Chapter 2
Design for Purpose

2.1 Limit State Design

Typical fabricated structures may have hundreds or even thousands of meters of weld. Thus, many potential fatigue cracking locations are present that must be considered during design development and production. The challenge is to optimize a design so that the welds have sufficient fatigue strength and fabrication quality to withstand the loads during the economic life of the structure or piece of equipment. Quality systems for welds are described in the so-called weld class systems, such as ISO 5817 or Volvo's old STD 181-0001. In these systems, acceptance limits are given for different weld geometry features or imperfections. Based on these limits, a weld is associated with a quality level, e.g., B, C, or D. Intuitively, a high-quality level, B, is assumed to perform better during the service than a weld with a C or D quality level. The problem with the existing weld quality systems is that they were initially developed as a measure of workmanship with respect to fabrication, i.e., as a measure of the skill of the individual or machine performing the operation. As such, they have been incorporated into a number of training and education programs for welders and weld inspectors. Numerous studies have shown that the link between the existing weld quality classes and fatigue performance is not consistent. Some acceptance criteria for some weld features or imperfections are found to have little or no influence on fatigue strength. For features which do influence fatigue strength, the acceptance criteria between quality classes do not result in uniform changes in the fatigue strength. Realizing that fatigue is highly affected by the local geometric features and imperfections of the weld, systems such as ISO 5817 could have been a good tool for quality measures regarding fatigue.

Designers of welded structures, on the other hand, think of weld quality in terms of performance. In this realm, quality would mean that a weld is able to perform its required function during the economic life of the component or structure. The required function may be major such as resistance to fatigue failure, sufficient strength with respect to extreme loads, impermeability, or corrosion resistance; or the

B. Jonsson et al., *IIW Guidelines on Weld Quality in Relationship to Fatigue Strength*, IIW Collection, DOI 10.1007/978-3-319-19198-0_2

required function could be a minor functional property such as hardness, resistance to abrasion, visual appearance, or surface finish. This way of thinking is consistent with modern design guidelines for structures which are based on limit state design considerations. One important feature of limit state design is the existence of clearly identified conditions or limits that constitute failure or feasibility for a structure. For a designer, any discussion of quality must relate the definition of weld quality with the limit state(s) that quantify failure. Fatigue strength is one of the most demanding limit state design criteria for welded structures.

2.2 Fatigue Versus Static Loading

The characteristic of the predominant load on the component is a major guiding consideration when formulating quality guidelines for load-carrying structures. For predominantly statically loaded welds, design calculations are based on the average stress in the weld net area. For this reason, ductility of the heat-affected zone (HAZ) and weld metal and sufficient weld throat thickness are the most important features. Imperfections such as porosity, undercuts, or cold laps have very little influence on the static capacity as long as the weld is ductile and the imperfections are small enough so as not to unexpectedly reduce the weld cross-sectional area. Thus, the ISO 5817 guideline includes many acceptance criteria which are not relevant for static loaded joints. Throat thickness is by far the most significant geometric feature of a weld subjected to predominantly static loading. Weld type (butt, fillet, V, K) does not significantly influence the strength for equal throat thickness.

Ductility and throat thickness are ensured by preproduction tests to validate the welding procedure specification (WPS). The same specification should ensure that crack-like imperfections are not formed during welding. For welded structures in high-strength steel, matching or overmatching of the weld metal strength may be difficult to achieve. In this case, insufficient static strength of the filler material can be compensated by adding filler material. Loss of ductility, however, cannot always be compensated for by adding material so this is considered to be the most important basic requirement of welding. Joint ductility is assumed in all types of structural durability assessment. The WPS provides a guideline which ensures the deformation capacity and strength of the joint. Thus, when defining the welding parameters, it is important to prioritize those parameters that produce required quality. Following this, aspects which improve productivity can be considered. Some structures will naturally have only very low load-carrying requirements, and in these cases, optimization of production costs can bring significant savings for fabrication. One example of this type of weld may be, for example, long fixing welds in statically loaded structures.

For predominantly fatigue loaded structures, the demands of ductility and sufficient throat thickness must obviously be maintained. But, because fatigue strength is significantly influenced by the local characteristics of the joint, extra requirements with respect to weld geometry and imperfections are imposed. In addition to throat thickness and ductility, Jonsson et al., for example, identified seven additional weld

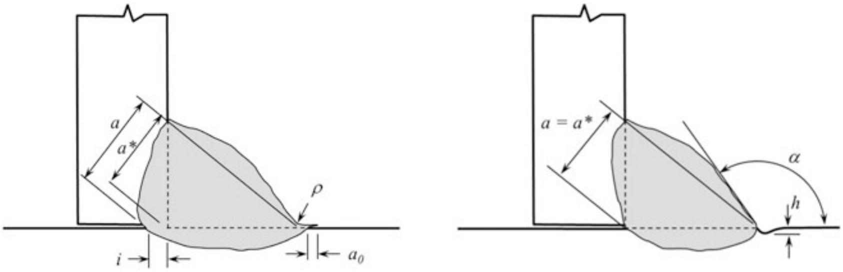

Fig. 2.1 Fillet weld geometry features which significantly influence fatigue strength. a Throat thickness, a^* fillet size, h depth of undercut, i weld penetration, ρ weld toe radius, a_0 cold lap length, and α weld angle

features which strongly influence fatigue strength: penetration, cold lap size, inner lack of fusion, weld toe transition radius, undercut size, joint misalignment, and porosity (see Fig. 2.1). It can be noted that in some technical literature, the cold lap imperfection shown in Fig. 2.1 is sometimes referred to as a micro-lack of fusion or a non-fused overlap. In technical literature, there is some inconsistency as to the definition of throat thickness, a, for partially penetrated welds. In this document, the definition is consistent with the Eurocodes, i.e., weld throat thickness includes also the penetration. The fillet size, a^*, is defined as being measured from the intersection of the plates as shown in Fig. 2.1. Thus, for fillet welds with no penetration, $a = a^*$; and for fillet welds with penetration, $a \approx a^* + i/\sqrt{2}$. Porosity is categorized based on pore location, diameter, and whether the pores occur singly or as a cluster. Weld angle can have an influence on fatigue strength. However, for fillet welds with high fatigue strength, weld angle is far less important than weld toe radius. For welds which have fatigue strength meeting IIW Recommendations, $\alpha \geq 90°$ is sufficient.

Root side fatigue can be the result of poor design or improper WPS. If a full penetration weld is not designated, lack of penetration may serve as a large initial defect. The greater the defect, the shorter the expected life so the root side fatigue strength can vary from near zero to a value far exceeding the fatigue strength of the weld toe or plate edge. Designing against fatigue is thus strongly dependent on the needed weld penetration. This value is determined by analysis using the effective notch method, fracture mechanics, or other suitable method. It is suggested that root side penetration be specified on the production drawing and that the quality requirement is simply that penetration is equal to or greater than this value.

2.3 Weld Quality and Design

Weld quality with respect to fatigue is controlled largely based on the local geometry of the weld toe. In any single welded joint, there may be numerous fatigue critical locations depending on the weld type and direction of loading.

In multipass welding, the notches occurring between beads can also be critical. If weld quality is limited to include only the weld toe geometry, it means that quality is controlled by the fabrication processes. Factors other than weld geometry that relate to the fabrication phase and that possibly affect the strength of the joint must be taken into consideration by the designer during the fatigue assessment process. For example, during design, the structural hot spot stress is normally calculated on the basis of an idealized and perfectly aligned welded joint. Consequently, any possible misalignment has to be taken explicitly into consideration in the FEA model or by applying an appropriate stress magnification factors k_m. This applies particularly to butt welds, cruciform joints, and one-sided transverse fillet-welded attachments on one side of unsupported plates.

Table 2.1 summarizes the relationships between the most common fatigue assessment methods and weld imperfections or misalignment. The nominal stress method partially addresses both imperfections and misalignment in the fatigue resistance (S–N) curves. The hot spot stress and notch stress S–N curves were developed for welds representing typical workshop quality. The notch stress method could be applied to some weld imperfection issues; for example, the influence of undercuts or pores could be modeled using a fictitious radius and the influence of weld angle can also be considered.

Angular distortion and misalignment errors shown in Fig. 2.2 do not fully belong to the quality level even though they occur during the welding process. The S–N curves for hot spot stress or notch stress already include a small magnification factor (5 %) for secondary stresses due to misalignment. The maximum degree of misalignment must be specified by the designer and taken into account as additional

Table 2.1 Relations between fatigue assessment methods, imperfections, and misalignments

Fatigue assessment method	Imperfections	Misalignment
Nominal stress	Some imperfection acceptance limits are specified for some joint types	Acceptance limits are specified for different joint types—additional misalignment must be computed by magnifying factor for the fatigue action
Structural stress	Normal workmanship imperfections are included in the fatigue resistance (S–N) curve	Up to 5 % increase in stress is included in the fatigue resistance (S–N) curve—additional misalignment must be computed by magnifying factor for the fatigue action
Notch stress	Normal workmanship imperfections are included in the fatigue resistance (S–N) curve—some other imperfection types, e.g., large undercut could be modeled	
Linear fracture mechanics	Normal workmanship imperfections are included in the Paris law data—some other imperfection types, e.g., large pores could be modeled	

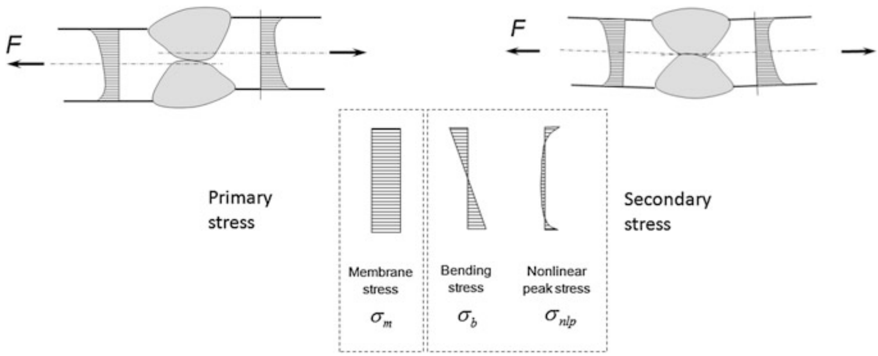

Fig. 2.2 Angular distortion and misalignment imperfections in butt welds

structural stress loading. This is a departure from current practice, but the procedure is analogous to considering the additional structural stress concentration produced by the step effect from butt-welded joints between plates of different thicknesses. The designer should be concerned about this kind of imperfection and should determine the permissible structural asymmetries for different types of loading. If maximum misalignment is not specified, then values found in the IIW Recommendations for nominal stress-based fatigue assessment should be used.

2.4 Practical Design for Purpose

Based on the type of loading, differentiation must be made between various joint categories. Design criteria and quality requirements will depend heavily on the primary function of the joint. Applied loads and structural geometry together establish the joint function. The simple welded T-joints shown in Fig. 2.3 can have numerous functions based on the applied forces, F1–F4.

If the joint is loaded by the force component F1, the weld is a shear-loaded longitudinal weld. Web-to-flange welds in plate girders are typical examples of this type of weld. In such cases, the acceptance criteria related to the weld toe are rarely significant, but failure from the weld root may occur.

For the longitudinal weld loaded by F2, weld start and stop positions become critical and the waviness of the fusion line may have strong influence on fatigue strength. If the joint is loaded by the force component F3, the weld is a non-load-carrying accessory weld and the weld toe geometry at the base plate to weld fusion line becomes crucial, i.e., cold lap size, weld toe transition radius, and undercut size. Welds loaded by F3 can also be considered as moderately demanding with respect to fabrication. A non-loaded accessory weld will never be critical in static loading cases but will often lead to fatigue failure.

For load-carrying fillet welds subjected to F4, the weld toe geometry at the attachment-to-weld fusion line is critical. Cold lap size, inner lack of fusion, weld

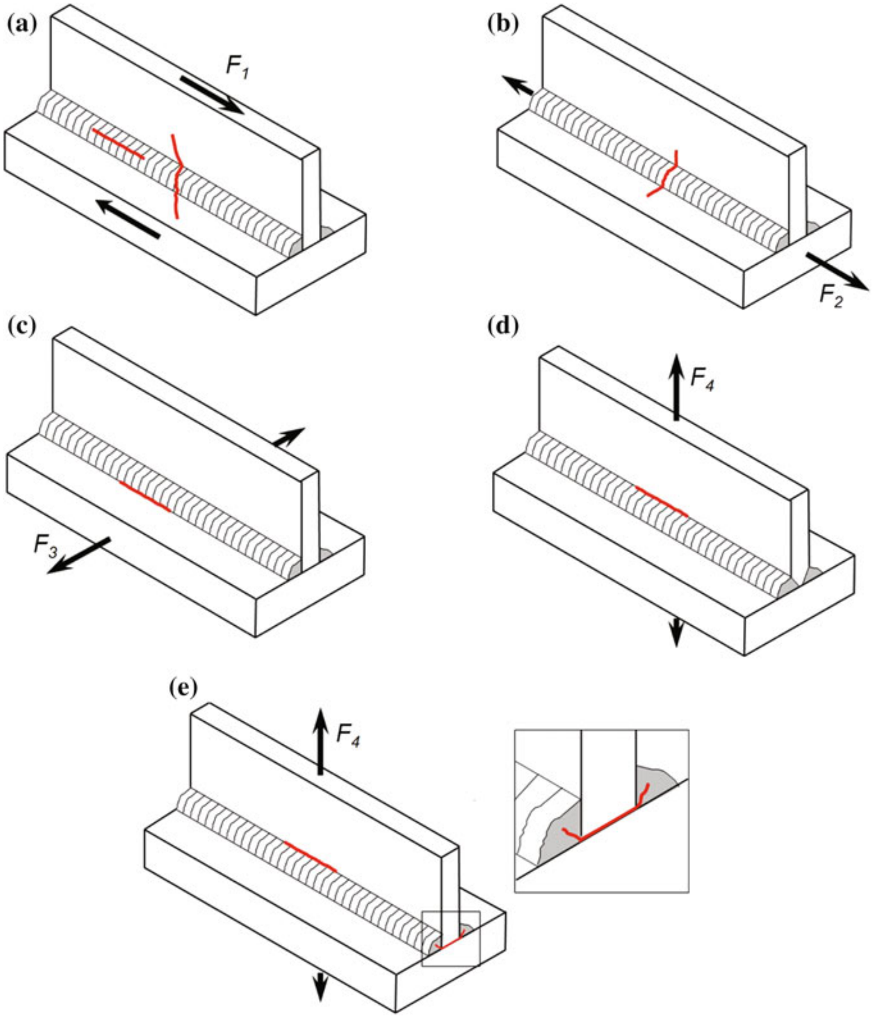

Fig. 2.3 Joint classification is determined based on joint loading/function: **a** longitudinal shear-loaded fillet weld, **b** longitudinal normal-loaded fillet weld, **c** transverse normal non-load-carrying fillet weld, **d** transverse normal load-carrying fillet weld, toe cracking, and **e** transverse load-carrying fillet weld, root cracking. *Red lines* indicate fatigue critical points

toe transition radius, undercut size, joint misalignment porosity, and weld penetration all potentially have strong influence on the fatigue strength of the joint. For a weld loaded with force F4, a root side fatigue crack may also develop depending on the degree of penetration. Welds loaded by F4 are the most demanding both with respect to design and fabrication because both the weld toe side and root side must be considered.

http://www.springer.com/978-3-319-19197-3

IIW Guidelines on Weld Quality in Relationship to Fatigue Strength
Jonsson, B.; Dobmann, G.; Hobbacher, A.F.; Kassner, M.; Marquis, G.
2016, XIII, 115 p. 58 illus., 32 illus. in color., Hardcover
ISBN: 978-3-319-19197-3