

Chapter 2

The Structural Hot-Spot Stress Approach to Fatigue Analysis

2.1 Field of Application

The structural hot-spot stress approach applies to welded joints for which:

- the fluctuating principal stress acts predominantly transverse to the weld toe (or the ends of a discontinuous longitudinal weld);
- the potential fatigue crack will initiate at the weld toe or end.

In Fig. 2.1, the hot spot approach applies to cases (a-e). For reasons that will be discussed later, it is also necessary to distinguish between joints that are fully load-carrying and non-load carrying. Cases (c) and (h) represent load carrying fillet welds, whereas case (b) represents non-load carrying fillet welds. Fillet welds at cover and collar plates (lugs), case (d) and (i), are actually partial-load carrying welds. Also end welds in cases (e) and (j), representing gussets or brackets welded on plates, are partial-load carrying. If there is any doubt about the choice of category, the joint should be assumed to be load-carrying. The structural hot-spot stress approach presented here is not applicable to cases where the crack will grow from the weld root and propagate through the weld throat, cases (f-j) in Fig. 2.1. Good design practice aims to avoid this kind of behaviour because the crack is not visible before it has propagated through the weld. However, approaches also exist for their assessment [1], which are partly classified as structural approaches. Moreover, the structural hot-spot approach does not apply to continuous welds subject to longitudinal loading. The nominal stress approach [2] is sufficient for such cases.

The weld detail being assessed will often be situated in a bi-axial stress field. Then it is usually sufficient to apply the structural stress approach to that principal stress which acts approximately perpendicular (between 30° and 90°) to the weld toe, see Sect. 2.3. If necessary, the other principal stress can be considered using the fatigue class for longitudinally-loaded welds in the nominal stress approach according to Ref. [2].

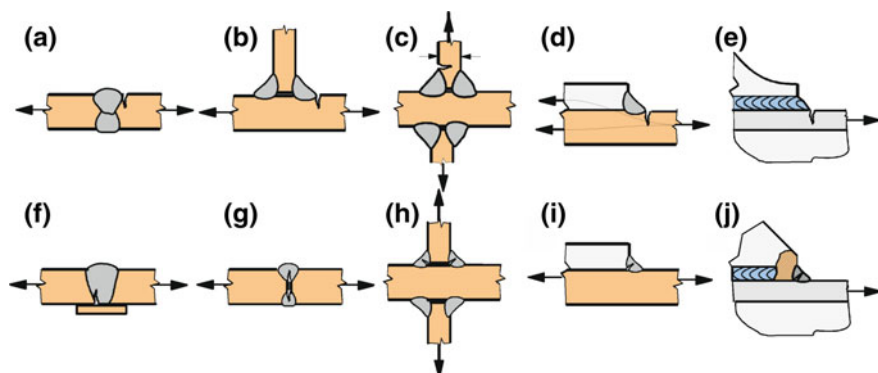


Fig. 2.1 Examples of fatigue crack initiation sites in welded joints

2.2 Types of Hot Spot

Hot spots can be classified as two types, as shown in Fig. 2.2:

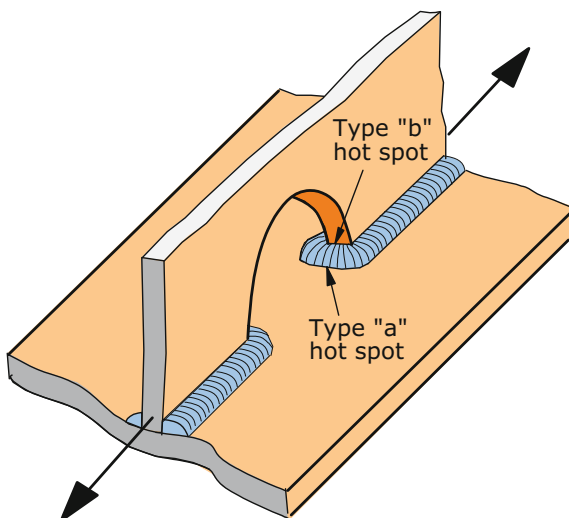
Type “a” The weld toe is located on a plate surface, see also Fig. 2.1a–e.

Type “b” The weld toe is located on a plate edge, see also Fig. 2.3.

Different methods are used to determine the hot-spot stress for each type.

Figure 2.3 shows various weld details containing Type “b” hot-spots at the short weld toe or weld end on the plate edge. These welds are classified as load-carrying, except in cases where $L < 100$ mm.

Fig. 2.2 Examples of the two hot-spot types, in a welded girder: Type “a” is located on the surface of the lower flange, Type “b” is located on the edge of the web plate in a scallop



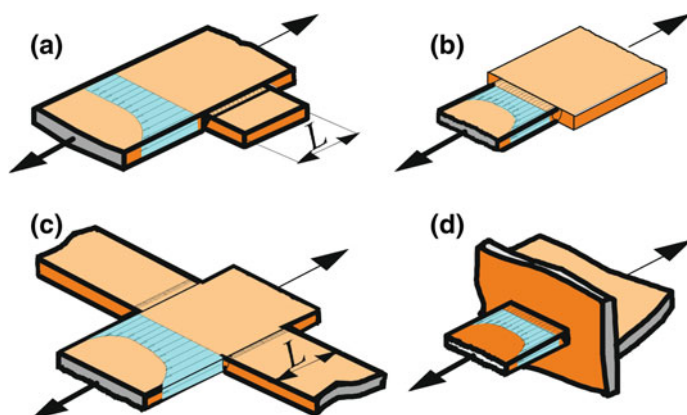


Fig. 2.3 Various details with Type “b” hot-spots at a plate edge, including edge gussets, crossing beam flanges and other details with sharp in-plane notches. *Note* The details shown in Fig. 2.3 represent high structural stress concentrations and correspondingly low fatigue resistance. Therefore, where possible, rounded details and ground corner radii are preferable

In the following sections, recommendations are given concerning mainly Type “a” hot-spots. Type “b” hot-spots are considered in Sects. 3.3 and 4.3.2.

2.3 Definition of the Structural Stress at a Type “a” Hot-Spot

The hot-spot is the critical location at the weld toe (or weld end) where a fatigue crack can be expected to initiate. The structural hot-spot approach is based on the range of the structural stress at the hot-spot (called the “structural hot-spot stress range”). Structural stress, σ_s , is the sum of membrane stress, σ_m , and shell bending stress, σ_b , on the surface of the member, Fig. 2.4.

In many practical cases the larger principal stress range is approximately perpendicular to the weld. Thus, it is interpreted directly as the hot-spot stress. More generally, the hot-spot stress is defined as follows.

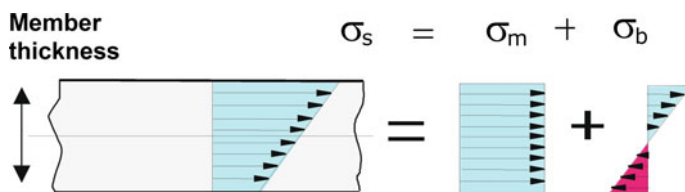


Fig. 2.4 Illustration of the structural stress as the sum of membrane and shell bending stresses on the surface of a member

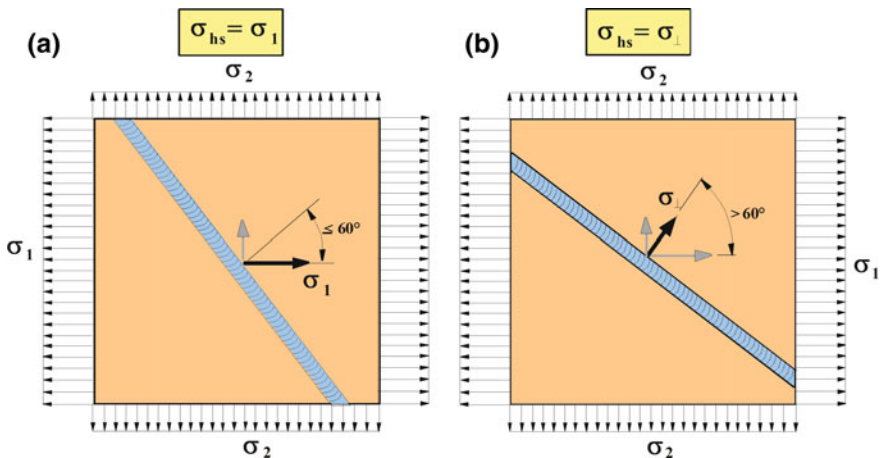


Fig. 2.5 Definition of the stress component used as hot-spot stress in a case when both principal stresses are tensile

- The principal stress with largest range if its direction is within $\pm 60^\circ$ of the normal to the weld toe, Fig. 2.5a.
- If the direction of the principal stress with largest range is outside the above range, the stress component normal to weld toe, $\sigma_\perp$, Fig. 2.5b, or the minimum principal stress, σ_2 , whichever shows the largest range.

In the case of doubt, especially when the directions of the principal stresses change during a load cycle, the partial load factor, γ_F , should be increased sufficiently.

The weld toe represents a local notch, which leads to a non-linear stress distribution through the plate thickness, Fig. 2.6. This consists of three parts: the membrane stress, the shell bending stress and the non-linear stress peak, σ_{nlp} , due to the notch effect of the weld. This notch effect depends on the size and form of the weld and the weld toe geometry. The basic idea of the structural hot-spot approach is to exclude this non-linear stress peak from the structural stress, because the designer cannot know the actual local weld toe geometry in advance. The effect of the notch is implicitly included in the experimentally-determined $S-N$ curve. Thus, only the two linearly distributed stress components are included in the structural stress.

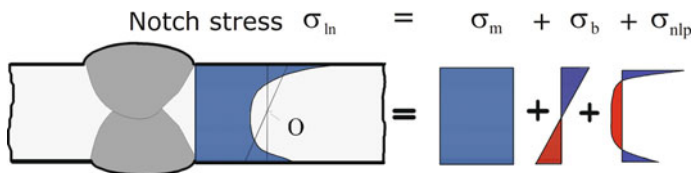


Fig. 2.6 A typical non-linear stress distribution across the plate thickness at a Type “a” hot-spot

It is sometimes argued that the structural hot spot stress is an arbitrary, ill-defined quantity, which does not actually exist. However, according to the above definition, it is an unambiguous quantity, at least for Type “a” hot-spots. Provided the actual non-linear stress distribution is known, the membrane and shell bending stress components can be calculated. However, if it is not known, the structural hot-spot stress must be estimated by extrapolation from the stress distribution approaching the hot-spot.

2.4 Use of Stress Concentration Factors

2.4.1 Modified Nominal Stress

The effect of local increases in stress due to geometric features such as structural discontinuities or misalignment can be taken into account by the use of appropriate stress concentration factors. These are used in conjunction with the nominal stress to give the modified nominal stress, σ_{nom} , in the region concerned.

Thus, relevant σ_{nom} must include the effects of the macro-geometric features like large openings, beam curvature, shear lag and eccentricity, as illustrated in Fig. 2.7. Such features are not included in the catalogue of classified details in conventional fatigue design rules based on the use of nominal stress.

2.4.2 Structural Stress Concentration Factors, K_s

Stress concentration factors (SCFs) have been published for many types of structural discontinuity. In situations where the nominal stress can be calculated easily, such as weld details in bars or beams, they can be used to estimate the structural hot-spot stress. However, they should be used with care since they might not

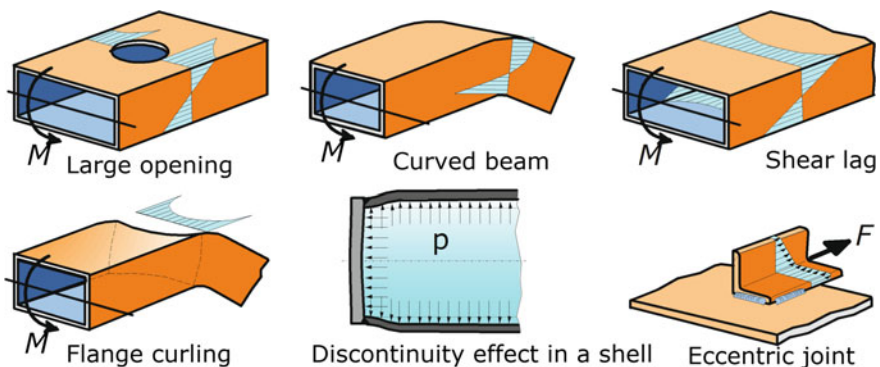


Fig. 2.7 Macro-geometric features which enhance the nominal stress σ_{nom} . In some cases, secondary shell bending stresses are induced

comply with the current definition of structural stress. There is scope for developing valid stress concentration factors, denoted K_s , using FEA and presenting them in the form of parametric formulae. Unfortunately, such formulae are only available in the open literature for a few weld details, see Sect. 5.2.

In principle, the structural hot-spot stress is then given by:

$$\sigma_{hs} = K_s \cdot \sigma_{nom} \quad (2.1a)$$

where σ_{nom} is the modified nominal stress in the area of the hot spot.

In many cases, it is reasonable to use the structural stress concentration factors for axial and bending loading separately. The total structural stress is then:

$$\sigma_{hs} = K_{s,a} \cdot \sigma_{nom,a} + K_{s,b} \cdot \sigma_{nom,b} \quad (2.1b)$$

where

- $K_{s,a}$ is the structural stress concentration factor in the case of axial loading
- $K_{s,b}$ is the structural stress concentration factor in the case of bending
- $\sigma_{nom,a}$ is the modified nominal stress due to the axial loading
- $\sigma_{nom,b}$ is the modified nominal stress at the point of interest due to the bending moment

In cases of biaxial bending and even more complicated cases, such as tubular joints with several brace members joined to a chord, the equation can be expanded correspondingly for each hot-spot.

2.4.3 Stress Magnification Factor Due to Misalignment K_m

It is often found that the results of FEA and strain measurements are not in good agreement. One reason is the fact that the FE model is an idealisation of the actual geometry of the structure. In reality, this may be different from the model due to fabrication inaccuracy and welding distortions. Misalignment of the types shown in Fig. 2.8 produces secondary shell bending stresses in a plate loaded by a membrane

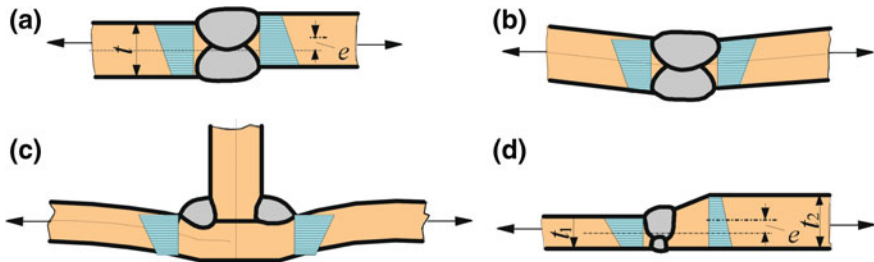


Fig. 2.8 Typical misalignments: **a** offset misalignment, **b** and **c** angular misalignments, **d** eccentric joint

force. Consequently, the designer should always take into account the type and extent of expected misalignment (e.g. based on material or fabrication dimensional tolerances) in the stress calculations.¹ Usually, it is desirable to perform the finite element analysis using a model with ideal geometry, ignoring the fabrication misalignments. In that case, a magnification factor, K_m , can be used for estimation of the modified nominal stress:

$$\sigma_{\text{nom}} = K_m \cdot \sigma_{\text{nom,m}} + \sigma_{\text{nom,b}}, \quad (2.2)$$

where

- K_m is a magnification factor, Sect. 5.1;
- $\sigma_{\text{nom,m}}$ is the membrane part of the nominal stress;
- $\sigma_{\text{nom,b}}$ is the shell bending part of the nominal stress.

Sometimes the nominal stress components are unknown. Then it is sufficient to replace them in Eq. (2.2) with the structural hot-spot stress components, $\sigma_{\text{hs,m}}$ and $\sigma_{\text{hs,b}}$. This will be conservative.

It should be noted that in some cases the behaviour of misaligned joints under load is significantly non-linear, depending on the level of applied stress, see Sect. 5.1. In such a case, Eq. (2.2) must be applied for both σ_{max} and σ_{min} . The modified stress range is then the difference between the modified maximum and minimum stresses. However, it is conservative to apply Eq. (2.2) directly to stress range, as would also be appropriate when the K_m factor is independent of the stress level.

It would be advisable to include fabrication tolerances and recommended K_m values for typical details in design guidance developed specifically for particular structures, e.g. cranes and ship hulls.

¹Misalignment is addressed in different ways in the IIW Fatigue Design Recommendations [2], depending on its source:

1. Some misalignment effects are already taken into account in the fatigue classes referred to nominal stresses. The same is true for the structural hot-spot stress classes, but only for the small amount corresponding to up to 5% stress increase [2]. Particularly for butt joints, cruciform joints and transverse attachments, additional misalignment effects resulting from fabrication inaccuracy and welding distortion should be taken into account by increasing the stress or dividing the fatigue class by K_m .
2. Designed eccentricities, as shown in Fig. 2.8d, should be taken into account by calculating the extra shell bending stress.

However, in this Designer's Guide, it is recommended that all sources of extra stress, including misalignments resulting from fabrication inaccuracy and welding distortion, are taken into consideration in the stress calculations.

2.5 Effect of Component Size on the Fatigue Resistance

The fatigue strength of welded joints is size dependent. This size effect is a combination of

- geometric;
- statistical; and
- technological effects.

The geometric effect is often dominant. It depends on the stress gradient in the crack growth direction. In thick plates with geometrical discontinuities like that shown in Fig. 3.1, the non-linear stress peak appears in a relatively deep surface layer (low gradient) which gives rise to faster crack growth and shorter life compared to similar details in thinner plate.

The statistical effect refers to the greater probability of introducing large flaws as the extent of welding increases.

The technological effect refers to other characteristics of welded joints that are influenced by size. For example, the choice of welding process and procedure may be dictated by section thickness and welding residual stresses will be higher in the case of large components.

In the structural hot-spot approach, the geometric size effect is taken into account by multiplying the fatigue strength by a so-called thickness correction factor, $f(t)$, which depends mainly on the thickness of the stressed plate, see Sect. 6.1. For Type “b” hot-spots, the plate thickness has only a small effect on the fatigue strength, because the geometric effect now depends mainly on the width of the plate. At the present time, there is no generally accepted method to take into account the geometrical size effect in such cases. However, the extrapolation method for determining the hot-spot stress from strain gauge measurements presented in Sect. 3.2, with fixed extrapolation points, is also intended to take into account the geometric size effect. This is because the leading gauge picks up traces of the notch stress, which depends on the size of the component.

References

1. Fricke, W.: IIW guideline for the assessment of weld root fatigue. *Weld. World* **57**, 753–791 (2013)
2. Hobbacher, A.F.: Recommendations for fatigue design of welded joints and components. 2nd edn. Springer (2016)

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Analysis of Welded Components

Designer's Guide

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