4.21 TUBE-TO-TUBESHEET JOINT STRENGTH

4.21.1 SCOPE

4.21.1.1 General.

(a) Tubes used in the construction of heat exchangers or similar apparatus may be considered to act as stays which support or contribute to the strength of tubesheets in which they are engaged. Tube-to-tubesheet joints shall be capable of transferring the applied tube loads. The design of tube-to-tubesheet joints depends on the type of joint, degree of examination, and shear load tests, if performed.

(b) Tube-to-tubesheet joints, except for as exempted in (c) and (d) below, shall have their strength determined by one of the following sections. Either 4.21.2 or 4.21.3 may be used at the discretion of the designer and as applicable. For designs that are within the scope of both sections, compliance with both is not mandatory.

(c) Back-face welded joints, such as shown in Figure 4.18.2(d), are not covered.

(d) Determination of tube-to-tubesheet joint strength is not mandatory for U-Tube Tubesheets (see 4.18.7).

(e) Some combinations of tube and tubesheet materials, when welded, result in welded joints having lower ductility than required in the material specifications. Appropriate tube-to-tubesheet joint geometry, welding method, and/or heat treatment shall be used with these materials to minimize this effect.

(f) In the selection of joint type, consideration shall be given to the mean metal temperature of the joint at operating temperatures and differential thermal expansion of the tube and tubesheet which may affect the joint integrity. The following provisions apply for establishing maximum operating temperature for tube-to-tubesheet joints.

(1) Tube-to-tubesheet joints where the maximum allowable axial load is controlled by the weld shall be limited to the maximum temperature for which there are allowable stresses for the tube or tubesheet material in Annex 3-A.

- Tube-to-tubesheet joints in this category are any of the following:
  
  (a) those with or without expansion complying with the following:
  
    (1) Tube-to-tubesheet joints having full-strength welds as defined in accordance with 4.21.1.2(a) shall be designed in accordance with 4.21.2.2 and do not require shear load testing.
    
    (2) Tube-to-tubesheet joints having partial-strength welds as defined in accordance with 4.21.1.2(b) and designed in accordance with 4.21.2.3 and do not require shear load testing.

  (b) those welded and expanded joints, such as Joint Types f, g, and h from Table 4.21.1, where the maximum allowable axial load is determined in accordance with 4.21.3.2 and is controlled by the weld

  (c) those welded-only joints, such as Joint Types a, b, b-1, and e from Table 4.21.1, where the maximum allowable load is determined in accordance with 4.21.3.2

(2) Tube-to-tubesheet joints where the maximum allowable axial load is determined in accordance with 4.21.3.2 considering friction only, such as Joint Types i, j, and k from Table 4.21.1, or is controlled by friction in welded and expanded joints, such as Joint Types f, g, and h from Table 4.21.1, shall be limited to temperatures as determined by the following:

- The operating temperature of the tube-to-tubesheet joint shall be withing the tube and tubesheet time independent properties as provided in Annex 3-A

- The maximum operating temperature is limited such that the interface pressure due to expanding the tube at joint fabrication plus the interface pressure due to differential thermal expansion, \( P_a + P_t \), does not exceed 58% of the smaller of the tube or tubesheet yield strength in Annex 3-D at the operating temperature for \( P_t \geq 0 \). For \( P_t < 0 \), where due to differential thermal expansion the tube expands less than the tubesheet, the maximum operating temperature is limited such that factor \( f_t \) remains of sufficient magnitude for the design loads. The interface pressure due to expanding the tube at fabrication or the interface pressure due to differential thermal expansion may be determined analytically or experimentally.

- As an alternate to (b) above, when or the tube expands less than or equal to the tubesheet, joint acceptability shall be determined by shear load test described in 4.21.3.3. Two sets of specimens shall be tested. The first set shall be tested at the proposed operating temperature. The second set shall be tested at room temperature after heat soaking at the proposed operating temperature for 24 hrs. The proposed operating temperature is acceptable if the provisions of 4.21.3.5 are satisfied.

- The Manufacturer shall prepare written procedures for joints which are expanded (whether welded and expanded or expanded only) for joint strength (see Annex 4-E). The Manufacturer shall establish the variables that affect joint repeatability in these procedures. The procedures shall provide detailed descriptions or sketches of enhancements, such as grooves, serrations, threads, and coarse machining profiles. The Manufacturer shall make these written procedures available to the Authorized Inspector

4.21.1.2 Definitions

(a) Full-Strength Weld - A full-strength tube-to-tubesheet weld is one in which the design strength is equal to or greater than the axial tube strength, \( F_a \). When the weld in a tube-to-tubesheet joint meets the requirements of 4.21.2.2, it is a full-strength weld and the joint does not require qualification by shear load testing. Such a weld also provides tube joint leak tightness.
(b) Partial-Strength Weld - A partial-strength weld is one in which the design strength is based on the mechanical and thermal axial tube loads (in either direction) that are determined from the actual design conditions. The maximum allowable axial load of this weld may be determined in accordance with 4.21.2.3 or 4.21.3. When the weld in a tube-to-tubesheet joint meets the requirements of 4.21.2.3, the joint does not require qualification by shear load testing. Such a weld also provides tube joint leak tightness.

(c) Seal Weld - A tube-to-tubesheet seal weld is one used to supplement an expanded tube joint to ensure leak tightness. Its size has not been determined based on axial tube loading.

(d) Welded-Only Joint - A tube-to-tubesheet joint which is made by welding the end of the tube to the tubesheet.

(e) Welded-and-Expanded Joint - A tube-to-tubesheet joint which is made by both welding and expanding.

(f) Expanded Joint - A tube-to-tubesheet joint which is made by expanding the tube into the tube hole in a manner that produces a determinable allowable axial joint load.

(g) Tube hole enhancement - A groove or other modification of the tube hole surface that increases the allowable axial joint load.

4.21.2 JOINT STRENGTH BY CALCULATION

4.21.2.1 Scope. These rules provide a basis for establishing weld sizes and allowable joint loads by calculation for full-strength and partial-strength tube-to-tubesheet welds. These rules apply to welded-only joints and welded-and-expanded joints in which the strength of the expansion is not considered. These rules cover the welds shown in Figure 4.21.1.

4.21.2.2 Full-Strength Welds. Full-strength welds shown in Figure 4.21.1 shall conform to the following requirements.

(a) The size of a full-strength weld shall be determined in accordance with 4.21.2.4.

(b) The maximum allowable axial load in either direction on a tube-to-tubesheet joint with a full-strength weld shall be $L_{max} = kF_t$.

4.21.2.3 Partial-Strength Welds. Partial-strength welds shown in Figure 4.21.1 shall conform to the following requirements.

(a) The size of a partial-strength weld shall be determined in accordance with 4.21.2.4.

(b) The maximum allowable axial load in either direction on a tube-to-tubesheet joint with a partial-strength weld shall be $L_{max} = k(F_t + F_y)$, but not greater than $kF_t$.

4.21.2.4 Weld Size Design Equations.

(a) The size of tube-to-tubesheet strength welds shown in Figure 4.21.1 shall conform to the following requirements.

(1) For fillet welds shown in Figure 4.21.1, sketch (a):

(a) Calculate the minimum required length of the fillet weld leg.

$$a_f = \sqrt{\left(0.75d_o\right)^2 + 2.73t\left(d_o - t\right)\frac{f_y}{f_y'} - 0.75d_o} \quad (4.21.1)$$

(b) For full-strength welds, $a_f \geq \max\{a_r, t\}$.

(c) For partial-strength welds, $a_f \geq a_r$.

(2) For groove welds shown in Figure 4.21.1, sketch (b):

(a) Calculate the minimum required length of the groove weld leg.

$$a_g = \sqrt{\left(0.75d_o\right)^2 + 1.76t\left(d_o - t\right)\frac{f_y}{f_y'} - 0.75d_o} \quad (4.21.2)$$

(b) For full-strength welds, $a_g \geq \max\{a_r, t\}$.

(c) For partial-strength welds, $a_g \geq a_r$.

(3) For combined groove and fillet welds shown in Figure 4.21.1, sketch (c) where $a_f$ is equal to $a_g$:

(a) Calculate the minimum required length of the combined weld legs.

$$a_f = 2\sqrt{\left(0.75d_o\right)^2 + 1.07t\left(d_o - t\right)\frac{f_y}{f_y'} - 0.75d_o} \quad (4.21.3)$$
Note to Editor that equations have been renumbered

(-b) For full-strength welds, \( a_c \geq \max(a_r, \epsilon) \)

(-c) For partial-strength welds, \( a_c \geq a_r \).

(-d) Calculate \( a_f \) and \( a_g \) using the following equations.

\[
af = \frac{ac}{2} \quad \text{ (4.21.4)}
\]

\[
ag = \frac{ac}{2} \quad \text{ (4.21.5)}
\]

(4) For combined groove and fillet welds shown in Figure 4.2.1, sketch (d) where \( a_f \) is not equal to \( a_g \), \( a_r \) shall be determined as follows:

(-a) Choose \( a_g \) and calculate the minimum required length of the fillet weld leg.

\[
a_r = \sqrt{[0.75d_o]^2 + 2.73(d_o - t)f_wf_f - 0.75d_c} \quad \text{ (4.21.6)}
\]

(-b) For full-strength welds \( a_c \geq \max[(a_r + a_g), \epsilon] \).

(-c) For partial-strength welds \( a_c \geq (a_r + a_g) \).

(-d) Calculate \( a_f \) using the following equation.

\[
a_f = a_c - a_g \quad \text{ (4.21.7)}
\]

(5) For inset fillet welds shown in Figure 4.2.1, sketch (e):

(-a) Calculate the minimum required length of the fillet weld leg.

\[
a_r = 0.75d_o - \sqrt{(0.75d_o)^2 + 2.73t(d_o - t)f_wf_f - 0.75d_c} \quad \text{ (4.21.8)}
\]

(-b) Full strength welds are not possible with this configuration.

(-c) For partial-strength welds, \( t \geq a_f \geq a_r \). If \( a_r > t \), joint load cannot be calculated in accordance with this section. See 4.213.

(6) For combined groove and inset fillet welds shown in Figure 4.2.1, sketch (f), \( a_r \) shall be determined as follows:

(-a) Choose \( a_g \) and calculate the minimum required length of the groove weld.

\[
a_r = \sqrt{[0.75d_o]^2 + 1.76t(d_o - t)f_wf_f - 0.75d_c} \quad \text{ (4.21.9)}
\]

(-b) For full-strength welds, \( a_c \geq \max[(a_r + a_f), (t + 0.3a_f)] \).

(-c) For partial-strength welds, \( a_c \geq (a_r + a_f) \).

(b) In weld strength factors used in (a) above shall be calculated using the following equations.

\[
f_d = 1.0 \quad \text{ for full-strength welds} \quad \text{ (4.21.10)}
\]

\[
f_d = \frac{f_d}{F_r} \quad \text{ for partial-strength welds} \quad \text{ (4.21.11)}
\]

\[
f_f = 1 - \frac{F_f}{S_w} \quad \text{ (4.21.12)}
\]

\[
f_g = 1 - \frac{F_g}{(f_dS_w)} \quad \text{ (4.21.13)}
\]

\[
f_w = \frac{F}{S_w} \quad \text{ (4.21.14)}
\]

where

\[
F_f = 0.55\pi a_f(d_o + 0.67a_f)S_w \quad \text{ for face fillet welds shown in Figure 4.2.1 (a), (c), (d)} \quad \text{ (4.21.12)}
\]

\[
F_f = 0.55\pi a_f(d_o + 0.67a_f)S_w \quad \text{ for inset fillet welds as shown in Figure 4.2.1 (e) & (f)} \quad \text{ (4.21.15)}
\]

\[
F_g = 0.85\pi a_g(d_o + 0.67a_g)S_w \quad \text{ (4.21.17)}
\]

\[
F_t = \pi t(d_o - t)S \quad \text{ (4.21.18)}
\]
4.21.3 JOINT STRENGTH BY FACTORS

4.21.3.1 Scope. These rules provide a basis for establishing allowable joint loads through the use of strength factors. Some acceptable geometries and combinations of welded and mechanical joints are described in Table 4.21.1. Some acceptable types of welded joints are illustrated in Figure 4.21.2.

(a) Geometries, including variations in tube pitch, fastening methods, and combinations of fastening methods, not described or shown, may be used, provided qualification tests have been conducted and applied in compliance with the procedures in 4.21.3.3 and 4.21.3.4.

(b) Materials for welded tube-to-tubesheet joints which do not meet the requirements of Part 6, but in all other respects meet the requirements of this Division, may be used if qualification tests of the tube-to-tubesheet joint have been conducted and applied in compliance with the procedures in 4.21.3.3 and 4.21.3.4.

4.21.3.2 MAXIMUM AXIAL LOADS

The maximum allowable axial load in either direction on tube-to-tubesheet joints shall be determined in accordance with the following:

\[ L_{\text{max}} = k A_s f_r \] \hspace{1cm} \text{Joint Types a, b, c, d, e} \hspace{1cm} (4.21.19)

\[ L_{\text{max}} = \min(k A_s f_{re}, k A_s) \] \hspace{1cm} \text{Joint Types f, g, h} \hspace{1cm} (4.21.20)

\[ L_{\text{max}} = \min(k A_s f_{f, f, f, T}, k A_s) \] \hspace{1cm} \text{Joint Types i, j, k} \hspace{1cm} (4.21.21)

where

\[ A_t = \pi (d_o - t)t \] \hspace{1cm} (4.21.18)

\[ f_T = \frac{P_o + P_f}{P_o} \] \hspace{1cm} (4.21.19)

The following equations may be used to calculate \( P_o \) and \( P_f \):

\[ P_e = S_y, t \left( t + r_0 \right) \left( \frac{S_y}{S_y, t} + 1.945 - 1.384 \frac{d_i}{d_o} \right) \] \hspace{1cm} (4.21.20)

\[ P_o = P_e \left[ 1 - \left( \frac{d_i}{d_o} \right)^2 \right] - \frac{2}{\sqrt{3}} S_y, t \ln \left( \frac{d_o}{d_i} \right) \] \hspace{1cm} (4.21.24)

\[ R_m = r_0 - \frac{t}{2} \] \hspace{1cm} (4.21.22)

\[ P_f = \frac{R_m E}{d_o} \left[ a d_i \left( T - T_m \right) - a d_o \left( T - T_m \right) \right] \] \hspace{1cm} (4.21.23)

\[ \left( d_i \frac{2}{t} - R_m \right) + R_m \left( 2 g \frac{E I}{E_o} - 0.3 \right) \] \hspace{1cm} (4.21.26)
4.21.3.3 SHEAR LOAD TEST

4.21.3.3.1
Flaws in the specimen may affect results. If any test specimen develops flaws, the retest provisions of 4.21.3.3.11 shall govern.

4.21.3.3.2
If any test specimen fails because of mechanical reasons, such as failure of testing equipment or improper specimen preparation, it may be discarded and another specimen taken from the same heat.

4.21.3.3.3
The shear load test subjects a full-size specimen of the tube joint under examination to a measured load sufficient to cause failure. In general, the testing equipment and methods are given in the Methods of Tension Testing of Metallic Materials (ASTM E 8). Additional fixtures for shear load testing of tube-to-tubesheet joints are shown in Figure 4.21.3.

4.21.3.3.4
The test block simulating the tubesheet may be circular, square or rectangular in shape, essentially in general conformity with the tube pitch geometry. The test assembly shall consist of an array of tubes such that the tube to be tested is in the geometric center of the array and completely surrounded by at least one row of adjacent tubes. The test block shall extend a distance of at least one tubesheet ligament beyond the edge of the peripheral tubes in the assembly.

4.21.3.3.5
All tubes in the test block array shall be from the same heat and shall be installed using identical procedures.
(a) The finished thickness of the test block may be less but not greater than the tubesheet it represents. For expanded joints, made with or without welding, the expanded area of the tubes in the test block may be less but not greater than that for the production joint to be qualified.
(b) The length of the tube used for testing the tube joint need only be sufficient to suit the test apparatus. The length of the tubes adjacent to the tube joint to be tested shall not be less than the thickness of the test block to be qualified.

4.21.3.3.6
The procedure used to prepare the tube-to-tubesheet joints in the test specimens shall be the same as used for production.

4.21.3.3.7
The tube-to-tubesheet joint specimens shall be loaded until mechanical failure of the joint or tube occurs. The essential requirement is that the load be transmitted axially.

4.21.3.3.8
Any speed of testing may be used, provided load readings can be determined accurately.

4.21.3.3.9
The reading from the testing device shall be such that the applied load required to produce mechanical failure of the tube-to-tubesheet joint can be determined.
4.21.3.3.10

For determining $f_{r, \text{test}}$ for joint types listed in Table 4.21.1, a minimum of three specimens shall constitute a test. The value of $f_{r, \text{test}}$ shall be calculated in accordance with 4.21.3.4.1 using the lowest value of $L_{\text{test}}$. In no case shall the value of $f_{r, \text{test}}$ using a three specimen test exceed the value of $f_{r, \text{test}}$ given in Table 4.21.1. If the value of $f_{r, \text{test}}$ so determined is less than the value for $f_{r, \text{test}}$ given in Table 4.21.1, retesting shall be performed in accordance with 4.21.3.3.11, or a new three specimen test shall be performed using a new joint configuration or fabrication procedure. All previous test data shall be rejected. To use a value of $f_{r, \text{test}}$ greater than the value given in Table 4.21.1, a nine specimen test shall be performed in accordance with 4.21.3.3.11.

4.21.3.3.11

For joint types not listed in Table 4.21.1, to increase the value of $f_{r, \text{test}}$ for joint types listed in Table 4.21.1, or to retest joint types listed in Table 4.21.1, the tests to determine $f_{r, \text{test}}$ shall conform to the following.

(a) A minimum of nine specimens from a single tube shall be tested. Additional tests of specimens from the same tube are permitted, provided all test data are used in the determination of $f_{r, \text{test}}$. If a change in the joint design or its manufacturing procedure is necessary to meet the desired characteristics, complete testing of the modified joint shall be performed.

(b) In determining the value of $f_{r, \text{test}}$, the mean value of $L_{\text{test}}$ shall be determined and the standard deviation, sigma, about the mean shall be calculated. The value of $f_{r, \text{test}}$ shall be calculated using the value of $L_{\text{test}}$ corresponding to -2 sigma, using the applicable equation in 4.21.3.4. In no case shall $f_{r, \text{test}}$ exceed 1.0.

4.21.3.3.12

Once shear load tests have been successfully completed for a tube-to-tubesheet joint design, the Manufacturer that produced the test specimen may use the calculated $f_{r}(\text{test})$ for any production tube-to-tubesheet joint design that the Manufacturer produces having the same geometry, material nominal composition, specified ultimate tensile strength, and fabrication procedure used for the shear load test specimen. The fabrication procedure shall contain or reference the test qualification information required by 4-E.5.2 and/or Section IX, QW-193.1, as applicable.

4.21.3.4 ACCEPTANCE STANDARDS FOR JOINT EFFICIENCY FACTOR DETERMINED BY TEST

4.21.3.4.1

The value of $f_{r, \text{test}}$ determined by testing shall be calculated as follows.

$$f_{r, \text{test}} = \frac{L_{\text{test}}}{A_S f_y}$$

Joint Types a, b, b-1, c  
(4.21.24)  
(4.21.28)

$$f_{r, \text{test}} = \frac{L_{\text{test}}}{A_S f_y d_y}$$

Joint Types f, g, h, i, j, k  
(4.21.25)  
(4.21.29)

4.21.3.4.2

The value of $f_{r, \text{test}}$ shall be used for $f_{r, \text{test}}$ in the equation for $L_{\text{max}}$.

4.21.3.5 ACCEPTANCE STANDARDS FOR PROPOSED OPERATING TEMPERATURES DETERMINED BY TEST

The proposed operating conditions shall be acceptable if both of the following conditions are satisfied.

$$L_{1, \text{test}} \geq A_S f_y f_T (S_u/S_{tu})$$  
(4.21.26)  
(4.21.30)

$$L_{2, \text{test}} \geq A_S f_y f_T$$  
(4.21.27)  
(4.21.31)
\[ a_c = \text{length of the combined weld legs measured parallel to the longitudinal axis of the tube at its outside diameter. For fillet only welds, } a_c = a_f. \text{ For groove only welds, } a_c = a_g. \text{ These dimensions are illustrated in Figures 4.21.1 and 4.21.2.} \]

- \( a_f \) = fillet weld leg
- \( a_g \) = groove weld leg
- \( a_r \) = minimum required length of the weld leg(s) under consideration
- \( A_t \) = tube cross-sectional area.
- \( d_i \) = nominal tube inside diameter.
- \( d_o \) = nominal tube outside diameter.
- \( E \) = modulus of elasticity for tubesheet material at \( T \).
- \( E_t \) = modulus of elasticity for tube material at \( T \).
- \( f_d \) = ratio of the design strength to the tube strength

\[ f_e = \text{factor for the length of the expanded portion of the tube. } f_e = \min \left( \frac{l}{d_u}, 1.0 \right) \text{ for tube joints made with expanded tubes in tube holes without enhancement and } f_e = 1.0 \text{ for tube joints made with expanded tubes in tube holes with enhancement. An expanded joint is a joint between the tube and tubesheet produced by applying an expanding force inside the portion of the tube to be engaged in the tubesheet. The expanding force shall be set to values necessary to effect sufficient residual interface pressure between the tube and hole for joint strength.} \]

- \( f_r \) = ratio of the fillet weld strength to the design strength
- \( f_r = \text{factor to define the efficiency of joint, set equal to the value of } f_{r, \text{test}} \text{ or } f_{r, \text{notest}} \text{. } f_{r, \text{test}} \text{ is equal to the value calculated from results of test in accordance with 4.2.1.3.4 or as tabulated in Table 4.21.1, whichever is less, except as permitted in 4.2.1.3.11. } f_{r, \text{notest}} \text{ is equal to maximum allowable value without qualification test in accordance with Table 4.21.1.} \]
- \( f_{r, \text{test}} \) = factor to define the efficiency of joint established in a test.
- \( f_{r, \text{notest}} \) = factor to define the efficiency of joint established without a test.
- \( f_{re} \) = factor for the overall efficiency of welded and expanded joints. This is the maximum of the efficiency of the weld alone, \( f_r(b) \), and the net efficiency of the welded and expanded joint.
  \[ f_{re} = \max \left[ f_s f_f f_r b, f_r(b) \right] \]
- \( f_T \) = factor to account for the increase or decrease of tube joint strength due to radial differential thermal expansion at the tube-to-tubesheet joint. Acceptable values of \( f_T \) may range from 0 to greater than 1. When the \( f_T \) value is negative, it shall be set to 0.
- \( f_w \) = weld strength factor
- \( f_g \) = factor for differences in the mechanical properties of tubesheet and tube materials. \( f_g = \min \left[ \frac{S_g}{S_w}, t \right], 1.0 \right) \text{ for expanded joints. When } f_g \text{ is less than 0.60, qualification tests in accordance with 4.21.3.3 and 4.21.3.4 are required.} \]
- \( F_d \) = design strength, but not greater than \( F_t \)
- \( F_f \) = fillet weld strength, but not greater than \( F_t \)
- \( F_g \) = groove weld strength, but not greater than \( F_t \)
- \( F_t \) = axial tube strength
- \( k \) = tube load factor.
  \- 1.0 for loads due to pressure-induced axial forces
  \- 1.0 for loads due to thermally-induced or pressure plus thermally-induced axial forces on welded-only joints where the thickness through the weld throat is less than the nominal tube wall thickness \( t \).
  \- 2.0 for loads due to thermally-induced or pressure plus thermally-induced axial forces on all other tube-to-tubesheet joints.
- \( l \) = expanded tube length.
- \( L_{\text{max}} \) = maximum allowable axial load in either direction on the tube-to-tubesheet joint.
- \( L_{\text{test}} \) = axial load at which failure of the test specimens occur.
- \( L_{1, \text{test}} \) = lowest axial load at which failure occurs at operating temperature.
- \( L_{2, \text{test}} \) = lowest axial load at which failure of heat soaked specimen tested at room temperature occurs.
\( P_e \) = tube expanding pressure.
\( P_o \) = interface pressure between the tube and tubesheet that remains after expanding the tube at fabrication. This pressure may be established analytically or experimentally, but shall consider the effect of change in material strength at operating temperature.
\( P_f \) = interface pressure between the tube and tubesheet due to differential thermal growth. This pressure may be established analytically or experimentally.
\( R_m \) = mean tube radius.
\( r_o \) = tube outside radius.
\( S \) = allowable stress from Annex 3-A for the tube at the design temperature. For a welded tube, \( S \) is the equivalent allowable stress for a seamless tube.
\( S_T \) = tensile strength for tube material from the material test report
\( S_i \) = allowable stress from Annex 3-A of the material to which the tube is welded (see 3.3.7.4)
\( S_o \) = tensile strength for tube material at operating temperature from Annex 3-D.
\( S_{wo} \) = tensile strength for tube material at room temperature from Annex 3-D.
\( S_w \) = allowable stress in weld, \( S_w = \min(S_i, S_o) \)
\( S_{yw} \) = tube specified minimum yield strength at the design temperature from Annex 3-D.
\( S_{yw} \) = tubesheet specified minimum yield strength at the design temperature from Annex 3-D.
\( T \) = tubesheet design temperature
\( T_o \) = ambient temperature.
\( t \) = nominal tube wall thickness.
\( \alpha \) = mean coefficient of thermal expansion of tubesheet material at \( T \).
\( \alpha_c \) = mean coefficient of thermal expansion of tube material at \( T \).
## 4.21.5 TABLES

### Table 4.21.1

**Efficiencies for Welded and/or Expanded Tube-to-Tubesheet Joints**

<table>
<thead>
<tr>
<th>Joint Type</th>
<th>Description [Note (1)]</th>
<th>Notes</th>
<th>$f_{r,\text{test}}$ [Note (2)]</th>
<th>$f_{r,\text{no test}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Welded only, $a_i &lt; 1.4t$</td>
<td></td>
<td>1.00</td>
<td>0.85</td>
</tr>
<tr>
<td>b</td>
<td>Welded only, $a_i = 1.4t$</td>
<td></td>
<td>0.70</td>
<td>0.65</td>
</tr>
<tr>
<td>c</td>
<td>Welded only, $a_i &gt; t$</td>
<td></td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>Welded, $a_i = 1.4t$, and expanded</td>
<td>(3)</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>f</td>
<td>Welded, $a_i &lt; 1.4t$, and expanded Enhanced with two or more grooves</td>
<td>(3), (5), (6), (7), (8)</td>
<td>0.95</td>
<td>0.75</td>
</tr>
<tr>
<td>g</td>
<td>Welded, $a_i &lt; 1.4t$, and expanded Enhanced with single groove</td>
<td>(3), (5), (6), (7), (8)</td>
<td>0.85</td>
<td>0.65</td>
</tr>
<tr>
<td>h</td>
<td>Welded, $a_i &lt; 1.4t$, and expanded Not enhanced</td>
<td>(3), (5), (6)</td>
<td>0.70</td>
<td>0.50</td>
</tr>
<tr>
<td>i</td>
<td>Expanded Enhanced with two or more grooves</td>
<td>(5), (6), (7), (8)</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>j</td>
<td>Expanded Enhanced with single groove</td>
<td>(5), (6), (7), (8)</td>
<td>0.80</td>
<td>0.65</td>
</tr>
<tr>
<td>k</td>
<td>Expanded Not enhanced</td>
<td>(5), (6)</td>
<td>0.60</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**NOTES:**

(1) For joint types involving more than one fastening method, the sequence used in the joint description does not necessarily indicate the order in which the operations are performed.

(2) The use of the $f_{r,\text{test}}$ factor requires qualification in accordance with 4.21.3.3 and 4.21.3.4.

(3) The value of $f_{r,\text{no test}}$ applies only to material combinations as provided for under Section IX. For material combinations not provided for under Section IX, $f_r$ shall be determined by test in accordance with 4.21.3.3 and 4.21.3.4.

(4) For $f_{r,\text{no test}}$, refer to 4.21.1.2(b). Refer to 4.21.2.

(5) If $d_a/(d_a-2t) < 1.05$ or $d_a/(d_a-2t) > 1.410$, $f_r$ shall be determined by test in accordance with 4.21.3.3 and 4.21.3.4.

(6) If the nominal pitch (center-to-center distance of adjacent tube holes) is less than $d_a + 2t$, $f_r$ shall be determined by test in accordance with 4.21.3.3 and 4.21.3.4.

(7) The manufacturer may use other means to enhance the strength of expanded joints, provided however, that the joints are tested in accordance with 4.21.3.3 and 4.21.3.4.

(8) For explosive and hydraulic expansion, grooves shall be a minimum of $1.1(d_a - t)^{0.5}$ wide. For explosively or hydraulically expanded joints with single grooves meeting this requirement, $f_r$ for Joint Type f may be used in lieu of that for Joint Type g, and $f_r$ for Joint Type i may be used in lieu of that for Joint Type j, as applicable.

*total weld size $(0.7a_i + a_d) \geq t$*

*total weld size $(0.7a_i + a_d) < t$*
Figure 4.21.1
Some Acceptable Types of Tube-to-Tubesheet Strength Welds

(a) Clad material (if present) typical

(b) 

(c) ac = af + ag
af = ag

(d) ac = af + ag
af = ag

See replacement Figure later in proposal
Figure 4.21.2
Some Acceptable Types of Tube-to-Tubesheet Joints

(a) Some Acceptable Weld Geometries Where \( a_D \) Is Greater Than or Equal to 1.4\( t \)

(b) Some Acceptable Weld Geometries Where \( a_D \) Is Less Than 1.4\( t \)

See replacement figure later in proposal
Figure 4.21.3
Typical Test Fixtures for Expanded or Welded Tube-to-Tubesheet Joints

Hydraulic Method

Alternate Arrangement for Nonweldable Tubes
Figure 4.21.1: Tube-to-Tubesheet Joints Acceptable to Determine Joint Strength by Calculation

- **Face-Fillet Weld**
  - Typical clad material (if present)
  - Where: $a_c = a_f + a_g$ and $a_f = a_g$

- **Groove Weld**
  - Typical chamfer or groove to achieve $a_g$
  - Where: $a_c = a_f + a_g$

- **Combination Face-Fillet & Groove**
  - Where: $a_c = a_f + a_g$ and $a_f = a_g$

- **Inset Fillet Weld**
  - Where: $a_f \leq t$

- **Combination Inset Fillet & Groove**
  - Where: $a_c = a_g + a_f$ (with fillet weld $a_f$)
  - Fill in excess of $a_c$ is optional

- **Combination Face-Fillet & Groove**
  - Where: $a_c = a_g + a_f$ and $a_f \neq a_g$
  - Where: $a_c = a_g$ (if no fillet weld)
  - Where: $a_c = a_g + a_f$ (with fillet weld $a_f$)

- $a_f$, $a_g$, $a_c$, $d_o$, $t$ are variables in the diagrams.
NOTES:
(1) Sketches (a) through (d) show some acceptable weld geometries where thickness through the weld throat may be sized $\geq t$.
(2) Sketches (e) through (i) show some acceptable weld geometries where thickness through the weld throat is less than $t$.
(3) For these geometries where weld length cannot be established by dimensions prior to weld, dimension $a_c$ shall be verified during WPS qualification per QW-193 and design strength shall be calculated in accordance with 4.21.3.2.