Integrated fatigue design and manufacturing for welded structures

Gary Marquis

Lappeenranta University of Technology, Lappeenranta, Finland

ABSTRACT Production engineering and structural design research have historically progressed as separate disciplines with each focussing on its own narrow field of interest. However, the drives to reduce production costs by increasing welding speeds and selecting designs incorporating higher strength steels for fatigue-loaded structures have made it necessary that these research disciplines proceed in close cooperation. This integrated research approach includes joint efforts in several key technologies, e.g., high-speed welding processes, high strength materials, cost-effective NDE, post-weld treatments and FE-based design assessment tools. The current paper focuses on a crucial aspect this integrated research, i.e., the need to develop a suitable quality classification system for weld subjected to fatigue loading. Current weld quality systems for welds were developed primarily with static loading in mind and are not directly suitable for fatigue loaded components. Experimental and analytical methods are used to present a simple method for classifying weld fatigue strength.

1 INTRODUCTION

The primary load-carrying structures for transport vehicles and process equipment are typically complex welded constructions in steel or aluminium. Many Nordic countries have a similar fabrication cultures for welded structures. Production numbers are typically small and competitiveness is attained through innovative product design and high quality production. In order to produce competitive products, the complex demands associated with lead-time, cost-effectiveness, high quality and reduced fuel consumption need to be balanced against those of durability and structural integrity. These demands have led many manufactures to select designs incorporating high strength steels and new approaches to production engineering. Higher nominal operating stresses have increased the sensitivity of advanced structures to fabrication defects and weld geometry variation, i.e., penetration, throat thickness, flank angle and weld toe radius, etc. Improved fatigue strength in traditionally “weak” locations of a structure may simply shift the failure site to the weld root side with little overall improvement in strength. As interest in higher strength materials has increased, the need for integrated research involving high-speed welding processes, cost-effective NDE, and post-weld treatments has become essential. It is increasingly clear that research in manufacturing technology, inspections techniques, fatigue design, etc. can not be performed as separate research fields. Instead, the development of future generations of advanced fabricated structures with reduced weight and higher design stresses will depend on multidisciplinary research efforts. This integrated approach to developing advanced fabricated structures is shown schematically in Fig. 1 [1].

Design engineers and fabrication engineers often have very different views about the concept of weld quality. A designer will probably be most concerned about the *performance* and *durability* of a welded structure. By contrast a welding engineer often views weld quality from a process point of view, i.e., a high quality weld is fabricated according to well specified and well documented procedures. These points of view do no necessarily conflict, but it requires that there is adequate knowledge and correlation between the process aspects of the weld and the performance aspects.

Current practise often defines weld quality, like quality in general, in a comparative sense according to a better-or-worse scale. This type of quality determination works, at best, only when comparing alternatives. There are often factors in the comparison which act in opposite directions. Therefore, a true and unambiguous definition of quality necessitates quantitative measures. Firstly, the variable which defines weld quality unambiguously must be agreed. Unfortunately, such unambiguous variables have not been agreed and only several good compromises are available.

Weld acceptance limits, such as those in ISO 5817 [2], generally relate to what is regarded as good workmanship and focus on easily observed physical characteristics rather than the effect of the feature on structural integrity. These guidelines have been developed with primarily statically loaded welds in mind, but the limits are unsatisfactory with regard to predominantly fatigue loaded structures. An example taken from ISO 5817 is illustrated in Fig. 2. The ISO system divides welds into quality classes B, C and D. The difficulty with the system is that the classification is ultimately based on the worst characteristic of the weld out of a long list of potential characteristics. Some of the characteristics in the ISO system have little or no influence on weld strength while some important characteristics are omitted. Karlsson and Lenander [3] have used fracture mechanics to compute the fatigue life for different acceptance limits within two weld classification codes. In was shown that there is little or no relation between fatigue life and different weld classes. With respect to fatigue strength, geometric features of the weld are known to have a strong influence on fatigue strength. In ISO 5817, no requirement for weld toe radius is given even though qualitative evidence of the potential influence of weld toe geometry on fatigue strength is available. One the positive side, ISO 5817 is relatively simple because it focuses on the worst single feature. Strength, and especially fatigue strength, however, are controlled by the joint interaction of many of characteristics.

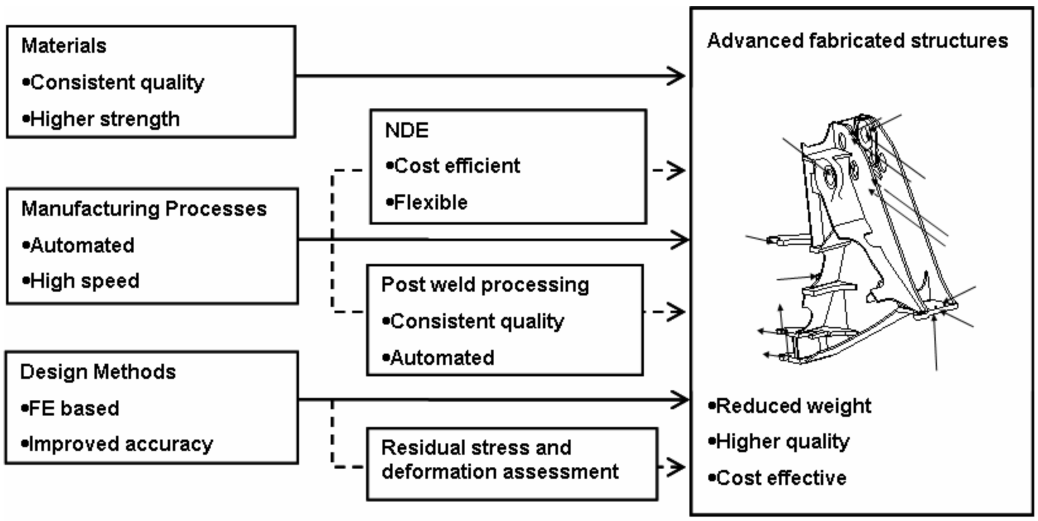


Fig. 1: Integrated research approach to develop advanced fabricated structures [1].

The current status is that European fabricators have no choice other than to design structures *assuming average* fatigue strength because guidelines that *define* high quality for welded structures and give instructions for taking advantage of high quality in design do not exist. One important research objective within the International Institute of Welding Commission on Fatigue of Welded Structures and Components is to develop a systematic approach to quantifying weld quality with respect to fatigue strength and give instructions on how to implement improved weld quality in design. Such an approach would need to take into account current limitations in automated weld processes, economically realistic inspection technologies, and weld improvement methods for high strength steel.

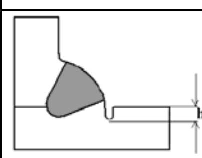
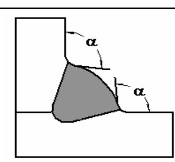
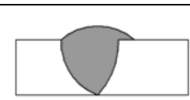
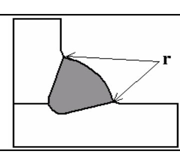
No.	**ISO 6520-1 Reference**	**Imperfection Designation**	**Type of joint**	**Limits for imperfections for quality levels**		
				D	**C**	**B**
1.7	5012	Continuous undercut Intermittent undercut		h ≤ 0,2 t, but max. 1mm	h ≤ 0,1t, but max. 0,5mm	Short imperfections: h ≤ 0,05 t, but max 0,5 mm
1.12	505	Weld toe angle		α ≥ 90°	α ≥ 105°	α ≥ 120°
1.13	506	Overlap		Short imperfection permitted	Not permitted	Not permitted
		Weld toe radius		Not defined		

Fig. 2: Weld class examples from current revision of ISO 5817 [2].

2 WELD QUALITY REQUIREMENTS

In order to initiate a discussion on weld quality for fatigue loaded components, it is first helpful to introduce the concept of design for purpose philosophy. At its most basic level, weld quality means that a weld is able to perform its required function during the life of the structure. The required function may be static load capacity, corrosion, wear resistance any number of other mechanical characteristics. Most modern design guidelines for structures are based on limit state design considerations. One important feature of limit state design is the existence clearly identified limit states which define the conditions or limits that constitute failure or feasibility for a structure. In any discussion of quality, therefore, it is reasonable connect the definition of weld quality with the limit state or states that quantify failure. Such criteria can be any major or minor functional property like hardness, resistance to abrasion, resistance to corrosion, impermeability, appearance, surface finish, etc.

Quality levels can be divided into basic and demanding levels depending on whether fatigue is expected to contribute to the potential failure, see Fig 3. For predominantly statically loaded joints, quality can be defined according to the basic level. The most essential requirement for the basic level is ductility of the filler material and heat-affected zone (HAZ). This is normally ensured by pre-production procedure tests to validate the welding procedure specification (WPS). The same specification should ensure that crack-like imperfections are not formed during welding. Yield strength of the material is an important consideration, but this can be compensated by adding material. Loss of ductility, however, cannot be compensated by adding material so this is considered to be the most important basic requirement of welding. Ductility is a basic assumption in all types of structural durability assessment. The WPS is basically 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.

Steps to improve workshop should be considered only after ductility is achieved. Some structures will naturally have only very low static or fatigue strength requirements and, in these cases, optimization of a production process to reduce costs can result in significant savings. On example of this type of weld may be, for example, long fixing welds in statically loaded structures.

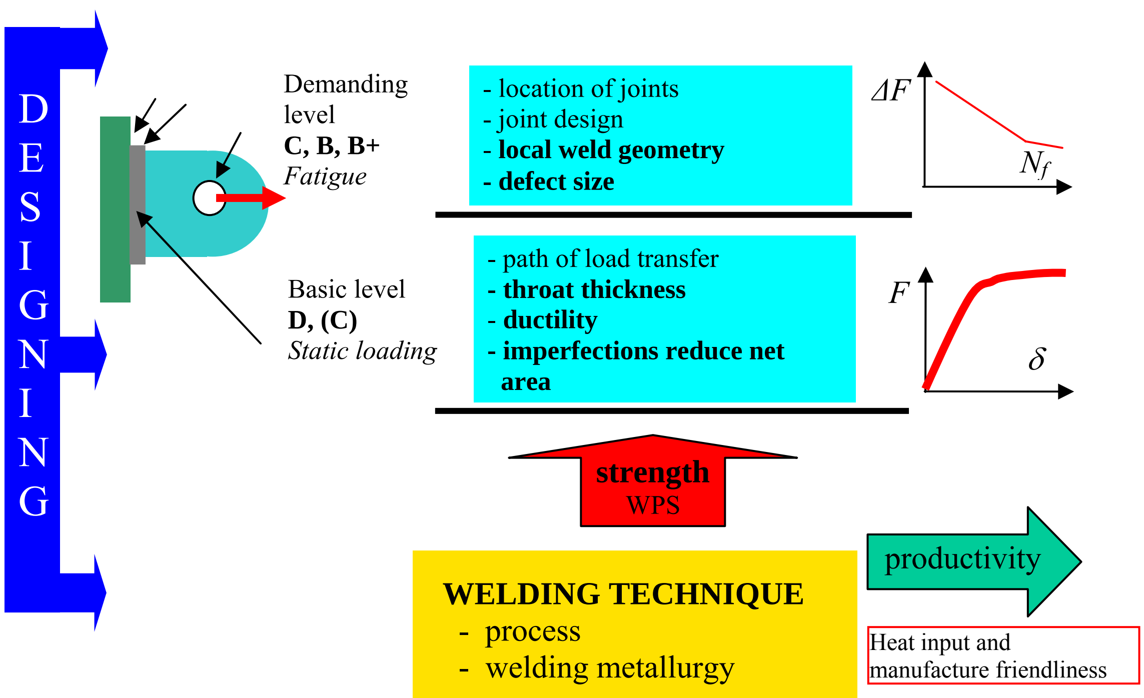


Fig. 3: Quality can be divided into basic and demanding level according to loading

The basic quality level D, fulfils the ductility requirement so that it should not be necessary to perform separate computations for avoiding brittle fracture for a statically loaded structure. The demanding weld quality level, level C, retains the basic ductility requirements but also imposes extra requirements for the weld geometry. This level is intended mainly for fatigue loaded structures. Quality level C requirements for imperfections may also be required for some predominantly statically loaded joints if the consequences for failure would be particularly severe, e.g., pressurized equipment. Another reason for imposing C-level requirements for static loading could be to improve in-service inspectability. Connecting the extent of inspection with the quality level requirement prevents the need to consider the same effect indirectly with additional partial safety factors.

Capacity of a fatigue-loaded joint is controlled by the weakest location of the detail. By contrast, the capacity of a ductile statically loaded joint is determined by the average stress in the net area. This fundamental difference could lead to the situation in which the number of critical details in a construction, in a single joint or in a single weld could increase several fold if an expected static loading turns into fatigue loading. Because fatigue strength is affected by the combined effect of numerous parameters the resulting fatigue strength for nominally identical joints can vary significantly. For this reason it is proposed to introduce several different strength levels whose equivalent quality levels are denoted here as C, B and B+. If a joint is designed such that the possibility for root side fatigue is eliminated, the weld shape and toe geometry dictate the strength of welds loaded transverse with respect to the weld toe line. Root side fatigue can be the result of improper fabrication quality, but it cannot be assigned its own quality level because the fatigue strength can vary from near zero to the strength of the weld toe.

3 WELD GEOMETRY AND FATIGUE STRENGTH

3.1 Analytical studies

In practice, structural durability is most frequently controlled by the fatigue strength of load-carrying or accessory welds. The important stress quantity is the structural or notch stress transverse to weld toe or, in fracture mechanics terminology, the stress intensity factor range, ΔK. The stress intensity factor is a product of the structural stress range, $\Delta\sigma_{hs}$, initial crack x_i due to fabrication, the crack shape correction factor $Y(x)$ and the notch stress factor, M_k, which can be related to weld toe geometry.

$$\Delta K = \Delta\sigma_{hs} M_k(\theta, \rho, x)\sqrt{\pi x} \cdot Y(x) \tag{1}$$

The M_k factor is related to the weld toe contact angle θ, curvature radius ρ and the size of the initial crack x_i. Provided that the initial defect x_i is due to a sharp undercut, the stress intensity is opening mode (mode I). A cold lap defect causes a shear mode stress intensity (mode II) or combined mode I-II. Other, but more secondary, geometry factors that influence weld quality are the depth of the smooth undercut, weld leg length, general weld convexity-concavity and throat thickness, a. Systematic fracture mechanics studies have shown that if fatigue strength is to be maximized, the initial crack depth should be $a_0 \leq 0.05$ mm and ρ should be as large as possible [4-6]. A simplified relationship has been proposed for high quality fillet welded cruciform joints when $(\rho/T) \geq 0.02$ and the initial crack depth, $x_i < 0.05$ mm [6].

$$\Delta\sigma_{mean} = 159.9\left(\frac{\rho}{T}\right)^{0.125} \quad \text{and} \quad \Delta\sigma_{char} = 110.1\left(\frac{\rho}{T}\right)^{0.125} \tag{2}$$

In Eq. (2) T is the plate thickness, $\Delta\sigma_{mean}$ is the 50% survival probability fatigue strength at $2\text{x}10^6$ cycles to failure and $\Delta\sigma_{char}$ is the 95% survival probability fatigue strength at $2\text{x}10^6$ cycles to failure.

3.2 Experimental studies

Most published experimental fatigue data for welded structures does not include full details of the weld geometry. However, several studies have included this information for non-load-carrying cruciform joints failing from cracks at the weld toe [7-12]. In total these six publications report 168 experimental fatigue data points. Of these, 152 were used to help verify Eq.(2) which was derived based on fracture mechanics modelling. The 16 excluded data points had $N_f > 2\times10^6$ and were not included so as to avoid any potential threshold effects. The corresponding average values of geometrical parameters are given in Table 1. The reported experimental data is shown in Fig. 4.

The experimental results, presented as fatigue strengths at 2×10^6 cycles are shown in Fig. 5 as a function of the reported ρ/T, i.e., Table 1 values. The experimental data, which all had fatigue lives $N_f < 2\times10^6$ were extrapolated to $N_f = 2\times10^6$ using an assumed SN slope of -1/3. There is some scatter in the results but there is a clear trend for increasing fatigue strength with increasing ρ/T. These points represent actual experimental data so factors like initial crack depth variation between specimens, actual crack shape, small crack growth behaviour, welding residual stresses, secondary bending during testing and the degree of penetration may also vary in the test specimens. In spite of these experimental uncertainties, the experimental mean curve $\Delta\sigma_{mean} = 156.3\ (\rho/T)^{0.12}$ at 2×10^6 cycles computed using regression analysis is very close to the fracture mechanics predicted mean curves given in Eq. (2), $\Delta\sigma_{mean} = 159.9\ (\rho/T)^{0.125}$ at 2×10^6 cycles. Similarly, the characteristics fatigue strength $\Delta\sigma_{char} = 107.3\ (\rho/T)^{0.12}$ at 2×10^6 cycles nearly coincides to the fracture mechanics based predicted characteristic curve, $\Delta\sigma_{char} = 110.1\ (\rho/T)^{0.125}$.

Table 1. Average values of geometrical parameters used in this study.

	T [mm]	ρ [mm]	θ [^{o}]	a [mm]
LUT 2006 [5]	6	0.01 – 3.9*	38 – 93*	-5
NIMS 1979 [7]	9	0.465	39.2	4.59
Ibid.	20	0.470	50.9	7.35
Ibid.	40	0.546	37.4	8.45
NIMS 1980 [8]	20	0.650	35.0	6.93
Ibid.	20	0.400	43.0	8.00
Branco et al. 1999 [9] – TIG	3	6	10	2
Ibid. - Plasma	3	6	7	2
Lindqvist 2002 [10]	12	0.62	45	6.5
Kuhlmann 2005 [11] - As-welded	12	1.1	41	4
Ibid. - TIG-dressing	12	7.0	41	4

* Variable, values measured for each specimen

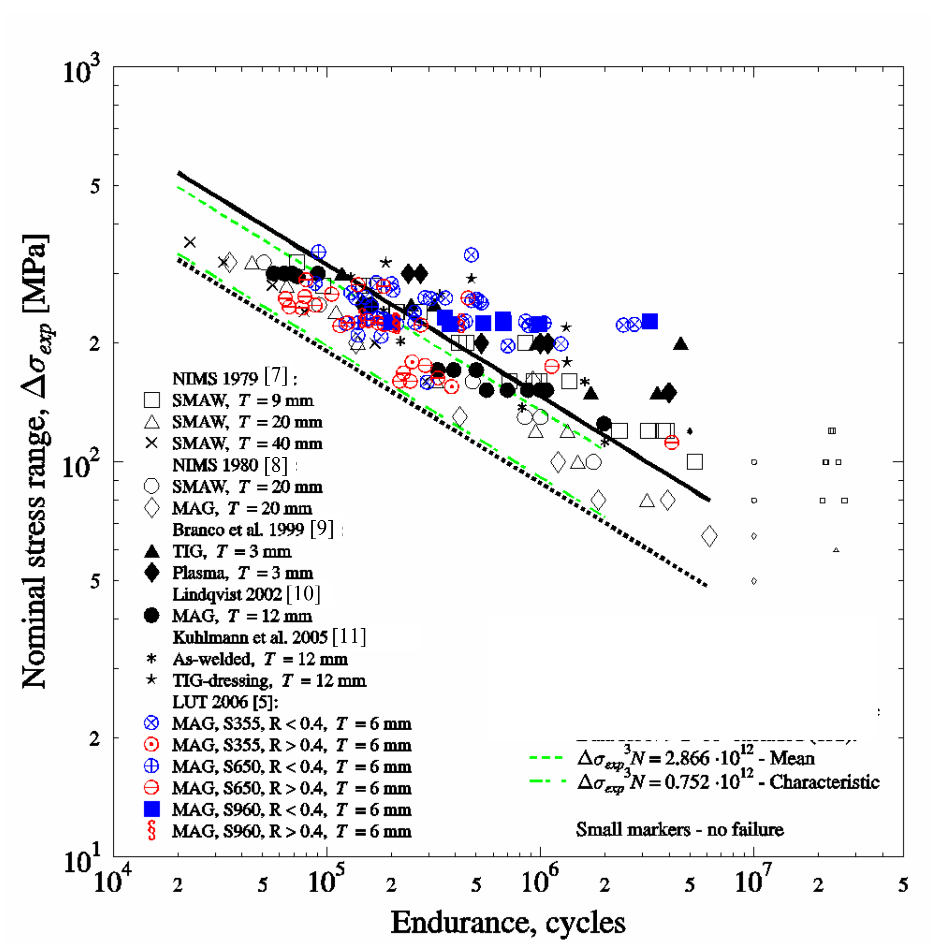


Fig 4 Fatigue test results for as-welded cruciform specimens from studies in Table 1

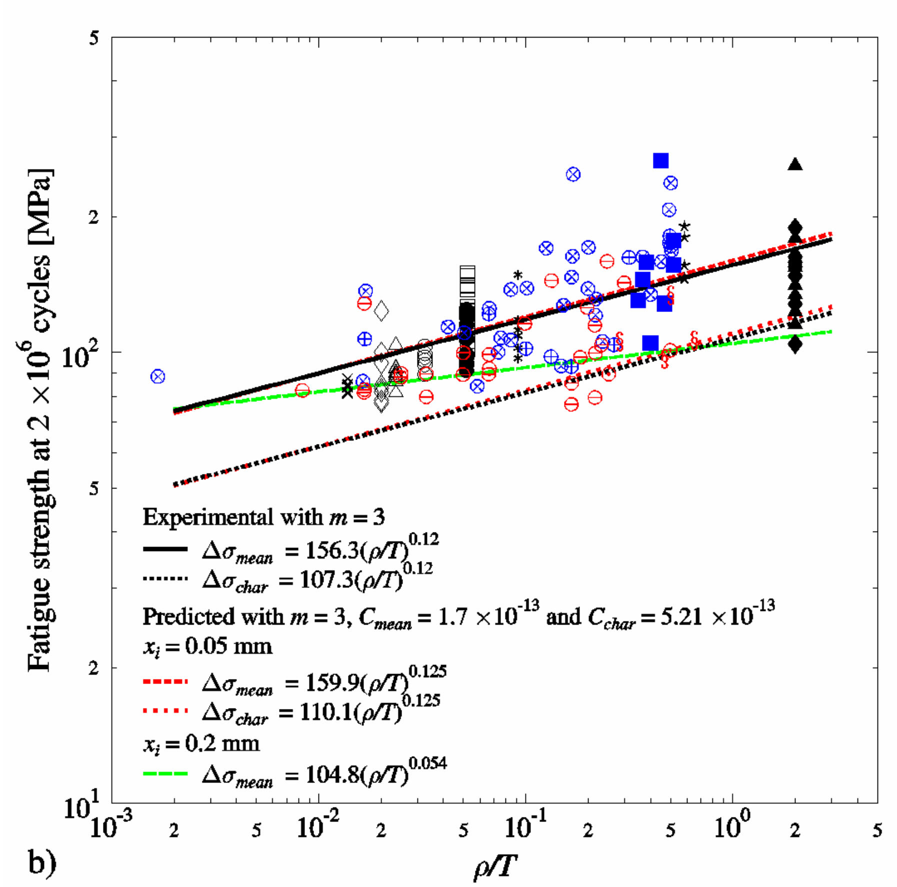


Fig. 5. Experimental fatigue strengths at 2×10^6 cycles, (assumed SN slope of -1/3) plotted as a function of reported ρ/T.

In Figs. 6 the experimentally observed fatigue strengths and predicted strengths for each of the 152 data points are compared. The analytical fatigue strength were based on x_i = 0.05 mm, a Paris law exponent m = 3.0 and Paris law coefficients $C_{char} = 5.21\times10^{-13}$ and $C_{mean} = 1.7\times10^{-13}$.

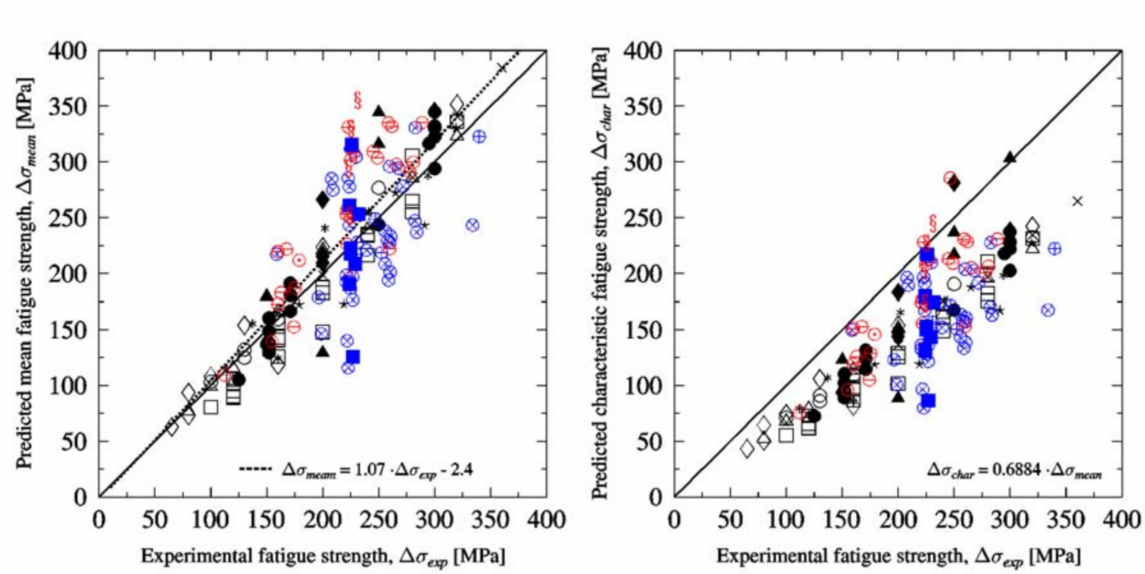


Fig. 6. Correlation between experimental fatigue strengths and fracture mechanics based fatigue strength computed using an assumed semi-elliptical toe crack with $x_i = 0.05$ mm, m=3.0 and a) $C_{mean} = 1.7\times10^{-13}$ and *b)* $C_{char} = 5.21\times10^{-13}$

DISCUSSION AND CONCLUSIONS

Design engineers and fabrication engineers often have very different views about the concept of weld quality. A designer is most concerned about the *performance* and *durability* of a welded structure while a welding engineer is most concerned about a well documented, repeatable and low costs manufacturing process. Achieving high quality welded structures for fatigue loaded structures requires input from both weld processing and durability studies. The development of future generations of advanced fabricated structures with reduced weight and higher design stresses will depend on integrated and multidisciplinary research efforts. The influence of local geometric parameters on the fatigue strength of non-load-carrying cruciform fillet welded joint under tensile loading has been studied using linear elastic fracture mechanics calculations and based on previously reported experimental fatigue data. The reported experimental data included important details about the weld profiles obtained during fabrication.

On the basis of theoretical calculations and comparisons between analytical and experimental results, the following conclusions can be made:

1) Local geometrical variations of the weld and weld throat size have only a small effect on the fatigue strength, if the depth of an initial toe crack is greater than 0.2 mm. As the depth of the initial toe crack increases, the local geometrical effects virtually disappear.

2) The effect of weld angle on the fatigue strength is small when the toe radius is large. For high quality welds, the weld toe radii should be large and the initial crack depth should be very small. According to this study the fatigue strength of joints with large toe radii increases approximately 20-40% as the initial crack depth decreases from 0.2 mm to 0.05 mm.

3) Based on statistical analysis, the best fit between predicted and experimental mean fatigue strengths of high quality welds is achieved when an initial semi-elliptical toe crack with depth of 0.05 mm is assumed.

5) If the predicted and experimental fatigue strengths at 2×10^6 cycles (m = 3) are drawn as a function of ρ/T, the corresponding fitted curves are almost identical when an initial semi-elliptical toe crack with depth of 0.05 mm is assumed. The results are based on 152 experimental data points.

Analytical predicted based on fracture mechanics

$$\Delta\sigma_{mean} = 159.9\left(\frac{\rho}{T}\right)^{0.125} \quad \text{and} \quad \Delta\sigma_{char} = 110.1\left(\frac{\rho}{T}\right)^{0.125} \quad \text{when} \quad \frac{\rho}{T} \geq 0.02$$

Experimental data based on regression analysis

$$\Delta\sigma_{mean} = 156.3\left(\frac{\rho}{T}\right)^{0.12} \quad \text{and} \quad \Delta\sigma_{char} = 107.3\left(\frac{\rho}{T}\right)^{0.12} \quad \text{when} \quad \frac{\rho}{T} \geq 0.02$$

REFERENCES

1. Björk, T., Samuelsson, J. and Marquis, G., The need for a weld quality system for fatigue loaded structures, Welding in the World, 51, issue 11/12, 2007.
2. EN-25817 Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded - Quality levels for imperfections, **1993**, European Committee for Standardisation.
3. Karlsson, N. and Lenander, P. H., Analysis of Fatigue Life in Two Weld Class Systems, Master thesis in Solid Mechanics, LITH-IKP-EX—05/2302—SE, Linköpings University, Sweden, **2005**
4. Nykänen T., Marquis G. and Björk T., Fatigue analysis of non-load-carrying fillet welded cruciform joints, Engineering Fracture Mechanics, Volume 74, Issue 3, pp. 399-415, February 2007.
5. Nykänen T, Marquis G and Björk T, Effect of weld geometry on the fatigue strength of fillet welded cruciform joints, Proceedings of the International Symposium on Integrated Design and Manufacturing of Welded Structures, March 13-14, 2007, Eskilstuna, Sweden, Editors: G. Marquis, J. Samuelsson, H. Agerskov and P. J. Haagensen, ISBN 978-952-214-363-1 ISSN 1459-2924, 23 pages, March 2007
6. Nykänen T, Marquis G and Björk T, Effect of local geometrical variations on the fatigue strength of fillet welded joints, Proceedings of the IX Finnish Mechanics Days, Lappeenranta University of Technology, Finland, pp. 359-377, 2006.
7. NIMS 1979, Data sheets on fatigue properties of non-load-carrying cruciform welded joints of SM50B rolled steel for welded structure -Effect of Specimen Size-. http://tsuge.nims.go.jp/
8. NIMS 1980, Data sheets on fatigue properties for non-load-carrying cruciform welded joints of SM50B rolled steel for welded structure -Effect of Welding procedure-. http://tsuge.nims.go.jp/
9. Branco CM, Maddox SJ, Infante V and Gomes EC, Fatigue performance of tungsten inert gas (TIG) and plasma welds in thin sections, Int. J Fatigue 1999 21 587-601.
10. Lindqvist J, Fatigue strengths thickness dependence in welded constructions, Master thesis, Borlänge, Sweden, 2002.http://hem.passagen.se/johanlindq/Exjobb.pdf
11. Kuhlmann U, et al., Erhöhung der Ermüdungsfestigkeit von geschweißten höherfesten Baustählen durch Anwendung von Nachbehandlungsverfaren, Stahlbau, Stahlbau 74 (2005), H. 5, S. 358-365.