ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 66 (2013) 49 – 61

Procedia Engineering

www.elsevier.com/locate/procedia

5th Fatigue Design Conference, Fatigue Design 2013

S-N Curves for Welded, Non-Welded or Improved Welded Details of Marine Structures

Guy Parmentier, Michel Huther *

Bureau Veritas, Marine Division, 67/71 Boulevard du Château, 95571 Neuilly-Sur-Seine, France

Abstract

Fatigue cracking is surely the more common failure mode of marine structures. The return experience shows that in the majority of the cases, cracks start at welded joints and so the verification methods developed since the 70s deal with welded joints. More recent cases on FPSOs have shown that cracks can also start from non welded areas and the development of the ULCS (Ultra Large Container Ships) points out the necessity of methods for the hatch corners which are non welded areas. To provide a solution for the design of these ships Bureau Veritas developed a local stress S-N curve formulation including as-welded, non welded and improved welded details. The formulation is based on the accumulated knowledge in fatigue verification approaches since the 70s, the marine return experience and the analysis of available published data. The paper presents the development of the formulation starting by the definition of a S-N curve for as-welded joints covering the low and high cycle domains, then the extension of to the stress release welded joints with different R levels and finally the generalisation to non welded and improved welded details. The non-welded detail S-N curves include the effects of the yield strength on the low cycles domain and of the mean stress level on the slope of the high cycles domain. The defined S-N curves are calibrated versus existing methods for welded joints and mechanical component fatigue verification and also versus test data. Finally, an illustration of a practical application on two ship deck details is given showing acceptable results.

Selection and peer-review under responsibility of CETIM

Keywords: Cyclic fatigue, S-N curves, Welded details, Improved welded details, Non-welded details, Marine structures

---

* Corresponding author. Tel.: 33 (0)1 55 24 74 99
E-mail address:guy.parmentier@bureauveritas.com

Selection and peer-review under responsibility of CETIM
doi:10.1016/j.proeng.2013.12.061

1. Introduction

The development at the end of the sixties, in shipbuilding and offshore, of design tools using computers allowed the development of large and very large units with structural strength and so steel weight optimization [1,2,3,4]. The reduction of the steel weight obtained by the adjustment of the safety margins thanks to the new design tools, associated with the use of high strength steels, lead to make cumulative fatigue the major in-service failure mode.

To handle this challenge, a large European cooperative research program was launched within the CECA (European Community for Coal and Steel) the results of which were published in 1987 [5]. During the same period classification societies developed researches on cyclic fatigue of ship structures [6] with publication of guidance notes [7] and rules for very large tankers [8].

The research results and the return experience have shown clearly that welded joints are the weak points with respect to cumulative fatigue, so the design rules were only focussed on welded joints. Different approaches were considered, nominal stress with tables of details [9] and [10], hot spot stress [11,12,13], notch stress [14] and local stress [24,26].

But more recent fatigue failure return experiences on FPSOs [15] and the development of ULCS/Ultra Large Container Ships [16] with thick non welded hatch corners raised the question of the verification of non welded ship structure details. FPSO repairs considering welded joint post weld treatments also raised the question of the S-N curve to be used.

Since the seventies, numerous information and data have been accumulated and published. The presented work aims to provide a synthesis of these published data with proposal of S-N curves for linear welded joints adapted to the various ship and offshore building problems.

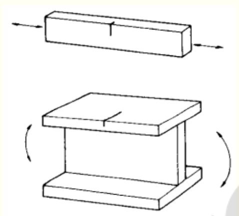
2. Background

The existing rules for fatigue verification of welded steel ship and offshore structure provide S-N curves defined in terms of stress range and applied for all used steel strength [11,17].

2.1. Available data

For the performed work, available data have been collected and analysed. The oldest test data for linear weld joints are given for as-welded joints in terms of nominal stress without consideration of the mean stress assuming that the welding residual stresses are high enough to delete the mean stress influence on the fatigue life. Two main sources have been considered [9,18]. The documents also give data for non-welded details: as-rolled plates (Table 1).

Table 1: S-N curves for as-rolled plates [9]

Plain steel		**m**	**log(K_{50})**	**Stdv(logK)**
	In the as-rolled condition, or with cleaned surfaces but with no flame-cut edges or re-entrant corners	4	15.3697	0.1822
	As above, but with any flame-cut edges subsequently ground or machined to remove all visible sign of the drag lines	4		
	As above, but with the edges machine flame-cut by a controlled procedure to ensure that the cut surface is free from cracks	3.5	14.0342	0.2041

When a part of the stress range in compression the influence has been considered and it has been shown that the life time is increased. Firstly a correction factor has been developed based on the Goodman formula [19]:

$$\Delta S_{eff} = S_{max} - 0.6\ S_{min} \qquad \text{for Smin} < 0 \qquad (\text{tension} > 0 \text{ and compression} < 0) \qquad (1)$$

This formula being very rough, later a new formulation based on a physical model and test results has been developed for unwelded base material and wrought products with negligible residual stresses, stress relieved welded components [18]. The fatigue strength is increased by a factor f(R), R being the stress ratio, which is equivalent to a reduction of the applied stress range by a factor 1/f(R):

$f(R) = 1.6$ for $R < -1$ or completely in compression (2)
$f(R) = -0.4R + 1.2$ for $-1 \leq R \leq 0.5$
$f(R) = 1.0$ for $R > 0.5$

Referring the notch stress approach it has been considered the BV rules for steel ship [17] for which a rather long return experience exists. The stress range for fatigue verification is defined as:

$$\Delta S_N = K_F\, K_G\, \Delta S_{nom} \qquad \text{or} \qquad \Delta S_N = K_F\, \Delta S_{HS} \tag{3}$$

with ΔS stress range, N = notch, nom = nominal, HS = hot spot
K stress concentration factor, G = local geometrical effect, F = notch effect

Referring the mean stress influence a study has been performed in Japan on stress release 579 MPa yield stress steel butt-welds [20,21] providing S-N curves for different values of the R ratio and tests performed with Smax = Sy (figure 1).

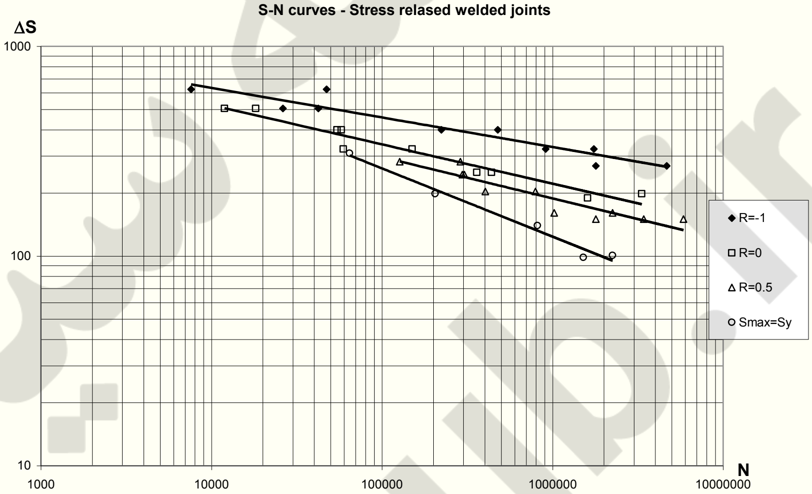


Figure 1: S-N curve of stress released butt-weld versus R ratio

Concerning the low cycles domain, the data from [22] covering 100 cycles to 40 000 cycles have been considered (figure 2).

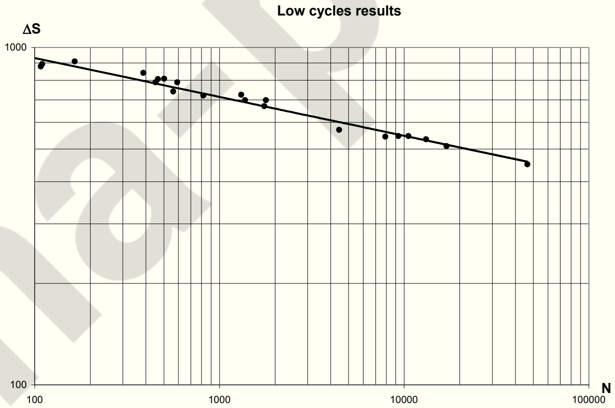


Figure 2: Low cycle domain S-N curve for high tensile steels, Sy = 420 and 515 MPa

The weld joint toe can be represented by a notch on a smooth material. The notch effect on fatigue life has been also analysed [23,24] (figure 3).

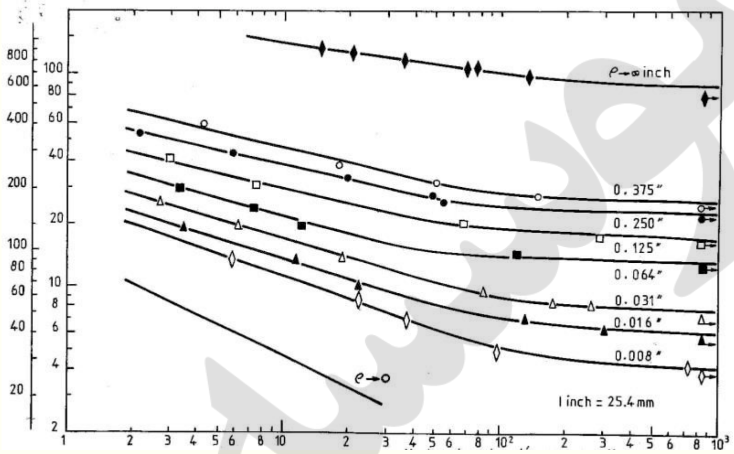


Figure 3: HY130 steel S-N curves versus notch size (ΔS - Nx10^3) [24]

Finally, a large experience exists for mechanical components which provides data on the influence of the ultimate strength. The fatigue limit ($N > 10^7$) for $R = -1$ is given by:

$$S_D(-1) = 0.9\, S_{ult}(0.58 - 1.4\, 10^{-4}\, S_{ult}) \qquad (4)$$

and surface roughness on the fatigue limit [25] (figure 4).

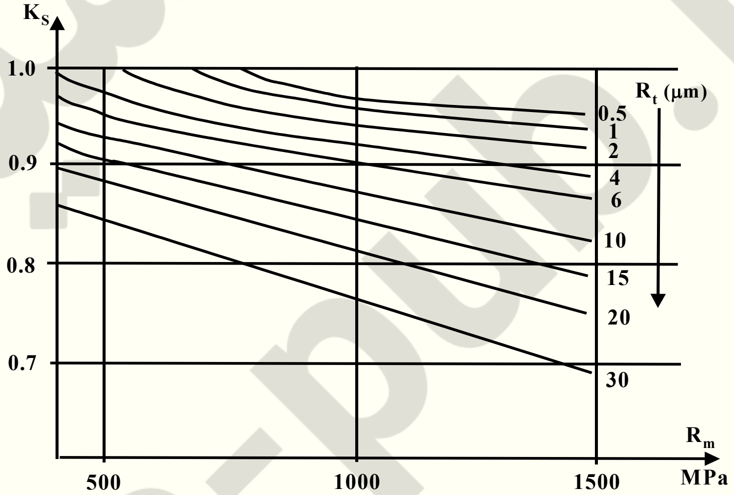


Figure 4 - Fatigue limit correction factor Ks versus steel ultimate strength Rm and surface roughness Rt

2.2. Existing approaches

Three approaches can be found in the existing rules (figure 5):

- nominal stress
- hot spot stress
- notch stress

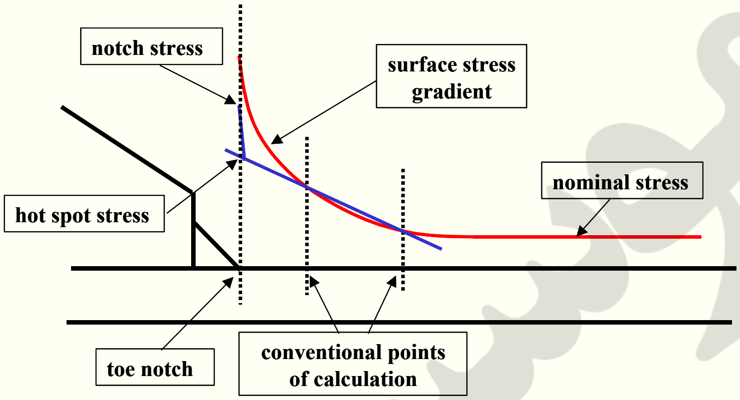


Figure 5: Stress definitions at the weld toe

These three approaches are clearly defined in the last issue of the IIW recommendation [18].

- Fatigue cracks appear at weld toes, so the nominal stress, as it does not incorporate neither global and local geometrical variation effects requires a catalogue of details with the difficulty to found the design detail within the catalogue. The IIW recommendation provides [18], for example, some 80 details.
- The hot spot stress incorporates the global geometrical variation of the component effects but not the weld toe shape, toe radius and weld profile slope. As these two parameters differ with respect to the type of weld, butt weld, T-joints, etc there is also various S-N curves, but much more limited. The IIW recommendation provides, for example, 9 details.
- The notch stress corresponds to the stress at the weld toe, including all local effects. So it is independent of any geometry and only one S-N curve is needed, as shown in the IIW recommendation.

to which it has to be added for non welded details the local stress approach.

The S-N curves are defined in terms of stress range, for as-welded joints, without consideration of the mean stress level taking into account that the welding residual stresses can be equal to the yield strength Sy which imposes that the maximum of the applied elastic stress range is always equal to Sy. The figure 6.illustrates this result for an elastic stress range and tensile mean stress leading to a theoretical maximum stress exceeding Sy. After the first cycles, due to the material S-ε curve, the maximum stress is limited to Sy and the mean stress reduced.

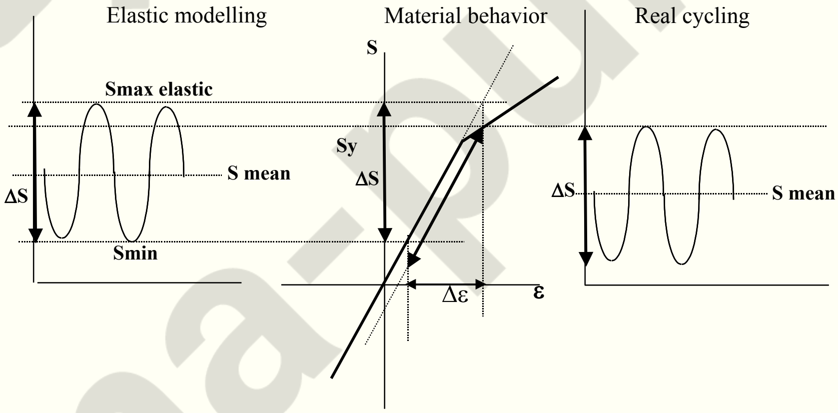


Figure 6: S-N curve impact on cycling stress range and mean for calculated Smax > Sy

2.3. General principle

To obtain a general formulation applicable to welded and non-welded details, the principle has been to define S-N curves for smooth specimens and then to develop factors which take into account the residual stress levels, the stress concentrations due to the weld profile and the notch effect due to the weld toe.

For as-welded joints, the basic S-N curve is modified taking into account a welding residual stress equal to the steel yield strength Sy. The obtained S-N curve is verified versus three documents data, [20,21,22].

For as-welded details with compression where Smax can be lower than Sy, S-N curves are defined based on the [20,21] data for the high cycles domain and [22] data for the low cycles domain.

For non welded details, the results for as-welded joints with Smax < Sy are taken as a basis and adjusted taking into account the [9,25] data.

Considering the material S-ε curve (see figure 6), the main ideas are that (figure 7):

- for the low cycles domain the S-N curve is independent of the ratio R as after very few cycles R becomes equal to -1 but may be function of Sy
- for the high cycles domain, from test results, the slope parameter m is function of the ratio R, not becoming lower than 3
- the high cycles domain curves for different R values converge to the same low cycle curve

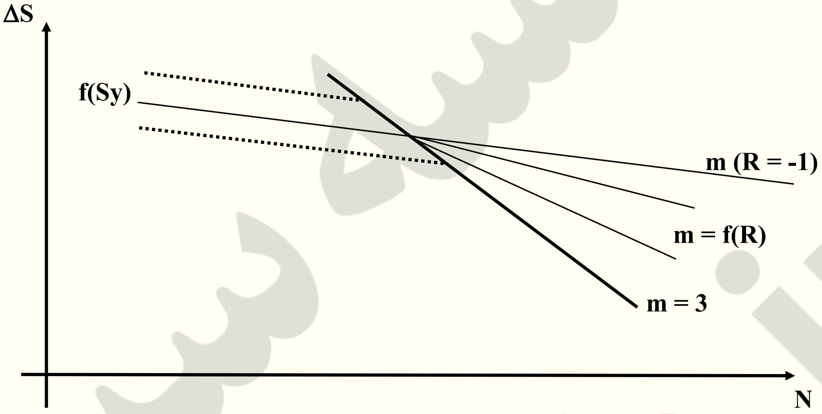


Figure 7: Basis for mean S-N curves versus Sy and R ratio

3. Basic S-N curves

The starting S-N curve is the smooth material design curve, similar to a local approach stress curve, used by Bureau Veritas for the notch stress approach: $\Delta S^3\ N = 1.692\ 10^{13}$.

3.1. Mean curves

The development is performed using the mean curves and the final results are given in design curves. From the document [9], a CoV (coefficient of variation) on log(K) is determined equal to 0.016. Therefore, the starting mean curve is:

$$\Delta S^3\ N = 4.487\ 10^{13} \qquad (5)$$

The stress coefficient factor to be applied to the BV curve to obtain the m=3 [20,21] curves is $K_F = 2.9$. This value can be compared to the value corresponding to but weld, transverse load stress coefficient factor of [17], $K_F = 2.4$. Both values are of the same level.

Another comparison can be done with the [23] curves (figure 3). Considering the points corresponding to r = 0.008" (r = 0.2mm), a S-N curve with m=3 can be obtained: $\Delta S^3\ N = 3.816\ 10^9$. The K_F with respect to the BV curve is so $K_F = 22.7$.

It can be then determined the K_F between the [23] smooth material curve (r = ∞) and the r = 0.008 curve. The curve not being parallel, 2 values have been determined:

$N = 10^4$ $K_F = 13.2$ $N = 10^6$ $K_F = 33.1$

It is noted that the previous value $K_F = 22.7$ is well between these two limits which supports the selection of the BV curve.

3.2. As-welded details

For the high cycles domain the mean S-N curve is given by equation (5).

For the low cycles domain it can be observed that the [22] data and [20,21] data with R=-1 are perfectly in line (figure 8) with equation:

$$\Delta S^{8.5}\,N = 2.217\;10^{27} \qquad (6)$$

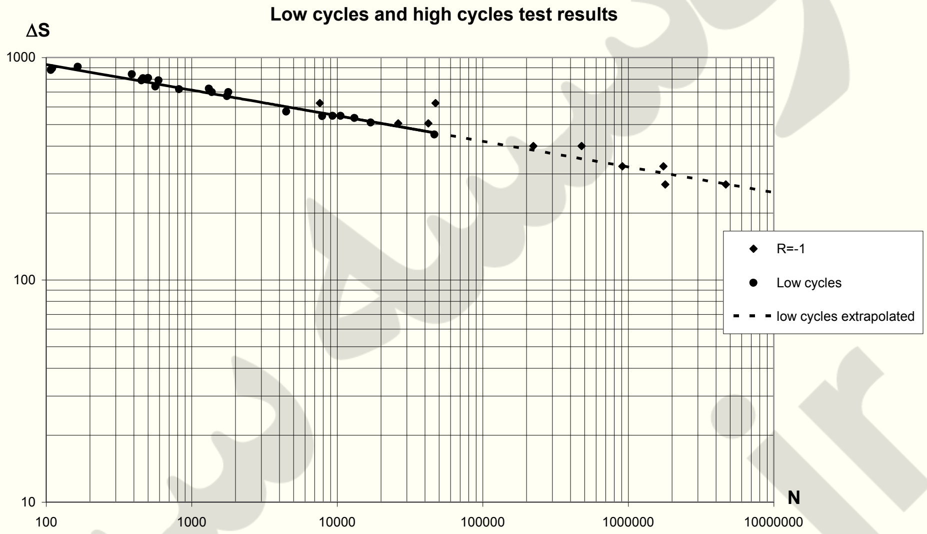


Figure 8: Low cycles and high cycle domain R = -1 data

Both are for welded joints. Applying the $K_F = 2.9$ found previously we obtain for a smooth material:

$$\Delta S^{8.5}\,N = 1.889\;10^{31} \qquad (7)$$

The intersection between the low cycles, equation (5), and high cycles curves (Smax = Sy), equation(7), is at:

$\Delta S = 1601$ MPa N = 10 934 which corresponds to $\Delta S = 2.765$ Sy

The S-N curves are given in terms of Eε, so to verify the found values it has been calculated the Eε of the Sy = 579 MPa steel considering that this value corresponds to $\varepsilon = 0.2\%$. The value is (with E = 200 000 MPa):

$$E(\varepsilon_e + \varepsilon_p) \cong E(Sy/E + 0.002) = 979 \text{ MPa}$$

and $\Delta S = 2\text{x}979 = 1958$ MPa.

From the [22] data, considering the Masson-Coffin curves it can be found the following values:

Table 2. Steel yield strength from Masson-Coffin curves [22]

Sy (MPa)	E (MPa)	εt (%)	E.εt (MPa)
420	195 000	0.402	784
420	195 000	0.361	704
515	208 000	0.553	1150
515	208 000	0.558	1150

which allows to fix the starting point of the low cycles domain at $\Delta S = 2.8$ Sy.

Considering the mean high cycles curve: $\Delta S^3\ N = K_{HCD} = 4.487\ 10^{13}$ and the low cycles domain curve: $\Delta S^{8.5}\ N = K_{LCD}$, we obtain from the intersection with Sy = 579 MPa steel [20,21,22]:

$$K_{LCD} = 1.206\ 10^{16}\ (Sy)^{5.5} \tag{8}$$

Using the same standard deviation than in (3.1) on log(K) for both curves we obtain the following design curves:

- low cycles domain: $\Delta S^{8.5}\ N = 4.551\ 10^{15}\ (Sy)^{5.5}$ for $\Delta S > 2.765\ Sy$ (9)
- high cycles domain: $\Delta S^3\ N = 1.692\ 10^{13}$ for $\Delta S \leq 2.765\ Sy$ (10)

3.3. Welded, stress released details

For welded, stress released details, Smax can be lower than Sy.

Considering (§2.3 and §3.2), the low cycles domain is a function of Sy. From return experience, the as-welded high cycles domain curve can be considered independent of Sy and from [20,21], m is a function of the ratio R (figure 1) with a lower limit m = 3.

A mean S-N curve is so defined as follows (figure 9):

- the lower curve is m = 3 for Smax = Sy as given in (§ 3.2)
- the low cycles domain curve is m = 8.5, R = -1 and K function of Sy as given in(§ 3.2)
- the high cycles domain curve for R = -1 is m = 8.5, in continuity with the low cycles domain
- the high cycles domain curves is m = f(R), obtained from ΔS at N = 2. 10^6

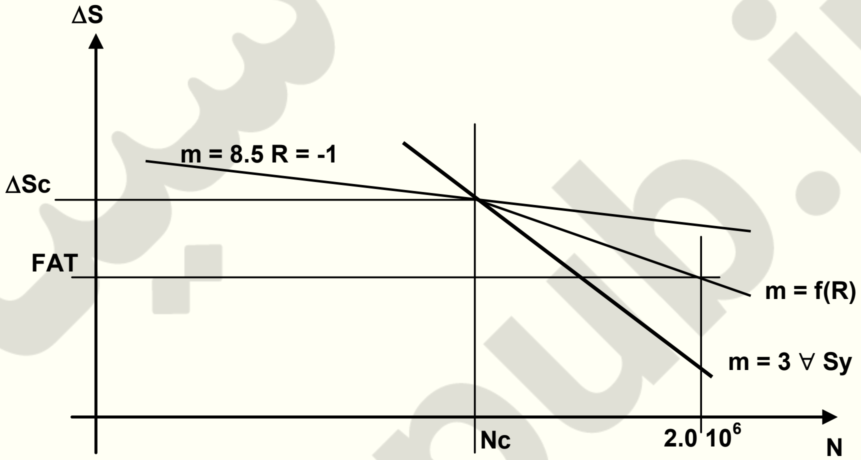


Figure 9: S-N curves versus R for a fixed Sy

The intersection point of the high cycles domain curves and the low cycle domain curve is: $Nc = 8.0\ 10^{11}\ (Sy)^{-3}$ and $\Delta Sc = 2.765\ Sy$

Noting FAT the ΔS at 2. 10^6 it can be calculated m and K of the high cycles domain S-N curves as follows:

$$m = \frac{3\log(Sy) - 5.602}{\log(Sy) + 0.442 - \log(FAT)} \tag{11}$$

$$K = 2.\ 10^6\ (FAT)^m \tag{12}$$

with $FAT(-1) = 12.613\ (Sy)^{0.647}$

From the figure 1 curves and noting that for the Smax = Sy curve R = 0.828 at N = 2 10^6, it can be obtain the relationship between FAT and R of figure 10 showing that it can be represented by a linear equation:

$$FAT(R) = (111.48 - 6.929\ (Sy)^{0.647})\ R + 5.71\ (Sy)^{0.647} + 111.48 \tag{13}$$

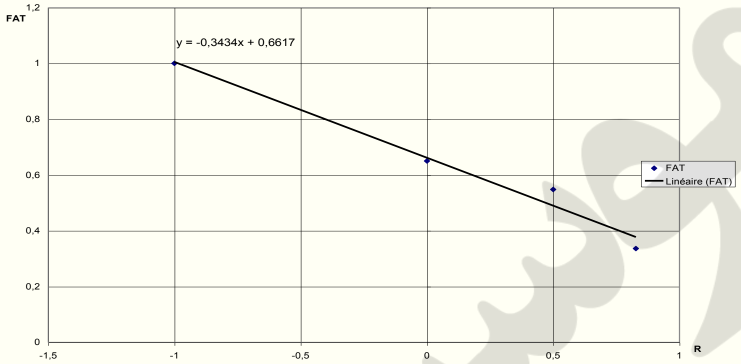


Figure 10: FAT(R)/FAT(-1) versus R

A comparison of the obtained S-N curves and the figure 1 curves shows a good fitting (table 3). The FAT(R) "mean nominal" have been obtained applying the notch concentration $K_F = 2.9$ (§ 3.1) and a standard deviation on log(K) of 0.211 equal to the mean of the values given by [9] without the E class.

Table 3. Proposed high cycles domain S-N curves and (A. Ohta) figure 1 curves

R	FAT(R) design	m	FAT(R) mean nominal	m OHTA	FAT OHTA
0.828	204,3	3,0	96,6	3	98.0
0.5	307,1	3,73	136,5	4.4	159.7
0	463,7	4,97	193,6	5.1	189.5
-1	776,9	8,5	299,6	8.5	291.5

The upper and lower level of the FAT when R increases are given by:

- lower level, when Smax = Sy: the as-welded curve (§ 3.2), FAT = 203.9 MPa (eq 11 with m=3)
- upper level, when R < 0: curve for Smin = -Sy as Smin cannot be lower than -Sy

For R increasing, FAT(R) is ≥ 203.9 MPa ∀ Sy and R. We must so write:

$$FAT(R) = (111.48 - 6.929\,(Sy)^{0.647})\,R + 5.71\,(Sy)^{0.647} + 111.48 \quad \text{not being} < 203{,}9 \qquad (14)$$

The maximum values of R for different values of Sy covering the steel yield range of (A. Hobbacher) lead to the values given in table 4 which are in agreement with the values of the Smax = Sy curve of (A. Ohta).

Table 4. Rmax versus Sy from equation (14)

Sy (MPa)	235	579	960
Rmax	0.821	0.823	0.823

For R < 0, R ∈ [0 , -∞] and so theoretically FAT(R) ∈ [FAT(0) , -∞] which not acceptable.

But considering that Smin cannot be lower than -Sy we can calculate the lower possible value of R from the formula:

$$Smin = \frac{R}{1-R}FAT$$

For the 3 Sy of table 4 we found the table 5 values.

Table 5. Minimum R value versus Sy from equations (14) and (15)

Sy (MPa)	235	579	960
FAT	446	950	1480
Rmin	-1.1	-1.6	-1.8

The design S-N curves can be so defined by:

- low cycles domain: equations with R = -1
- high cycles domain:

$$\Delta S^{m} N = (2.\ 10^{6})\ (FAT)^{m}$$

$$FAT(R) = (111.48 - 6.929\ (Sy)^{0.647})\ R + 5.71\ (Sy)^{0.647} + 111.48 \qquad (15)$$

$$R \text{ not being taken} > \frac{5.71(Sy)^{0.647} - 92.28}{6.929(Sy)^{0.647} - 111.48} \qquad \text{nor} \qquad < -1$$

$$m = \frac{3\log(Sy) - 5.602}{\log(Sy) + 0.442 - \log(FAT)} \qquad (16)$$

3.4. Non welded details

Non welded details are similar to stress released welded details without notch, but, as the S-N curves (§ 3.3) are defined for a smooth material, a surface roughness effect Kr has to be considered.

Values of Kr can be determined from figure 4 ($Kr = 1/Ks$) and [17] (BV rules - Part B Chap 7 Sec 4 Tab 12) ($Kr = K_F$).

To verify the proposal we have first calculated Kr values from the ref [9] class B and C details:

- class B: as-rolled condition, or with cleaned surfaces but with no flame-cut edges or re-entrant corners or with any flame-cut edges subsequently ground or machined to remove all visible sign of the drag lines
  $m = 4$ $\quad K_{50} = 2.343\ 10^{15}$ $\quad$ Stdv(logK) = 0.1822
- class C: as-rolled condition, with the edges machine flame-cut by a controlled procedure to ensure that cut surface is free from cracks
  $m = 3.5$ $\quad K_{50} = 1.082\ 10^{14}$ $\quad$ Stdv(logK) = 0.2041

The steel is defined as steel girder which allows to assume Sy = 235 or 315 MPa. Due to the date of the publication, the tests are assumed to have been performed at R = 0.1. Applying the formula of (§ 3.3) it has been calculated the parameters given in table 6.

Table 6. S-N curves versus Sy

Sy (MPa)	235	315
FAT(0.1)	294.23	330.05
m	4.4	4.5

Referring [9] class C curve it can be considered that the edges machine flame-cut have some thermal residual stresses which increase R and so decrease m. For m = 3.5 and Sy = 235 MPa, the corresponding R value is equal to 0.53 which appears coherent with a medium residual stress level.

The design [9] class B design curve corresponds to FAT = 150.0 MPa and so the following Kr can be calculated:

$$Kr = 294.23/150.0 = 1.96$$

which is within the range of the values given by (BV rules 2007), $K_F \in [1.4\ ,\ 2.0]$.

Then we also calculated Ks from the mechanical component approach. The fatigue limit is given by equation (3) and using the Goodman correction formula we have with Ks = roughness correction factor:

$$S(R)_D = Ks\,\frac{(1-R)S_{ult}S(-1)_D}{(1+R)S(-1)_D + (1-R)S_{ult}} \qquad (17)$$

Taking Sy = 235 MPa, $S_{ult} \in [400\ ,\ 520]$ MPa and R = 0.1 we found $S(0.1)_D \in [119.6\ Ks\ ,\ 152.4\ Ks]$. Assuming a fatigue limit is at $N = 10^6$ cycles S_D can be calculated from the FAT:

$$FAT^{m}\ (2\ 10^{6}) = (2S_D)^{m}\ (10^{6}) \qquad S_D = 0.5\ FAT\ (2)^{1/m}$$

which provides for the [9] class design B curve (FAT = 150 MPa) S_D = 89.1 MPa. So, for the [9] class design B curve, $Ks \in [0.58\ ,\ 0.74]$, which is coherent with the Ks values of figure 4.

The curves to be used are the stress released S-N curves (equations (15) and (16)), the calculated stress range being multiplied by a roughness correction factor Kr which can be determined from existing standards.

3.5. Improved welded details

Improvement by post weld treatment can have two effects:

1. improvement of the weld profile without change of the tensile residual stresses
2. improvement of the weld profile and change of the residual stresses to compression

In the first case the S-N curve to be used are the stress released S-N curves, equations (15) and (16), and the effect of the post weld treatment is a reduction of the notch stress factor.

In the second case the curves to be used are the stress released S-N curves, equations (15) and (16) and the effect of the post weld treatment is:

- a reduction of the notch stress factor
- a compressive residual stress assumed equal to -Sy

In such case, for the high cycles domain:

$$R = \frac{-Sy + Smean - 0.5\Delta S}{-Sy + Smean + 0.5\Delta S} \qquad (18)$$

where

Smean: load mean stress
ΔS: load stress range

4. Application illustration

To evaluate the applicability of the proposed rules, they are applied to two deck details of a container ship with classification rules [17] minimum scantling. The ship characteristics are:

Length	266 m
Breadth	32 m
Depth	21.5 m
Draught	12 m
Cb	0.67
V	24 kn
Steel	Sy = 355 MPa

Two details are considered, a welded deck longitudinal scallop at and a deck plate hatch corner at midship:

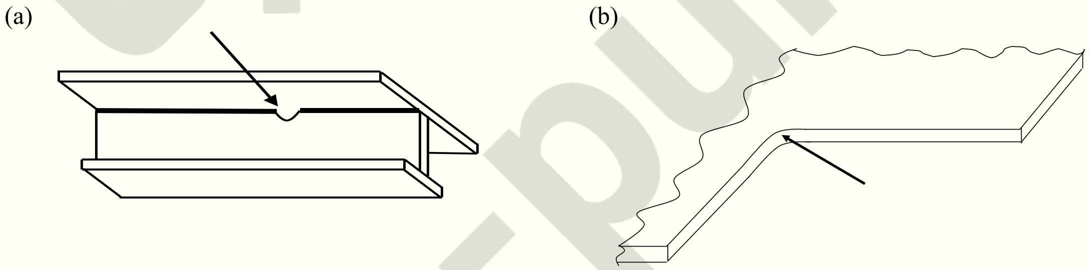


Figure 10: Container ship deck details, (a) scallop, (b) hatch corner

The long term distribution of the stress ranges is calculated with the BV rules 2007 [17] providing the following values:

maximum wave nominal stress	129.0 MPa
minimum wave nominal stress	-152.8 MPa
hogging maximum static stress	114.0 MPa
sagging maximum static stress	-90.2 MPa
Weibull shape coefficient ξ	0.906
life time total number of cycles	$5.53\ 10^7$

The S-N curves are determined with the proposed formula, two different slopes for low and high cycles domain, plus a third slope (2m-1) for $N > 10^7$ to take into account the randomness of the wave loads as specified by [17].

4.1. Scallop

The concentration factors are the following:

Kg = 1.1 from finite element calculation
Km = 1 no misalignment
$K_F = 2.62$ fillet weld, contoured end, stress perpendicular to weld ($\lambda = 2.15$)

The Miner sums D are calculated with the proposed S-N curves and a curve with a slope parameter equal to (2m-1) for $N > 10^7$. The results are the following:

hogging condition D = 1.02
sagging condition D = 0.03

which are to be compared with the [17] value D = 1.03.

4.2. Hatch corner

The concentration factors are:

Kg = 1.8 from stress concentration factor formula
$K_F = 1.4$ from BV rules, Pt B Ch 7 Sec 4 [4.3] Tab 12) [17]

The Miner sum D for hogging condition is calculated with the proposed S-N curves and a curve with a slope parameter equal to (2m-1) for $N > 10^7$. The result is the following:

hogging condition D = 0.25

which appears a perfectly coherent value.

5. Conclusion

Based on publication of S-N curves for welded linear joints and the mechanical component fatigue limit practice, formula for S-N curves applicable to notch stress for welded details, and hot spot stress plus roughness effect for non welded details, also applicable to welded, stress released and post weld treated steel details have been developed.

The S-N curves are two slopes curves, different for low cycles and high cycles domains. The low cycles domain curves have a constant m parameter and a constant K value function of the steel yield strength. The point of slope change is a function of the steel yield strength.

The high cycles domain curves have a parameter m function of the R ratio, except for as welded details for which m = 3, and a constant K function of the R ratio and yield strength excepting for maximum value of R (as-welded details)

The proposed formula have been applied to two container ship deck details showing that the found Miner sum are in good agreement with the actual practice and return experience.

The proposed formula represents a first approximation but fills a lack in ship and offshore design as the existing standards only provide S-N curves for as welded details.

New publication of data, in particular concerning the low cycles domain and the non welded details, will allow to improve the proposed formula.

References

[1]. Neptune-Gascogne platform, Bulletin Technique du Bureau Veritas, Special Issue, 1967, 32-33

[2] "Batillus", Bulletin Technique du Bureau Veritas, juillet/novembre/décembre 1976, janvier 1977

[3] Le 4ème géant est livré … Le Prairial, Bulletin Technique du Bureau Veritas, janvier 1981

[4] The Enchoa production platform, Bulletin Technique du Bureau Veritas, Vol 11, N° 3, july 1982

[5] SIMS'84, 3rd International ECSC Offshore Conference on Steel Marine Structures (SIMS'84), Delft, Netherland, June 15 - 18, 1987

[6] M. Huther, P. Benoit, J. Poudret, Fatigue analysis method for LNG membrane tank details, Extreme loads response SSC/SNAME symposium, Arlington (USA), 1981

[7] BV NI 188, Cyclic Fatigue of Welded Joints on Steel Ships - Bureau Veritas NI 188 DNC R00 E, March 1988.

[8] BV rules 1980, Rules and Regulations – Steel Vessels, Longitudinal strength of very large oil tankers (tentative rules), chapter 5, section 5.26, 1980

[9] T.R. Gurney, Fatigue Design Rules for Welded Steel Joints, The Welding Institute Research Bulletin, Vol 17, May 1976

[10] A. Hobbacher, Recommendation for Fatigue Design of Welded Joints and Components, IIW document XIII-1539-96 / XV-845-96, July 1996

[11] ARSEM (Association de Recherche sur les Structure Metalliques Marines), Design Guides for Offshore Structures - Welded Tubular Joints, Edition TECHNIPS, 1987

[12] M. Huther, J. Henry - Recommendations for Hot-spot Stress Definition in Welded Joints - IIW Document XIII-1416-91

[13] Michel Huther, Henri-Paul Lieurade, Application of the hot spot stress method, IIW International Conference, March 1997

[14] BV NI 393, Fatigue Strength of Welded Ship Structures – Bureau Veritas NI 393 DSM R01 E – July 1998

[15] P. Cambos, M. Huther, A. Vazeille, Fatigue analysis of LNG carriers, Oils tankers and FPSOs, SNAME, 2005

[16] G. de Jong, M. Huther, A comprehensive and practical strength assessment methodology for container ships taking into account non linear and hydro-elastic loading, RINA, 2008

[17] BV rules 2007, Rules for classification of steel ships, Fatigue check of structural details, Part B, chapter 7, Le section 4, June 2007

[18] A. Hobbacher, Recommendation for Fatigue Design of Welded Joints and Components, IIW document IIW-1823-07, December 2008

[19] T.R. Gurney, Fatigue of welded structures, Cambridge University Press, Second edition, 1978

[20] A. Ohta, Y. Maeda, S. Nishijima, H. Nakamura, Fatigue strength evaluation of welded joints containing tensile residual stresses, Int Journal Fatigue, July 1986

[21] A. Ohta, N. Suzuki, Y. Maeda, Shift of S-N curves with stress ratio - IIW document XIII-1922-02

[22] H.P. Lieurade, E. Haibbach, Etude en fatigue oligocyclique de la tenue d'assemblages soudés en croix en aciers à haute limite d'élasticité, Revue de métallurgie, mars 1978

[23] J.M. Barsom, R.C. McNicol, ASTM STP, 559, 1974, p183

[24] J.C. Bathias, J.P. Baïlon, La fatigue des matériaux, Presse Universitaire de Montréal, Maloine éditeur, 1980, 89-93

[25] A.Brand, J.F. Flavenot, R. Gregoire, C. Tournier, Données technologiques sur la fatigue, Publication CETIM, 3ème édition, 1992

[26] H.P. Lieurade, I. Huther, Dimensionnement des assemblages soudés en mécano-soudage - Calcul à la fatigue, 18ème Journées de Printemps, Société Française de Métallurgie et de Matériaux (SF2M), juin 1999