Annex I

Weld Misalignment

I Misalignment

I.2 Calculation of Stress Magnification Factor

The presence of misalignment, axial (eccentricity) or angular, or both, at a welded joint can cause an increase or decrease in stress at the joint when it is loaded, due to the introduction of local bending stresses [1], [2] and [3]. These will influence both stress intensity factors (Annex A) and reference stresses (Annex B). This applies to both butt and fillet welded joints, but only under loading which results in membrane stresses transverse to the line of misalignment. Bending stresses do not occur as a result of misalignment in continuous welds loaded longitudinally or at joints in plates subjected only to bending. However, misaligned joints in sections (e.g. beams, tubes) subjected to overall bending will experience combined membrane and bending stresses and additional bending stresses may arise due to the membrane stress component.

If more than one type of misalignment exists, the total induced bending stress is the sum of the bending stresses due to each type. Both tensile (positive) and compressive (negative) stresses will arise as a result of misalignment, depending on the surface or through-thickness position being considered. Account should be taken of the relevant sign when calculating the net effect of combined misalignments (combined axial and angular misalignment might act together, e.g. both tensile, or in opposition) and when calculating the total stress due to applied and induced stresses.

The bending stress due to misalignment depends not only on its type and extent, but also on factors that influence the ability of the welded joint to rotate under the induced bending moment. These factors include loading and boundary conditions, section shape and the presence of other members, which provide local stiffening. Special analysis (e.g. finite element stress analysis) is usually required to quantify their effects. Unless it can be demonstrated that restraint on the joint reduces the influence of misalignment, the induced bending stress should be calculated assuming no restraint.

Formulae for calculating the bending stress, σ_s, as a function of applied membrane stress, P_m, for a number of cases of misalignment are given in Tables I.1 and I.2 [1], [2] and [3]. For joints that experience combined membrane and bending stresses, the formulae are used in conjunction with the membrane stress component only. Apart from the weld root in a cruciform fillet weld, all the formulae give σ_s at the weld toe. If the stress is required at a different position through the thickness, for example when assessing buried flaws, the bending stress due to misalignment can be assumed to vary linearly through the material thickness to zero at its neutral axis.

It is sometimes convenient to express the effect of misalignment in terms of the maximum factor by which the applied stress (P_m) or stress range (ΔP_m) is magnified as a result of its presence. This magnification factor, k_m, is defined as:

$$k_m = \frac{P_m + \sigma_s}{P_m} = 1 + \frac{\sigma_s}{P_m} \qquad \text{(I.1)}$$

$$k_{\mathrm{m}} = \frac{\Delta P_{\mathrm{m}} + \Delta\sigma_{\mathrm{s}}}{\Delta P_{\mathrm{m}}} = 1 + \frac{\Delta\sigma_{\mathrm{s}}}{\Delta P_{\mathrm{m}}} \tag{I.2}$$

where

σ_{s} is the maximum induced bending stress due to the misalignment, which has the same sign as P_{m} (i.e. $\sigma_{\mathrm{s}}/P_{\mathrm{m}}$ is positive).

For combined misalignments (e.g. axial and angular):

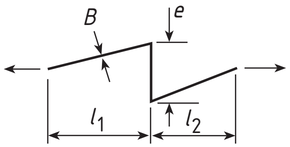
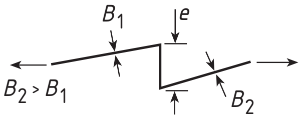
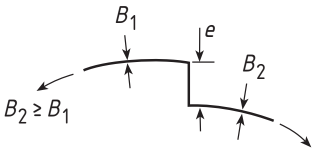
$$k_m = 1 + \left(k_m - 1\right)_{axial} + \left(k_m - 1\right)_{angular} \tag{I.3}$$

It may be noted that the guidance given in this annex may be unduly conservative if applied to through-thickness flaws. This is because the presence of such flaws will serve to reduce local bending stresses resulting from misalignment. In fact, the magnitude of local bending due to misalignment will decrease with increasing crack length for through-thickness flaws.

I.3 Bibliography

1. Maddox S J, Fitness for purpose assessment of misaligment in transverse butt welds subject to fatigue loading, London: International Institute of Welding. IIW document XIII-1180-85, 1985 (Unpublished).
2. Andrews R M, The effect of misalignment on the fatigue strength of welded cruciform joints, Fatigue and fracture of engineering materials and structures, 19 775-768, 1996. ISSN 8756-758X
3. Berg S and H Myhre, Fatigue strength of misaligned cruciform and butt joints, Norwegian maritime research. 5 (1) 29-39, 1977. ISSN 0304-1743.

Table I.1 — Formulae for calculating the bending stress due to misalignment in butt joints (*continued*)

Type	Detail	Bending stress, σ_s	Remarks
a) Axial misalignment between flat plates		$\frac{\sigma_s}{P_m} = \kappa\left\{\frac{e l_1}{B\left(l_1 + l_2\right)}\right\}$ where κ is a factor dependent on restraint	$\kappa = 6$ for unrestrained joint For remotely loaded joints, assume $l_1 = l_2$
b) Axial misalignment between flat plates of different thickness		$\frac{\sigma_s}{P_m} = \frac{6e}{B_1}\left(\frac{B_1^n}{B_1^n + B_2^n}\right)$	Relates to remotely loaded, unrestrained joints Use $n = 1.5$ supported by tests
c) Axial misalignment at longitudinal seam welds in tubes, pipes and vessels, with or without thickness change		$\frac{\sigma_s}{P_m} = \frac{6e}{B_1\left(1 - \nu^2\right)}\left(\frac{1}{1 + \left(B_2/B_1\right)^{0.6}}\right)$	—

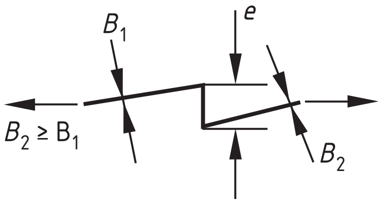
d) Axial misalignment at girth welds in tubes, pipes, vessels and at seams in spheres, with or without thickness changes		If $\sigma_s/P_m < 1$: $\frac{\sigma_s}{P_m} = \frac{6e}{B_1\left(1-\nu^2\right)}\left\{\frac{1}{1+\left(B_2/B_1\right)^{1.5}}\right\}$ If $\sigma_s/P_m \geq 1$: $\frac{\sigma_s}{P_m} = \frac{2.6e}{B_1}\left\{\frac{1}{1+0.7\left(B_2/B_1\right)^{1.4}}\right\}$ (Connelly and Zettlemoyer [240])	

Table I.1 — Formulae for calculating the bending stress due to misalignment in butt joints (*continued*)

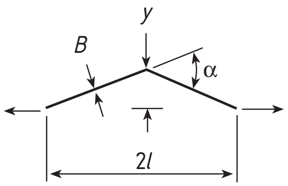
Type	Detail	Bending stress, σ_s	Remarks
e) Angular misalignment between flat plates	 α in radians	Assuming boundary conditions equivalent to: — fixed ends: $\frac{\sigma_s}{P_m} = \frac{3y}{B}\left\{\frac{\tanh(\beta/2)}{\beta/2}\right\}$ $= \frac{3\alpha}{4}\frac{2l}{B}\left\{\frac{\tanh(\beta/2)}{\beta/2}\right\}$ — pinned ends: $\frac{\sigma_s}{P_m} = \frac{6y}{B}\left\{\frac{\tanh(\beta)}{\beta}\right\}$ $= \frac{3\alpha}{2}\frac{2l}{B}\left\{\frac{\tanh(\beta)}{\beta}\right\}$ where, in each case $\beta = \frac{2l}{B}\left(\frac{3\sigma_m}{E}\right)^{0.5}$	The tanh correction (in curly brackets) allows for reduction in angular misalignment due to straightening of joint under tensile loading. It is always ≤1 and therefore it is usually conservative to ignore it. The exception is if, when combined with axial misalignment, the angular component has the effect of reducing the overall stress. Its effect is negligible for $2l/B < 10$ and it is independent of the assumed end fixing condition for $2l/B > 100$. Note, for compressive loading, without any lateral restraint, the “tanh” term becomes a “tan” term and it is no longer conservative to ignore it.

Table I.1 — Formulae for calculating the bending stress due to misalignment in butt joints (*continued*)

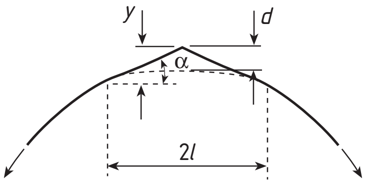
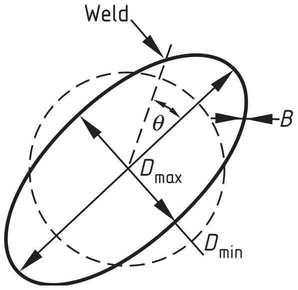
f) Angular misalignment at longitudinal or circumferential seams in tubes or vessels		Assuming boundary conditions equivalent to: — fixed ends: $\frac{\sigma_s}{P_m} = \frac{3d}{B(1-\nu^2)}\left\{\frac{\tanh(\beta/2)}{\beta/2}\right\}$ — pinned ends: $\frac{\sigma_s}{P_m} = \frac{6d}{B(1-\nu^2)}\left\{\frac{\tanh(\beta)}{\beta}\right\}$ where, in each case $\beta = \frac{2l}{B}\left\{\frac{3(1-\nu^2)P_m}{E}\right\}^{0.5}$	Assuming an idealized geometry, $d = \frac{y}{2}$ or $\frac{\alpha l}{2}$
g) Ovality in pressurized pipes or vessels	 θ in degrees	$\frac{\sigma_s}{P_m} = \frac{1.5(D_{max} - D_{min})\cos 2\theta}{B\left\{1 + 0.5\left(\frac{p_m(1-\nu^2)}{E}\right)\left(\frac{D}{B}\right)^3\right\}}$ where D is the mean diameter p_m is themaximum pressure at the operating condition being assessed.	Formula takes account of exact location of weld seam and beneficial change in shape of vessel due to pressurization. If, under fatigue loading, p_m varies, use the mean value during the time interval considered. A conservative estimate of σ_s is: $\frac{\sigma_s}{P_m} = \frac{1.5(D_{max} - D_{min})}{B}$

Table I.2 — Formulae for calculating the bending stress due to misalignment in cruciform joints (*continued*)

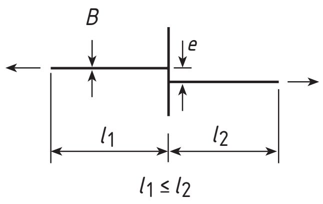
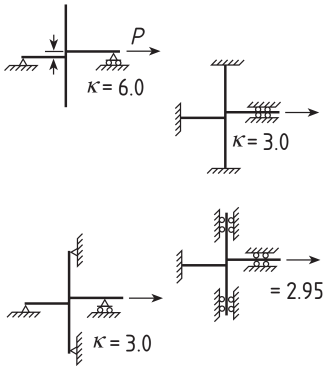
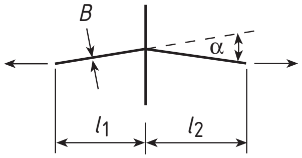
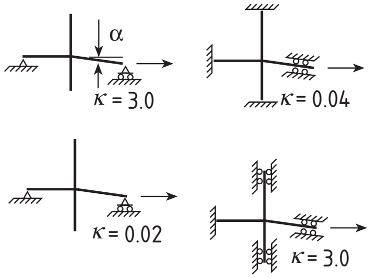
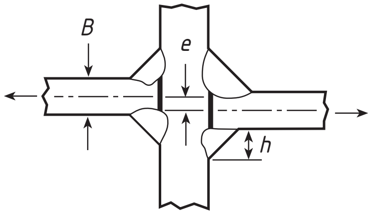
a) Axial misalignment in butt or fillet welded joints		$\frac{\sigma_s}{P_m} = \frac{\kappa e l_1}{B(l_1 + l_2)}$ where κ is a factor dependent on restraint, e.g. 	Refers to fatigue failure in plate from toe weld For unrestrained, remotely loaded joint, assume $\kappa = 6$ and $l_1 = l_2$

Table I.2 — Formulae for calculating the bending stress due to misalignment in cruciform joints (*continued*)

b) Angular misalignment in butt or fillet welded joints		$\frac{\sigma_s}{P_m} = \frac{\kappa \alpha l_1 l_2}{B(l_1 + l_2)}$ where κ is a factor dependent on restraint, e.g. 	Refers to fatigue failure in plate from toe weld
c) Axial misalignment in fillet welded joints		$\frac{\sigma_s}{\sigma_w} = \frac{e}{B + h}$ where σ_w is applied stress on weld throat	Refers to fatigue failure in plate from weld throat from root NOTE This case is not for use in the calculation of the stress intensity factor for a weld root flaw.