDTs are illustrated in Figure 5. The LVDTs were mounted with custom-made brackets to measure only the deformation within the leg dimension of the transverse and 45° welds and thereby avoid capturing a significant amount of the deformation of the base plate. The LVDTs were kept in place until fracture of one of the test welds in order to acquire the full load versus deformation curve. The tests were conducted quasi-statically, with static readings taken at multiple points during the test. The tests were stopped at rupture of one of the two test welds.

The gauge length used to calculate strain in the transverse weld specimens was taken as the average weld leg size measured at the LVDT locations. For the 45° welds, the gauge length was taken as this average divided by the sine of 45° to obtain the weld dimension parallel to the loading direction. The displacement measurements for the longitudinal welds were made over the full length of the test welds as well as over the gap between the weld tab and the splice plate. The gauge length used for strain calculations for these specimens was taken as the average weld leg size giving, in effect, a shear strain.

After fracture of the weld, the specimen was carefully removed from the testing machine to avoid any damage to the fracture surface. The area of the fracture surface, which includes the root penetration, was measured, and measurements of the angle of the fracture surface were taken at eight locations along the weld length using a vernier bevel protractor.

TEST RESULTS

Ancillary Tests

A summary of the ancillary test results from the base metal used for the transverse weld specimens and weld metal is reported in the following. Details of these tests are reported in Deng et al. (2003). The material properties for the base metal used in the fabrication of the longitudinal and the 45° weld test specimens were obtained from the mill certificates.

In all cases, the mean tensile strength of the all-weld-metal tension coupons exceeded the minimum requirement in the specifications of 480 MPa (70 ksi), but the amount by which the minimum strength was exceeded varied widely.

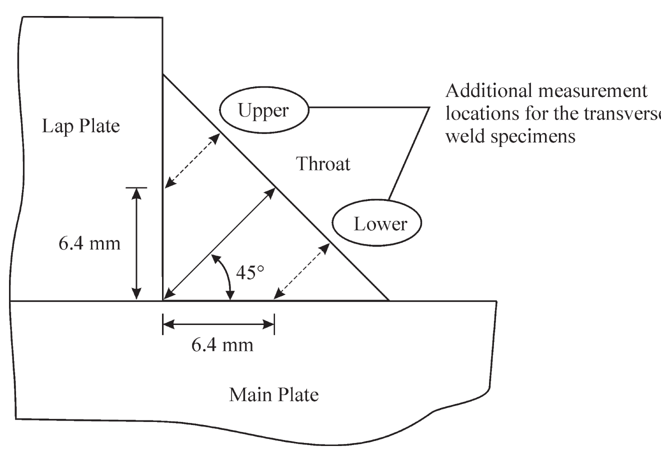


Fig. 4. Fillet weld measurements.

Table 3. Mean Weld Dimensions for Transverse Weld Specimens													
Specimen Designation	Front Face						Back Face						
	Shear Leg* (mm)	Tension Leg (mm)	45° Measurements			Weld Length (mm)	Shear Leg (mm)	Tension Leg (mm)	45° Measurements			Weld Length (mm)
			Upper (mm)	Throat (mm)	Lower (mm)				Upper (mm)	Throat (mm)	Lower (mm)	
T22-1	9.4	10.6	3.6	7.8	3.2	76.2	11.1	11.9	4.8	9.2	4.2	76.1
T22-2	10.3	10.0	3.3	8.0	3.6	76.1	10.8	11.5	4.9	9.0	4.0	76.1
T22-3	11.1	10.1	3.4	8.4	4.2	76.0	10.1	11.6	4.4	8.5	3.3	76.1
T26-1	12.4	11.6	4.8	9.5	4.9	76.0	13.2	10.6	3.7	9.0	4.8	76.3
T26-2	12.4	11.9	4.9	9.5	5.0	75.9	12.7	11.2	4.4	9.2	4.8	76.1
T26-3	13.0	11.7	4.6	9.3	5.1	76.2	13.0	11.6	4.4	9.3	5.0	76.2
T32-1	12.3	11.2	4.1	8.8	4.3	76.0	12.2	12.7	4.8	8.9	4.4	76.2
T32-2	11.4	11.7	4.4	9.1	4.6	76.1	12.1	12.7	4.7	9.0	4.7	76.1
T32-3	10.5	12.9	5.0	8.7	4.1	76.0	12.2	11.8	4.4	9.0	4.6	76.1

* The shear leg is parallel to the applied load; i.e. it is the leg against the main plate. The tension leg is the leg against the splice plate.

Table 4. Mean Weld Dimensions for 45° Weld Specimens								
Specimen Designation	Front Face				Back Face			
	Shear Leg* (mm)	Tension Leg (mm)	45° Meas. (mm)	Weld Length (mm)	Shear Leg (mm)	Tension Leg (mm)	45° Meas. (mm)	Weld Length (mm)
F1-1	11.3	10.8	8.7	73.7	11.8	11.0	8.6	72.5
F1-2	9.9	9.5	7.1	71.0	10.9	9.7	7.4	73.4
F1-3	9.5	10.0	8.0	71.7	11.1	10.4	8.3	74.0
F2-1	9.5	10.1	7.6	71.8	9.9	11.4	7.6	70.8
F2-2	10.7	11.2	8.1	72.7	10.3	11.0	8.2	71.0
F2-3	9.3	11.0	7.5	70.6	11.0	11.0	8.1	75.6
F3-1	10.0	12.3	8.8	70.2	10.5	13.4	8.8	71.1
F3-2	10.3	10.7	7.6	71.8	9.5	11.5	7.6	72.7
F3-3	9.2	12.6	7.6	72.1	9.5	13.0	8.6	70.1

* The shear leg is parallel to the applied load; i.e. it is the leg against the main plate. The tension leg is the leg against the splice plate.

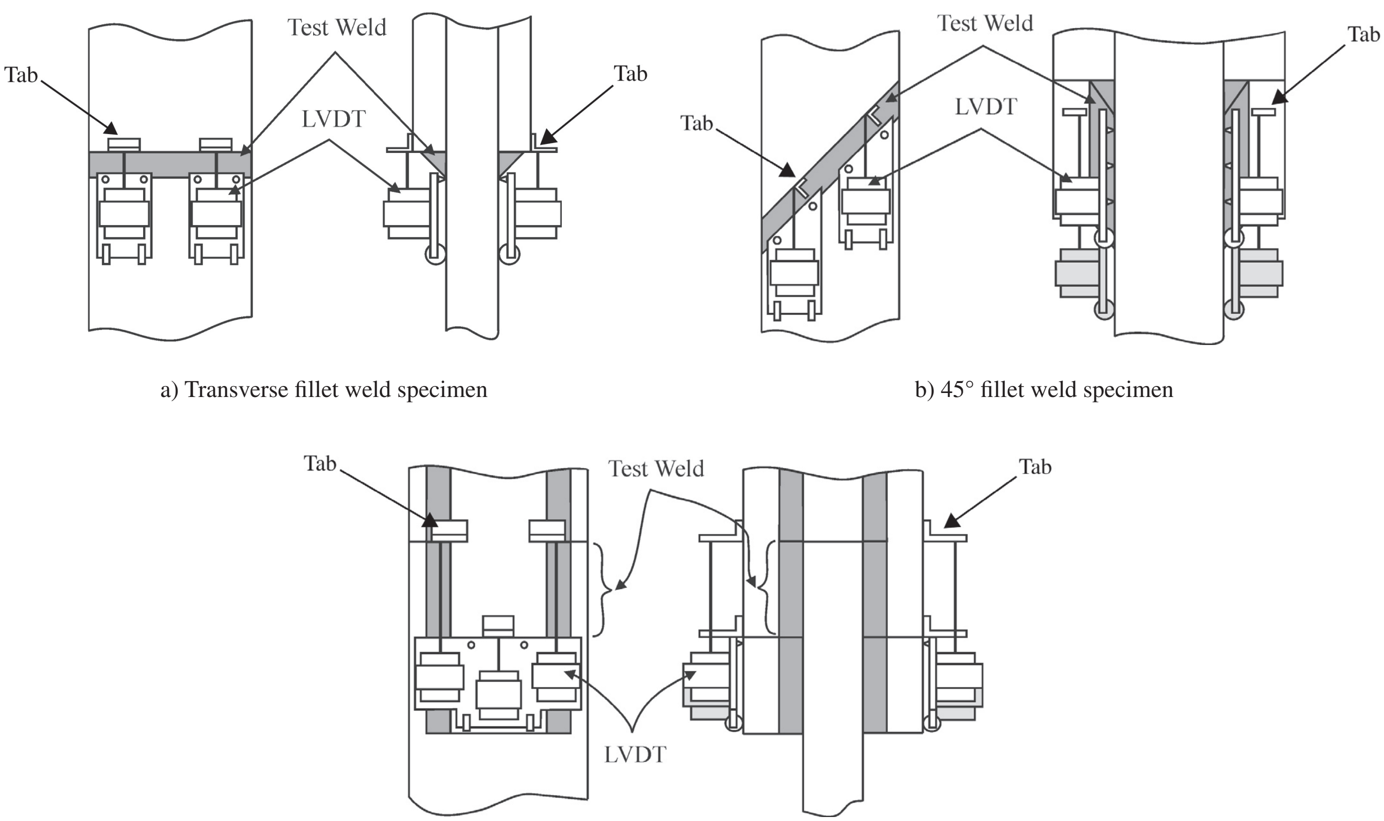
The mean static yield and tensile strengths for the weld metals with no toughness requirement were 470 MPa (68 ksi) and 618 MPa (90 ksi), respectively. For the weld metal with a toughness requirement, they were 402 MPa (58 ksi) and 493 MPa (72 ksi), respectively. The yield strengths reported here were determined using the 0.2% offset method [ASTM A370 (ASTM, 1997)].

The yield strengths of the base materials, either measured or determined from mill certificates, varied from 305 MPa (44 ksi) to 386 MPa (56 ksi) for the various plate thicknesses used in the test program. The tensile strengths varied from 462 MPa (67 ksi) to 538 MPa (78 ksi). The elongations at rupture also satisfied the minimum requirement of 21%, with values varying from 27% to 41%.

Table 5. Mean Weld Dimensions for Longitudinal Weld Specimens

Specimen Designation	Front Face								Back Face							
	Weld 1		Weld 2		45° Measurement		Weld Length		Weld 3		Weld 4		45° Measurement		Weld Length	
	MPL† (mm)	LPL‡ (mm)	MPL† (mm)	LPL‡ (mm)	Weld 1 (mm)	Weld 2 (mm)	Weld 1 (mm)	Weld 2 (mm)	MPL† (mm)	LPL‡ (mm)	MPL† (mm)	LPL‡ (mm)	Weld 3 (mm)	Weld 4 (mm)	Weld 3 (mm)	Weld 4 (mm)
L1-1	10.6	11.4	8.7	9.4	5.9	7.2	49.6	50.6	10.5	10.6	10.0	11.0	8.4	7.6	49.3	47.9
L1-2	11.3	11.5	11.7	10.4	7.8	7.8	49.9	50.0	11.0	9.6	10.9	9.4	7.6	7.4	50.4	49.6
L1-3	10.8	11.5	9.4	10.7	8.0	6.9	48.3	50.8	10.8	10.1	10.3	10.4	7.6	7.3	49.5	49.5
L2-1	10.9	12.0	10.7	11.4	9.2	8.2	48.0	49.7	10.8	11.3	11.6	11.2	8.0	7.3	49.6	49.5
L2-2	10.3	11.0	10.0	10.1	6.9	6.8	48.9	50.0	12.3	11.0	9.8	11.6	7.7	6.5	49.9	48.9
L2-3	11.2	11.9	9.8	11.2	9.0	7.3	49.8	49.8	10.5	11.8	10.5	11.0	8.2	7.9	46.6	49.2
L3-1	10.0	11.9	10.3	10.8	9.1	9.7	49.3	50.5	9.8	10.7	9.0	10.7	8.0	8.2	48.9	50.1
L3-2	9.5	12.2	9.7	11.4	7.6	6.8	48.3	49.6	9.6	12.0	10.0	11.1	8.3	7.4	50.3	49.2
L3-3	9.3	11.3	11.7	11.5	7.5	8.9	50.9	51.1	10.7	10.2	9.7	9.8	8.6	8.2	52.1	50.2

† Main Plate Leg – Size of the weld leg on the main plate.
‡ Lap Plate Leg – Size of the weld leg on the lap plate.



a) Transverse fillet weld specimen

b) 45° fillet weld specimen

c) Longitudinal fillet weld specimen

Fig. 5. Arrangement of instrumentation.

Table 6. Chemical Analysis of Filler Metals											
AWS Classification	Weight (%)										
	C	Mn	Si	P	S	Ni	Cr	Mo	V	Cu	Al
E70T-4	0.345	0.295	0.057	0.010	0.0036	0.024	<0.030	<0.050	0.0034	0.016	1.350
E70T-7	0.313	0.379	0.065	0.009	0.0032	0.017	0.340	<0.050	0.0046	0.019	1.110
E71T8-K6	0.106	0.806	0.088	0.015	0.0043	0.442	0.030	<0.050	0.0052	0.019	0.392

Standard Charpy V-Notch tests were conducted for each weld metal in duplicate at three different temperatures, namely, –29 °C (–11.5 °F), 21 °C (70 °F), and 100 °C (212 °F). In accordance with the ANSI/AWS A5.29 Specification (AWS, 1998), the notch was oriented in the thickness direction with fracture propagation along the axis of the weld. The average test results presented in Figure 6 show that the two electrodes without a specified toughness (E70T-4 and E70T-7) had similar impact energies at all three temperatures. The E71T8-K6 filler metal (with a specified toughness) exhibited four to five times higher impact energies than those without a specified toughness.

The chemical composition by weight of each filler metal used in this investigation is presented in Table 6. In all cases the element quantities satisfy the requirements of the applicable AWS filler metal specification. As expected, the filler metal with a minimum toughness requirement has a significantly higher nickel content and lower aluminum and carbon content than those without.

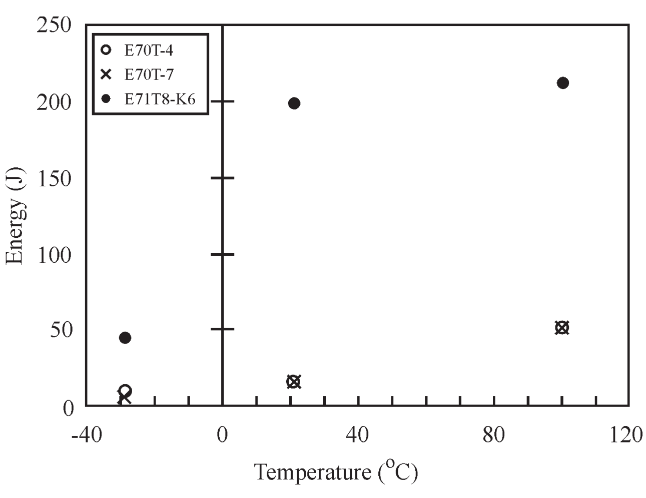


Fig. 6. Charpy V-Notch test results.

Fillet Weld Tests

A summary of the fillet weld test results is presented in Table 7. In most specimens, the test welds did not all fracture simultaneously. Because the loading becomes eccentric after the first fracture occurs, this summary presents the means of the results corresponding only to those welds that failed first. The mean test values were calculated from the data from the triplicate specimens. Test specimen F3-3 failed at one of the reinforced welds; hence, the values shown for designation F3 represent the mean of two, rather than three, tests. The data for the individual specimens are presented in detail elsewhere (Deng et al., 2003).

Test-to-Predicted Ratios

To evaluate the accuracy of the weld strength equation used in Chapter J of the AISC *Specification* (AISC, 2005), the test-to-predicted ratios were calculated for the test specimens. The mean ratio for each set of triplicate tests is given in Table 7. The weld strength equation can be expressed as

$$V_r = 0.60\,\phi\,A_w\,F_{EXX}\,(1.00 + 0.50\sin^{1.5}\theta) \qquad (2)$$

where

A_w = weld throat area, mm² (in.²)

F_{EXX} = minimum specified tensile strength of the weld metal, ksi (MPa)

θ = angle between the applied load and the axis of the weld

The predicted strengths were determined using a resistance factor, ϕ, of 1.0 and using a throat area based on measured leg sizes, and the weld tensile strength was determined from weld metal coupon tests.

Because it was observed that the measured strength for two of the filler metals was significantly higher than the nominal value, a second test-to-predicted ratio was calculated using the nominal weld strength [480 MPa (70 ksi) for all the filler metals used in this program]. Comparison of the two ratios permits an assessment of the effect of the filler metal overstrength itself.

Table 7. Summary of Fillet Weld Specimen Test Results									
Assembly Designation	AWS Classification	Mean Ultimate Load, P_u (kN)	Test/Predicted Ratio		Mean Ultimate P/A_{throat} (MPa)	Mean $P/A_{fracture}$ (MPa)	Mean Strain at P_u	Mean Fracture Strain	Mean Fracture Angle (°)
			Measured Weld Strength	Nominal Weld Strength					
T22	E70T-4	936	1.34	1.76	849	488	0.133	0.149	0
T26	E70T-7	1063	1.35	1.70	822	666	0.198	0.202	23
T32	E71T8-K6	1038	1.61	1.66	799	634	0.254	0.264	19
F1	E70T-4	765	1.35	1.77	738	569	0.095	0.101	22
F2	E70T-7	825	1.54	1.94	808	594	0.122	0.128	35
F3	E71T8-K6	740	1.60	1.65	687	583	0.131	0.156	28
L1	E70T-4	744	1.17	1.54	496	476	0.160	0.242	32
L2	E70T-7	812	1.35	1.69	545	475	0.143	0.272	27
L3	E71T8-K6	731	1.51	1.56	500	402	0.185	0.472	32

Both ratios indicate that Equation 2 is conservative for all the specimens tested. The overall mean ratio based on measured weld strength is 1.42, with maximum and minimum values of 1.67 and 1.12, respectively. The overall mean ratio based on nominal weld strength is 1.70, with maximum and minimum values of 1.96 and 1.47, respectively.

Weld Fracture Stress

The weld stresses at fracture shown in Table 7 were calculated based on the assumption that the two test welds shared the applied load equally. The stress was determined using two different areas: the measured fracture surface area, $A_{fracture}$, and the theoretical throat area, A_{throat}. The theoretical throat area was calculated based on the mean measured leg sizes of the welds and therefore does not include the additional area due to root penetration and weld face reinforcement. The fracture surface area, however, accounts for both quantities and consequently is often the larger of the two values. On average, the stress calculated with the nominal throat area was 27% higher than the stress determined based on the fracture surface area.

Weld Strain

Both the mean strain at ultimate load and at weld fracture are presented in Table 7. The overall mean fracture strains were 0.205, 0.125, and 0.329 for the transverse, 45°, and longitudinal welds, respectively.

For the 45° and transverse weld specimens, the strains were calculated by dividing the deformations measured with LVDTs by the corresponding gauge length. For the longitudinal specimens, the only strain given is the shear strain; the longitudinal strain was not determined because the deformation experienced by the welds was mostly due to shear since the base plates did not yield. The shear strain was calculated by dividing the average of the two overall deformation measurements on one face by the average of the main plate shear leg measurements. These deformations could be used to determine the shear strain because the base plates remained elastic. By averaging the two overall deformation measurements on one face of the test specimen, the effect of any in-plane specimen rotation on the displacement values is minimized. To quantify the observation that the overall and shear displacements were essentially the same, a comparison between the two deformation measurements was made by taking the ratio of the shear displacement values to the average of the two overall displacement values taken on the same specimen face. The mean ratio was 1.09 with a standard deviation of 0.077.

Fracture Angle

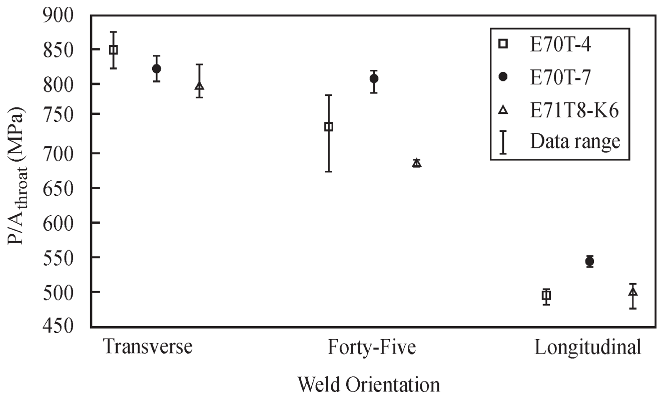
The mean measured angles of the weld fracture surface for each assembly are given in Table 7. The mean fracture angles for all specimens of each series were 14°, 28°, and 32°, measured from the surface of the main plate, for the transverse, 45°, and longitudinal welds, respectively.

In general, there were two locations in which weld fracture tended to occur: at the interface between weld passes and at the leg parallel to the applied load; in other words, the shear leg. Five of the nine transverse weld specimens fractured at the interface between the weld passes, while three failed at the shear leg. One had nonuniform failure planes, containing a combination of fracture at the shear leg and failure at some other location in the weld. Six 45° and eight longitudinal welds failed at the interface between the weld passes. The remaining welds (three 45° and one longitudinal) had fracture surfaces that ran partially along the interface between the weld passes and partially along the weld lap plate leg.

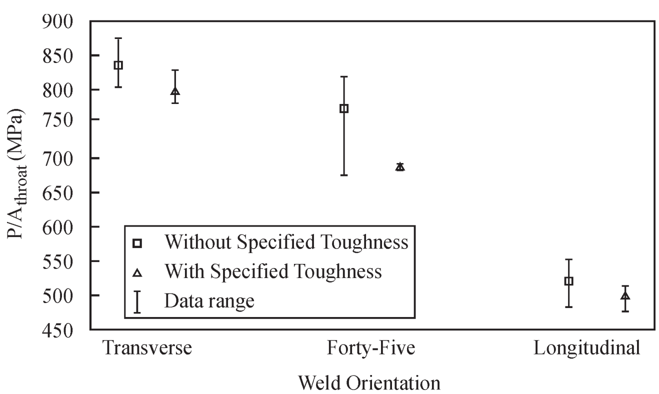
Effect of Weld Orientation

Figures 7 and 8, based on the theoretical throat and the fracture surface areas, respectively, show that there is a distinct decrease in weld strength as the weld orientation approaches the longitudinal case. The apparent discrepancy in Figure 8(a) between the E70T-4 welds and the other welds within the transverse weld test specimens is a result of the excess weld reinforcement observed in the E70T-4 specimens, causing failure of the weld along the shear face, whereas the other specimens in the group failed closer to the weld throat.

According to the stress versus strain curves of Miazga and Kennedy (1989), the fracture strains among fillet welds of different orientations vary, and there is no clear relationship between the two variables. The same conclusions can be reached using the data presented by Butler and Kulak (1971). However, the mean fracture shear strain of their

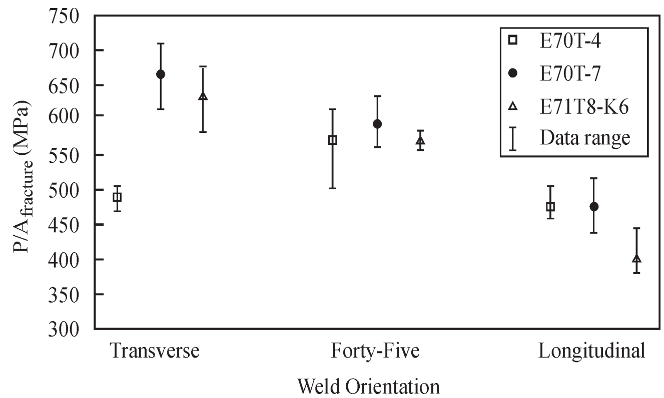


(a) Effect of filler metal classification and weld orientation on weld strength

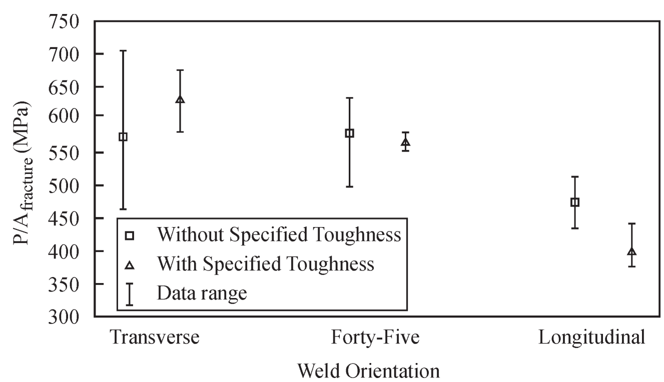


(b) Effect of filler metal toughness and weld orientation on weld strength

Fig. 7. Effect of weld metal classification, filler metal toughness, and weld orientation on fillet weld strength calculated using the theoretical throat area.



(a) Effect of filler metal classification and weld orientation on weld strength



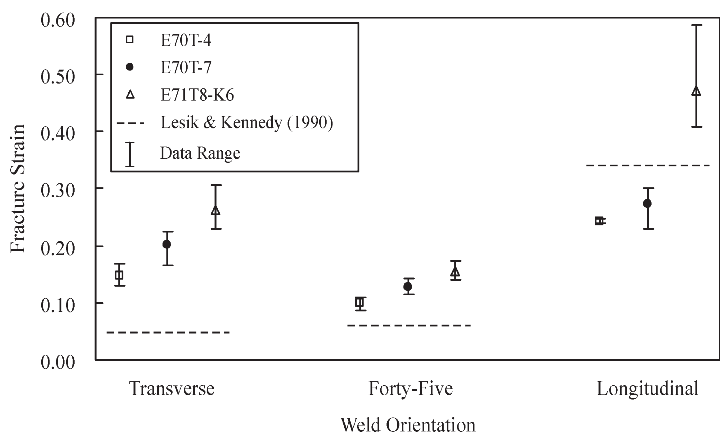
(b) Effect of filler metal toughness and weld orientation on weld strength

Fig. 8. Effect of weld metal classification, filler metal toughness, and weld orientation on fillet weld strength calculated using the fracture surface area.

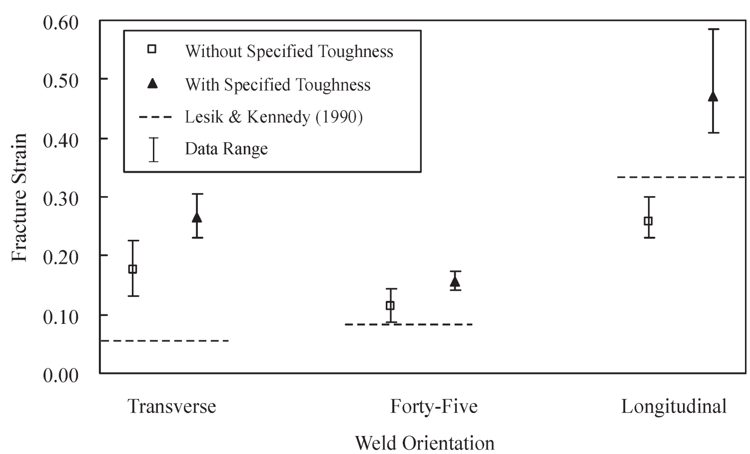
longitudinal welds was about four times as high as the mean fracture strain of their transverse and 45° welds. Similar observations can be made from the test results presented herein, as illustrated in Figure 9. There is no general trend showing an increase or decrease in fracture strain with loading angle, but the strains at fracture for the longitudinal welds are significantly higher than those for the other two weld orientations. For the filler metals without a toughness requirement, the mean fracture strain of the longitudinal welds is 1.5 and 2.3 times as high as the mean fracture strains of the transverse and 45° welds, respectively. For the welds with a toughness requirement, the mean fracture strain of the longitudinal welds is 1.8 and 3.0 times as high as the mean fracture strains of the transverse and 45° welds, respectively. There is also a much larger difference between the strain at ultimate load and the strain at weld fracture for the longitudinal welds. The mean ratio between the fracture strain and the strain at ultimate load is 2.0 for these welds, as compared to 1.1 for the other two weld orientations.

Effect of Filler Metal Classification on Fillet Weld Strength

Figures 7 and 8 compare the strengths of fillet welds according to filler metal classification, toughness, and weld orientation. In Figure 7(a), all the ranges of the transverse welds overlap, and the means are similar. There is only a 6% difference between the highest and lowest mean. These observations indicate that, for the E70 series filler metals evaluated, filler metal classification does not have a significant effect on



(a) Effect of filler metal classification and weld orientation on weld ductility



(b) Effect of filler metal toughness and weld orientation on weld ductility

Fig. 9. Effect of filler metal classification, filler metal toughness, and weld orientation on fillet weld ductility.

the strength of transverse welds. The same is true regarding weld toughness; it does not have a significant effect on the strength of transverse welds [Figure 7(b)]. However, Figure 8(a), which presents the stress at fracture calculated using the measured fracture surface area, appears to support the converse conclusion. This figure shows that the E70T-4 welds had at least 30% lower strength than the welds of the other two filler metal classifications. The apparent discrepancy between the E70T-4 welds and the other welds within the transverse weld test specimens was explained previously. When plotted according to toughness [Figure 8(b)], the strengths are seen to be similar for transverse welds.

The plots of the 45° weld specimen strengths calculated on the theoretical throat area (Figure 7) show that the mean strengths are within 15% of each other and the test data ranges overlap, indicating that electrode classification does not have a large effect on weld strength. The mean strengths for the E70T-4 and E71T8-K6 weld specimens are 91% and 85%, respectively, of the strength of the E70T-7 specimens, which displayed the highest strength of the three electrode classifications. Figure 8 shows that if the root penetration and face reinforcement are accounted for, the mean strength of the three electrode classifications fall within 4% of each other. Therefore, it is concluded that, for the E70 series filler metals evaluated, the filler metal classification and toughness level have little effect on weld strength.

The longitudinal weld strengths calculated using the theoretical throat area (Figure 7) indicate that the E70T-7 welds were approximately 10% stronger than the welds from the other two electrodes. Again, once the root penetration and face reinforcement are considered, the mean strength of the E70T-4 and E70T-7 specimens become very close, as shown in Figure 8(a). However, using the fracture surface area to calculate the strength increases the difference between the welds with and without a toughness requirement, as shown in Figure 8(b). The mean strength of the welds without a toughness requirement is 18% higher than that of the welds with a toughness requirement.

Effect of Filler Metal Classification on Fillet Weld Ductility

The strain at fracture was used as a measure of ductility of the welds. The strain was obtained by dividing the measured deformation by the gauge length over which the deformation was measured, namely, the weld leg size times the sine of the angle between the axis of the weld and the line of action of the applied load.

The effect of filler metal classification and toughness on ductility can be assessed from Figure 9. The figure indicates that there is a consistent trend between weld ductility and filler metal classification for all three weld orientations investigated in this program. The E70T-4 welds were the least ductile and the E71T8-K6 welds were the most ductile for all weld orientations, as indicated in Figure 9(a). The ratio between the mean fracture strains of the welds made with filler metals without a toughness requirement (E70T-4 and E70T-7) ranges from 1.12 to 1.35 for the three orientations. Electrode classification, therefore, appears to have a notable effect on fillet weld ductility, although the difference in ductility between the two electrode classifications with no toughness requirement is statistically small. In an earlier phase of the test program (Ng et al., 2004a and 2004b), the mean fracture strain of the transverse E70T-4 welds was found to be not statistically different from that of E70T-7 welds. Since the number of test results for E70T-4 and E70T-7 welds from the earlier phase was about 10 times the number of test results obtained in the current phase, it is believed that the weak trend observed in Figure 9(a) is not statistically significant.

The ratios of the mean fracture strains of the welds for which the filler metals have a toughness requirement to those made with the filler metals for which there is no toughness requirement are 1.51, 1.37, and 1.84 for the transverse, 45°, and longitudinal welds, respectively. These are shown in Figure 9(b). The superior ductility shown by the welds with a toughness requirement was also observed in the earlier phase of the research (Ng et al., 2004a and 2004b) and in the weld metal coupon tests. Therefore, it is concluded that welds with higher toughness levels tend to be more ductile than welds with lower toughness levels. However, it should be noted that all of the measured fracture strains of the transverse and 45° specimens discussed in this paper exceed by a significant margin the values predicted by the empirical equation presented by Lesik and Kennedy (1990) based on SMAW tests by Miazga and Kennedy (1989). The fracture strains of the longitudinal specimens with no specified toughness are somewhat lower, however.

EVALUATION OF SAFETY INDEX

In order to obtain a statistical evaluation of the level of safety provided by the AISC Specification and CSA-S16-01, the safety index, β, was determined for the fillet weld design equation using the test results of this study. The traditional target safety index for connections is 4.5; therefore, the design equations can be considered adequate when the evaluated indices are at least that high. The AISC *Specification* has adopted Equation 2 as the design equation for fillet welds, with the resistance factor, ϕ, taken as 0.75. The equation used in CSA-S16-01 is similar to Equation 2 except that the constant 0.60 (the shear factor) is taken as 0.67 and the resistance factor is also taken as 0.67. It is noted that the product of the shear factor and the resistance factor is equal to 0.45 for both standards, so the resulting safety indices will be the same. Therefore, the following calculations of the safety index are presented only for the AISC *Specification*.

The procedure outlined by Lesik and Kennedy (1990) was used to determine the magnitude of the safety index, β, which can be determined from the following equation for the resistance factor, ϕ (based on Galambos and Ravindra, 1978):

$$\phi = \Phi_\beta \, \rho_R \, e^{-\beta \alpha_R V_R} \tag{3}$$

The coefficient of separation, α_R, was set to 0.55 as suggested by Galambos and Ravindra. The value of ϕ is 0.75. The factor Φ_β is an adjustment factor that modifies ϕ when β is not equal to the safety index used for the evaluation of the load factors, which is normally 3.0, as discussed in Fisher, Galambos, Kulak, and Ravindra (1978). An equation developed by Franchuk, Driver, and Grondin (2004) was used to calculate this factor:

$$\Phi_\beta = 0.0062\beta^2 - 0.131\beta + 1.338 \tag{4}$$

The bias coefficient for resistance, ρ_R, is obtained from

$$\rho_R = \rho_G \, \rho_{M1} \, \rho_{M2} \, \rho_P \tag{5}$$

where

ρ_G = mean ratio of the measured-to-nominal values for the theoretical throat area

ρ_{M1} = mean ratio of the measured-to-nominal ultimate tensile strength for the weld metal

ρ_{M2} = mean ratio of the measured to the predicted shear strengths of the weld metal

The measured shear strength was taken as the strength of the longitudinal weld specimens calculated on the theoretical throat area (calculated from the measured leg sizes), while the predicted values were calculated by multiplying the shear factor (0.60) by the measured tensile strength from the weld metal coupons. Although the longitudinal weld stress determined using the measured fracture surface area is the actual measured shear strength, the weld stress determined using the theoretical throat area was used instead because the design equation assumes that welds fail at the theoretical throat. The professional factor, ρ_P, is the mean test-to-predicted capacity ratio calculated as

$$\rho_P = \text{Mean}\left(\frac{\textit{Test Capacity}}{A_{throat} \times \tau_u \times \left(1.00 + 0.50\sin^{1.5}\theta\right)} \right) \tag{6}$$

where

A_{throat} = the theoretical weld throat area calculated using the measured fillet leg sizes

τ_u = the measured shear strength obtained from the test results of the longitudinal weld specimens

The last variable in Equation 3 is the coefficient of variation, V_R, for the resistance, which is determined from

$$V_R^{\,2} = V_G^{\,2} + V_{M1}^{\,2} + V_{M2}^{\,2} + V_P^{\,2} \tag{7}$$

where each variable is the associated coefficient of variation for the bias coefficients described above.

In order to provide a broad view of the safety level provided by the design equations, the reliability analysis was carried out for each weld orientation separately and for all the specimens from Miazga and Kennedy (1989), Ng et al. (2004a and 2004b), and the present research combined. Because the sample sizes for the transverse, 45°, and longitudinal weld specimens from this research phase are small, the results are not as reliable as the results for the fourth group where all the specimens are considered.

The values of ρ_G and V_G for each group were determined using the test results from the specimens of Miazga and Kennedy (1989), Ng et al. (2004a and 2004b), and those tested in this phase of the research program. Because an upper limit had to be placed on the tolerance of weld sizes for the fabrication of test specimens, the value of ρ_G used for the reliability analysis tends to be lower than expected in civil engineering structures. The bias coefficient for weld metal tensile strength and the associated coefficient of variation, ρ_{M1} and V_{M1}, for each group were obtained from Lesik and Kennedy (1990) because they analyzed a much larger number of weld metal tension coupon tests than was conducted in this research. For the groups of test specimens from the current test program, ρ_{M2} was obtained from the test results from the longitudinal weld specimens of this program. These values are tabulated in columns 2 to 4 of Table 8. However, because the sample size is too small to provide a representative coefficient of variation, V_{M2} was taken from the work of Lesik and Kennedy (1990). For the group combining all the specimens from the three test programs (last column of Table 8), the values of ρ_{M2} and V_{M2} calculated from a large sample by Lesik and Kennedy were used. It is noted that these values are determined using data from SMAW welds and the mean is considerably lower than that obtained in this research phase. The professional factor and the associated coefficient of variation, ρ_P and V_P, were evaluated using the following values of τ_u: 411 MPa (60 ksi) for the E7014 welds [the filler metal tested by Miazga and Kennedy (1989) and used in some specimens tested by Ng et al. (2004a)], 496 MPa (72 ksi) for the E70T-4 welds, 545 MPa (79 ksi) for the E70T-7 welds, 608 MPa (88 ksi) for the E70T7-K2 welds [the second FCAW filler metal with a toughness requirement tested by Ng et al. (2004a and 2004b)], and 506 MPa (73 ksi) for the E71T8-K6 welds. The τ_u value for the E7014 welds was calculated from the longitudinal weld test results of Miazga and Kennedy, while the remaining values were determined from the longitudinal

Table 8. Reliability Analysis for AISC (1999)				
	Current tests 90° Specimens	Current tests 45° Specimens	Current tests 0° Specimens	Miazga and Kennedy (1989), Ng et al. (2004a and 2004b), and Current Tests
Sample Size	9	8	9	145
ρ_G V_G	0.977 0.112	0.977 0.112	0.977 0.112	0.977 0.112
ρ_{M1} V_{M1}	1.123 0.077	1.123 0.077	1.123 0.077	1.123 0.077
ρ_{M2} V_{M2}	1.602 0.121	1.602 0.121	1.602 0.121	1.248 0.121
ρ_P V_P	1.069 0.060	1.403 0.088	0.944 0.036	1.141 0.174
ρ_R V_R	1.878 0.192	2.465 0.203	1.658 0.186	1.562 0.252
β	**6.2**	**7.5**	**5.6**	**4.4**

weld tests conducted in the present test program. Because no longitudinal weld specimens were prepared with the E70T7-K2 filler metal, the τ_u value for these welds was obtained by multiplying the τ_u value for the E71T8-K6 welds by 1.20. This number is the ratio between the mean tensile strengths of the E70T7-K2 and the E71T8-K6 filler metals measured from the weld metal tension coupon tests presented by Ng et al. (2004a and 2004b).

Table 8 summarizes the data described above and the calculated safety indices. (Recall that, because the products of the shear factor and the resistance factor in the American and Canadian equations are equal, the safety indices for the CSA-S16-01 design equation are the same as for the AISC design equation.) The safety index for each group of test specimens from the current test program is greater than 4.5, the traditional target value for connections. The longitudinal welds show the lowest safety index at 5.6, while the 45° specimens show the highest safety index at 7.5. The safety index obtained from the combined specimens of Miazga and Kennedy (1989), Ng et al. (2004b), and the present research is 4.4, which is only slightly lower than the desired value of 4.5 and the overall safety index of 4.8 reported in Ng et al. (2004b) strictly for transverse weld specimens. Since the combined safety index of 4.4 is based on a value of measured weld size to nominal weld size, ρ_G, of 0.977, which is expected to be greater than 1.0 in structures where no upper tolerance limit is placed on weld size during fabrication, it is considered to represent a satisfactory level of safety.

SUMMARY AND CONCLUSIONS

Because the fillet weld design equation in the American and Canadian steel design standards is based upon research on the behavior of SMAW test specimens, the significant increase in weld strength recognized by these design standards as the loading angle increases might not be suitable for low toughness welds made with other welding processes such as FCAW, which is more commonly used for production welding. Therefore, an experimental program was conducted to investigate the effect of filler metal toughness on fillet weld behavior. The first phase of this test program included only transverse fillet welds. The variables in the first phase included filler metal classification (both filler metals with a toughness requirement and some without were tested), electrode manufacturer, fabricator, weld size, root notch orientation, and test temperature (Ng et al., 2004a and 2004b). A reliability analysis of the test results (102 test specimens) indicated that the current design equation provides a safety index greater than 4.5 for transverse welds.

The second phase, which formed the basis of the work presented herein, examined the effect of filler metal classification and toughness on the strength and ductility of fillet welds loaded at different angles with respect to their longitudinal axes. The results of this phase were obtained from 30 lap-spliced specimens with nominally 12.7 mm (½ in.) fillet welds. Twenty-seven test specimens were prepared using the FCAW process. The specimens were loaded in three different directions with respect to the weld axis: 0°, 45°, and 90°. Two FCAW filler metals with no specified toughness (E70T-4 and E70T-7) and one with a specified toughness (E71T8-K6) were chosen for the study.

The following are the primary conclusions drawn from an examination of the test results:

1. Filler metal classification and toughness level have little effect on the strength of transverse and 45° fillet welds. However, the longitudinal fillet welds made with the filler metals with a specified toughness had a lower mean strength than those with no specified toughness when normalized using the fracture surface area.

2. As observed in the first phase of the test program, fillet welds prepared using a filler metal with a toughness requirement were more ductile than fillet welds prepared using filler metals without a toughness requirement. The mean fracture strains of the welds with a toughness requirement were 51%, 37%, and 84% higher than those of the welds without a toughness requirement for the transverse, 45°, and longitudinal welds, respectively.

3. When weld fracture strain was used as the measure of weld ductility, no general relationship was observed between weld orientation and weld ductility. However, the ductility of the longitudinal welds was notably higher than the ductility of the 45° and transverse welds. The mean fracture strains of the longitudinal welds were 1.79 and 3.02 times those of the transverse and 45° welds, respectively.

4. The ratios between the ultimate strength of the welds loaded at an angle and the strength of the welds loaded longitudinally were comparable with the weld strength ratios determined by Miazga and Kennedy (1989). They also compared well with the ratios predicted by the AISC fillet weld design equation. The mean experimental transverse-to-longitudinal weld strength ratios were 1.71, 1.51, and 1.60 for the E70T-4, E70T-7, and E71T8-K6 welds, respectively, as compared with a predicted value of 1.50. The mean experimental 45° to longitudinal weld strength ratios were 1.49, 1.48, and 1.37 for the E70T-4, E70T-7, and E71T8-K6 welds, respectively, as compared with a predicted value of 1.30. The modifier for weld orientation in the design equation, therefore, appears to provide a conservative estimate of the strength of welds loaded at angles other than 0°.

5. The weld capacities predicted by the design equation are conservative for all specimens. The SMAW specimens had the lowest test-to-predicted ratios, 1.25 and 1.15, for predictions made using the nominal and measured weld strengths, respectively. The mean test-to-predicted ratios calculated with the nominal weld strengths for the FCAW specimens (all three electrode classifications combined) were reasonably consistent. These were 1.71, 1.78, and 1.60 for the transverse, 45°, and longitudinal weld series, respectively. When the test-to-predicted ratios are calculated using the measured weld strengths, those for the welds without a toughness requirement decreased substantially because of the amount of weld metal overstrength. The mean test-to-predicted ratios for the E70T-4, E70T-7, and E71T8-K6 assemblies were 1.34, 1.35, and 1.61, respectively, for the transverse welds; 1.35, 1.54, and 1.60, respectively, for the 45° welds; and 1.17, 1.35, and 1.51, respectively, for the longitudinal welds.

6. For each of the three weld orientations, the reliability analysis shows that the design equations in the American and the Canadian standards provide a level of safety that exceeds the traditional target safety index for connections of 4.5. The safety index determined from a larger data pool (4.4) is only slightly lower than this target and is considered to be acceptable.

FUTURE WORK

The present research has expanded the knowledge regarding fillet weld behavior, but the results also raised further questions that could be answered by future work in the following areas:

1. Contrary to expectations, the transverse welds were observed to have larger deformations than the 45° welds. Because the main plates of the transverse weld specimens yielded while those of the 45° weld specimens did not, part of the explanation could be the possibility that yielding might have had an impact on weld ductility. An investigation of whether or not the stress level of the base plate affects the behavior of fillet welds significantly should be conducted.

2. The longitudinal welds tested in this project were only 50 mm long (2 in.), which may not provide results that are representative of longer welds. Therefore, longitudinal welds longer than 50 mm (2 in.) should be tested to determine the relationship between weld length and weld behavior.

3. All of the welds tested in the first phase of this program (Ng et al., 2004a and 2004b) were isolated (only one weld orientation in the test specimens). Because of the stark differences in behavior observed for the different weld orientations, additional specimens should be tested to investigate the overall behavior of joints with weld groups having combinations of orientations. This investigation is currently under way at the University of Alberta.

4. The behavior of eccentrically loaded weld groups should be reevaluated in light of the new knowledge obtained from this comprehensive research program on concentrically loaded welds.

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