Annex F

Interaction of Multiple Planar Flaws: Alignment and Combination Rules

F Interaction of Multiple Flaws: Alignment and Combination Rules

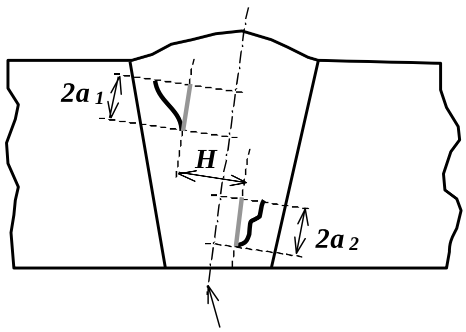
F.1 Introduction

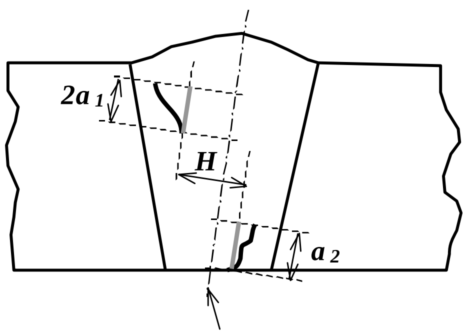
Multiple flaws in metallic structures will in some circumstances lead to more severe effects than single flaws alone. Assessment of the interaction behaviour is based on an evaluation of the alignment and combination of these multiple flaws. First, in the case of flaws that occur on different cross-sections (non-coplanar flaws), these are assessed for alignment. Alignment rules are given in paragraph F.2; for critical values of the spacing distance in between the flaws, they have to be aligned onto the same cross-section. Following, if multiple coplanar flaws exist, each flaw should be checked for interaction with each of its neighbours using the original flaw dimensions in each case. It is not normally necessary to consider further interaction of effective flaws. Combination rules are given in paragraph F.3.

F.2 Flaw alignment

Where non-coplanar flaws exist, each is first re-characterized as discussed in Annex E in order to obtain parallel cracks. The distance between the planes of the assumed cracks, *H*, is taken to be the minimum distance (measured in the direction of the maximum principal stress) that exists between the actual cracks. In this way, the problem is reduced to two cracks that will be either coplanar or in parallel planes (non-coplanar).

Closely spaced non-coplanar flaws have to be aligned onto the same cross-section (perpendicular to the maximum principal stress). The following alignment criterions are recommended:

<table>
<tr><th></th><th>ALIGNMENT CRITERION</th></tr>
<tr><td>Adjacent non-coplanar embedded flaws


Plane normal to the maximum principal stress</td><td>$H \leq \min(2a_1, 2a_2)$</td></tr>
<tr><td>Adjacent non-coplanar surface and embedded flaws


Plane normal to the maximum principal stress</td><td>$H \leq \min(2a_1, a_2)$</td></tr>
</table>

Figure F.1 – Flaw alignment criterion

Following the alignment, the flaws are evaluated for possible interaction according to the combination rules given in paragraph F.3. Multiple flaws on different cross-sections with a spacing distance higher than the above requirements need not be further assessed for possible combination. In this case the cracks tend to shield one another with the consequence that the effective crack driving force is lower than that for a single crack case.

F.3 Flaw combination

Multiple flaws on the same cross-section (co-planar flaws) may lead to an interaction and to more severe effects than a single flaw. If multiple flaws exist, each flaw has to be checked for combination with each of its neighbours using the original flaw dimensions in each case. It is not normally necessary to consider further combination of effective flaws.

F.3.1 Default Assessment (LEFM)

The combination rules for co-planar flaws are presented in Fig. F.2. If interaction between co-planar flaws is stated, they have to be combined into a single equivalent flaw for the purpose of the analysis. The dimensions of the effective (semi-) elliptical flaw are determined by the bounding rectangle. If the distance between coplanar flaws is too large for interaction the cracks can be treated separately. Only the worst-case flaw needs to be considered.

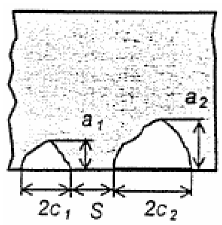
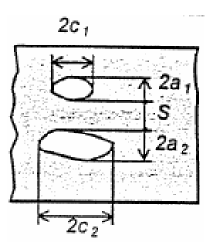
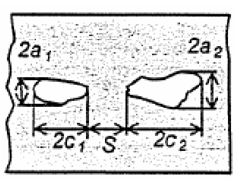
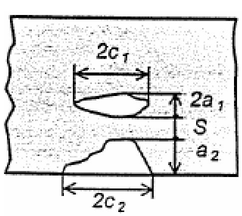
CASE	COMBINATION CRITERIA	EFFECTIVE DEFECT DIMENSIONS
A 	For a_1/c_1 or $a_2/c_2 > 1$: $S \le \min(2c_1, 2c_2)$ OR $S \le \max(0.5a_1, 0.5a_2)$ else: $S \le \max(0.5a_1, 0.5a_2)$	$a = \max(a_1, a_2)$ $2c = 2c_1 + s + 2c_2$
B 	$S \le a_1 + a_2$	$2c = \max(2c_1, 2c_2)$ $2a = 2a_1 + s + 2a_2$
C 	For a_1/c_1 or $a_2/c_2 > 1$: $S \le \min(2c_1, 2c_2)$ OR $S \le \max(a_1, a_2)$ else: $S \le \max(a_1, a_2)$	$2a = \max(2a_1, 2a_2)$ $2c = 2c_1 + s + 2c_2$
D 	$S \le \dfrac{2a_1 + a_2}{2}$	$2c = \max(2c_1, 2c_2)$ $a = 2a_1 + s + a_2$

Figure F.2 – Default Combination Rules

The simple combination rules presented above are based on the proximity rules included in BS 7910 [F.1] and ASME Section XI [F.2]. These are based on an arbitrarily determined allowable increase in the stress intensity factor of a single flaw due to the presence of a second flaw. This approach is developed based on LEFM principles and thus suitable for the assessment of brittle fracture dominated fracture. It should be applied whenever the failure mode for the most severe defect is "fracture controlled", i.e. K_r / L_r > 1.1. For "plastic-collapse dominated" cases, i.e. K_r / L_r < 0.4, an alternative assessment has to be applied, see subsection F.3.2. When 0.4 < K_r / L_r < 1.1, it is recommended that both approaches are applied and the larger of the two calculated effective flaw sizes used in subsequent calculations. The combination rules applied to determine the stress intensity factor and the plastic limit load have to be identical.

It is not necessary to apply the flaw interaction criteria in a fatigue assessment. However, if there is any doubt, multiple flaws should be combined.

F.3.2 Alternative Assessment (Plastic Collapse)

For situations where failure by brittle fracture can be excluded, an alternative assessment of the interaction behaviour can be applied.

The limit load solutions are available for local and global plastic collapse situations (see Section 5.3.1.11). Local collapse occurs when the spacing between different flaws or between the deepest flaw and the free surface (ligament) becomes plastic. In contrast to this, global collapse, or Net Section Yielding (NSY), occurs when the complete cross-sectional area containing the flaws becomes plastic. Eventually, in the case of Gross Section Yielding (GSY), the applied stress in the material remote from the plane containing the defects exceeds the yield strength. The proposed assessment procedure is based on the concept of GSY.

The combination rules for ductile material behaviour are based on the defect length limit $2c_{gsy}$. This limit is the maximum flaw length that will still enable GSY, and is calculated as:

$$2c_{gsy} = \frac{1-R}{1+R}\frac{Wt}{a_{\max}} \tag{F.1}$$

where *R* is the yield-to-tensile ratio of the base material, *W* is the plate width, *t* is the plate thickness and $a_{\max}$ is the depth of the deepest flaw

NOTE: The calculation of $2c_{gsy}$ is basically a flat plate solution and the flaws are re-characterised as rectangular shaped.

The level of yield strength mismatch has an important effect on the defect length limit. Therefore, for welded joints in which the level of yield strength mismatch is significant, the value of $2c_{gsy}$ may be estimated by

$$2c_{gsy} = \frac{M(1+R)-2R}{M(1+R)}\frac{Wt}{a_{\max}} \tag{F.2}$$

where *M* is the mismatch ratio $\sigma_{YW} / \sigma_{YB}$. For conformity, the yield-to-tensile ratio, R, is that of the parent metal. Up to values of *R* equal to 0.90, the level of weld metal mismatch has a greater effect on the calculated defect length than the yield-to-tensile ratio has. However, in cases where the weld metal strain hardening exponent differs significantly from that of the parent metal, the weld metal yield to tensile ratio should be used as input.

Having determined the value of $2c_{gsy}$, the combination rule becomes:

$$s \le \frac{1+R}{2R}\left(\sum 2c_i - 2c_{gsy}\right) \tag{F.3}$$

It is clear that if the total length of two (or more) co-planar flaws, excluding the spacing distance in between these defects, is less than the defect length limit $2c_{gsy}$, combination needs not be considered (in this case $s <$ 0).

Since the applied procedure is intended to cause gross-section yielding, the plastic collapse stress will be equal to or greater than the yield strength. For the conditions of net-section yielding (plastic deformation is confined to the plane of the flaws) and gross section yielding (yielding of remote cross section), the stress at plastic collapse is derived from the net-section area. The use of the length of the (longest) single flaw might underestimate the actual collapse load. For non-interacting defects a conservative estimate can be obtained by:

$$\sigma_{PC} = \sigma_f\left(1 - \frac{\sum 2c_i a_{\max}}{Wt}\right) \tag{F.4}$$

Interacting flaws are treated as a single flaw with dimensions determined by the envelope drawn around the flaws. The flaw length to be used in the assessment of the plastic collapse load should thus be the sum of the individual flaw lengths and their spacing. A conservative estimate of the collapse stress is given by:

$$\sigma_{PC} = \sigma_f\left(1 - \frac{\left(\sum 2c_i + s\right)a_{\max}}{Wt}\right) \tag{F.5}$$

The calculations of collapse stress do not account for the increased constraint at the inner tips of the flaws due to the presence of the ligament and the approach therefore, incorporates an element of conservatism. A further degree of conservatism is added due to the fact that the flaws have been re-characterised as rectangular defects.

NOTE: *For most structural steels, the value of W can be set at a maximum of 300 mm for plate widths exceeding 300 mm. For critical applications, the exact value of W can be obtained by experiments. For smaller plate widths, the actual plate width should be used.*

F.3.3 Advanced assessment

The combination rules discussed in paragraphs F.3.1 and F.3.2 need not be applied if *K* and limit load solutions can be obtained for the interacting flaws (e.g. by finite-element-simulations). Interaction behaviour can also be assessed by means of an experimental investigation using test specimens that are representative for the structural behaviour (e.g. wide plate tests). In both cases, experts' advice should be sought.

F.4 References

F.1 BS 7910:2005: 'Guide on methods for assessing the acceptability of flaws in metallic structures', British Standards Institution, 2005

F.2 ASME (2003) 'ASME Boiler and Pressure Vessel Code, Section XI – Division 1', American Society of Mechanical Engineers.