Tanker Structure Co-operative Forum

Guidance Note on Fatigue for Double Hull Oil Tankers Complying with the Common Structural Rules

SUMMARY

This guidance note covers areas to consider in connection with specification of new contracts for double hull oil tankers with length of 150 meters or greater to which the IACS Common Structural Rules (CSR) apply. The guidance note relates to specification of longitudinal elements and critical locations on transverse primary support members in the cargo region.

The guidance note includes an introduction to fatigue, details of additional items to include in a specification to take account of different design criteria for specific newbuilding contracts, and a practical explanation of the background of CSR fatigue requirements, including experience with design details prior to CSR.

The current version of the guidance note is amended according to CSR (2015), including Urgent Rule Change Notice 1 to 01 JAN 2015 version, and Corrigenda 1 to 01 January 2015

about the fatigue strength requirements and their Technical Background so as to be coordinated with the updating of IACS CSR.

Reference	Revision N°	Revision Date
TSCF IP 003/2012	0	2012/09/14
TSCFIP001/2017	1	2017/03/26

CONTENT

1 Introduction

1.1 Introduction

1.1.1 Scope

This guidance note covers areas to consider in connection with specification of new contracts for double hull oil tankers with length of 150 meters or greater to which the IACS Common Structural Rules (CSR) apply. This design guidance does not cover voluntary application of the CSR to other ship types.

This guidance note relates to specification of longitudinal elements and critical locations on transverse primary support members in the cargo region.

The guidance note includes:

- Details of additional items that would need to go into a specification to take account of different design criteria for specific newbuilding contracts.
- A practical explanation of the background of CSR fatigue requirements, including experience with design details prior to CSR.

1.2 Abbreviations & Definitions

Critical areas are defined as those areas where, by reason of a combination of factors including higher working stress under dynamic and static loads, geometric stress concentration caused by structural configuration, constructional misalignment/discontinuity and potential impact of corrosion will have a higher probability of failure during the life of the ship than the surrounding structures.

Critical locations are defined as the specific locations within the critical area that can be prone to fatigue damage for which design improvements are suggested.

CSR Common Structural Rules for Bulk Carriers and Oil Tankers (for Oil Tankers in this context), version 2015, including Urgent Rule Change Notice 1 to 01 JAN 2015 version, and Corrigenda 1 to 01 January 2015

FCA	Fatigue crack arrestor
FE	Finite element
GM	Metacentric height
HT	High tensile
HTS	High tensile steel i.e. yield stress 315N/mm2 and above
IACS	International Association of Classification Societies
NDT	Non-destructive testing
MS	Mild steel i.e. yield stress not exceeding 235N/mm2
SCF	Stress concentration factor
TIG	Tungsten Inert Gas welding
VLCC	Very Large Crude Carrier
OTBHD	Oil Tight Transverse Bulkhead

2 Introduction to fatigue

2.1 Brief historical review of classification requirements

Explicit requirement for verification of fatigue strength of ships structures was not generally introduced in classification rules before the mid 1990's. Prior to that fatigue cracking was indirectly considered by:

- Good workmanship and sound structural details in the 50's and the 60's.
- Lower permissible working stress inherent in mild steel structures prior to wider adoption of HTS thus also ensuring lower stress range and higher fatigue strength
- Conservative scantlings estimates based on simple formulas before introduction of sophisticated computational methods
- A stress reduction factor (also called material factor or higher strength steel factor) in response to the wider adoption of higher tensile steels (HTS) in the late 60's.
- Increased scantling requirements for side shell longitudinals as a consequence of service experience from the increased application of HTS in local structures in the early 90's.

It has been demonstrated through testing that material parameters (e.g. yield strength) have an impact on the fatigue strength of plain un-welded steel, and for machined plates the effect of yield strength on fatigue life is large. However, for welded joints the fatigue strength is essentially independent of the yield strength in the high cycle fatigue region due to the presence of crack-like flaws in the initial as-welded state and high tensile residual welding stresses. Controlling the fatigue strength by means of a yield stress reduction factor or an implicit scantling requirement alone was no longer considered to be a reliable and adequate measure in the face of the increasing number of fatigue damages reported during the 80's and 90's.

Procedures for the explicit verification of the fatigue strength of specified structural details that were originally introduced for the granting of a voluntary notation of enhanced fatigue strength eventually became mandatory requirements as part of the classification rules for tanker structures in the mid to the end of the 90's.

2.2 Basic description of fatigue

Fatigue may be defined as a degradation process of steel and welded connections due to a repetitive fluctuation of stresses and strains which develops inherent flaws into a crack. Although the stresses and strains may be well below the static resistance level of the material a failure may occur due to fatigue after a certain number of load fluctuations.

The fatigue process in a steel component will go through the following stages:

- Stage I: crack initiation
- Stage II: crack growth
- Stage III: final fracture

The total fatigue life is therefore normally described by the number of stress cycles to failure as follows:

$$N_{tot} = N_i + N_p + N_f \qquad (2\text{- }1)$$

Where:

N_i : Number of stress cycles in the crack initiation stage
N_p : Number of stress cycles in the crack growth (propagation) stage
N_f : Number of stress cycles in the final fracture (failure) stage

The total fatigue life of smooth machined/polished components is dominated by the crack initiation phase (stage I). The crack initiation phase is related to slip band mechanisms at a microscopic level on the component surface driven by shear stresses. The cracks will develop to a sub grain size and oriented 45 degrees to the maximum principal stress direction.

The total fatigue life of a welded component is dominated by the crack growth phase (stage II), due to the presence of initial micro-flaws along the fusion line in the weld thus reducing the duration of stage I substantially. In the crack growth phase the crack growth direction will become perpendicular to the largest principal cyclic stress and the maximum principal stress will be the driving force for crack propagation, by subsequent crack opening and closing and development of a crack front sharpening mechanism.

Final fracture (stage III) is characterized by a rapidly increasing growth rate that will result in ductile tearing and/or brittle fracture. This is either because the cross section is too small to transfer the load cycle or the crack front initiates a local brittle fracture. The time needed for crack growth in Stage III is not normally considered as contributing to the overall fatigue life in standard fatigue assessments for ship structures.

It is important to note that fatigue strength of welded connections is independent of the steel grade, i.e. fracture toughness and strength (yield stress or ultimate tensile strength), as the fatigue life is dominated by crack growth (stage II). It has also been demonstrated by testing that the crack growth rate is independent of steel strength. It should however be noted that in recent years, structural steel with special properties has been developed with higher resistance to fatigue initiation and growth, compared to conventional steels. This steel is denoted FCA steel (Fatigue Crack Arrestor). As the application of FCA steel is still very limited and general approval by class societies is still on-going, such steels with special fatigue properties will not be discussed further in this document.

2.3 Characterization of fatigue

2.3.1 General

The fatigue phenomenon is normally divided into two different mechanisms:

- Low-stress, high-cycle fatigue
- High-stress, low-cycle fatigue

Low-cycle fatigue is normally characterized by nominal stresses approaching the ultimate tensile strength of the material in each loading cycle, which may cause localized yielding also during the load reversal. For ship structures, operational measures, e.g. changing of loading condition from ballast to loaded condition may give stresses in this range in details of the internal stiffening and some primary member structural connections. Low cycle fatigue is normally associated with a number of cycles less than 10,000. Calculated strain is often used as a parameter to account for non-linear behavior in assessment of low cycle fatigue. A typical example of low-cycle fatigue is vessels frequently subjected to loading and discharge operations with the number of load cycles in the range of 500 – 1500.

High-cycle fatigue is normally characterized by more than 10,000 load cycles and the fatigue assessment is based on elastic stresses, i.e. nominal stresses lower than the yield strength. During a service life of 20 to 25 years, tankers will normally encounter between $6 \cdot 10^7$ to $1 \cdot 10^8$ wave load cycles. If 15% is spent on port calls, docking, repairs etc. (non-sailing time), the same figures will be between $5 \cdot 10^7$ to $8.5 \cdot 10^7$ wave load cycles. In ship structures, high-cycle fatigue is the most common reason for fatigue cracking, and will be the subject of discussion in this document.

In a broad manner, it can be said that fatigue cracking in welded structures is related to:

- The number and level of dynamic stress cycles
- The structural configuration
- The corrosive environment
- The mean stress condition

2.3.2 Fatigue testing

The fatigue assessment in CSR is based on the use of S-N curves. These curves are obtained from constant amplitude tests. In constant amplitude testing, the fatigue life of a machined component or a welded specimen is determined for a given condition related to stress ranges, the mean stress level (or the stress ratio R), testing environment and frequency of load cycles. In such testing, the specimen is subjected to cyclic constant amplitude loading until failure.

In fatigue tests, several identical specimens representative of typical fabrication and construction procedures, are tested at different stress ranges in order to obtain an S-N curve. Use of several specimens at each stress range is important in order to take into account the inherent variability in each specimen.

Most of the fatigue testing is performed at a constant stress ratio R, with $0 < R < 0.5$, and where R is defined as

$$R = S_{min}/S_{max} \tag{2-2}$$

where:

S_{min} : Minimum stress of the defined test stress range

S_{max} : Maximum stress of the defined test stress range.

A stress ratio of $0 < R < 1$ is therefore called a pure tension – tension test, see Figure 1.

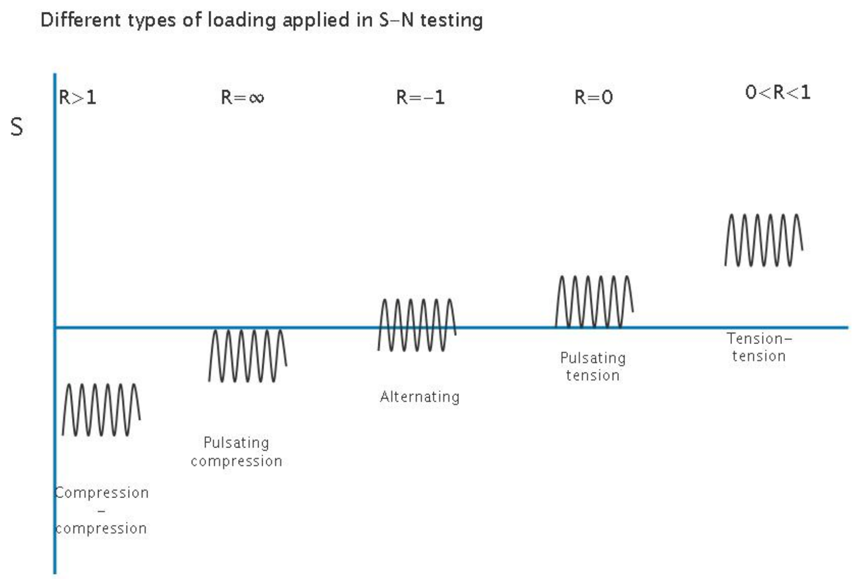


Figure 1 Different types of stress ratios applied in S-N testing.

Based on such testing, S-N curves are established for different configurations of welded details and gross geometry, fabrication quality, environment and stress level. For a machined component a low stress ratio is favorable with respect to fatigue life because stress variation on the compression side will not contribute to the fatigue damage to the same extent as variation on the tensile side. Only tensile stress variations will open the crack and propagate the crack. However, in welded connections tensile residual welding stresses are present at the weld toe and will increase the stress ratio, causing tensile stress ranges also for compressive loads. This is the reason for not taking the R ratio into account for welded joints, and why some restrictions are included on the mean stress level compensation in certain fatigue standards.

The fatigue strength of a welded component is defined as the stress range at which fluctuations at constant amplitude causes failure of the component after a specified number of cycles. The number of cycles to failure is known as the endurance or fatigue life.

2.3.3 Definition of the S-N curves

2.3.3.1 The S-N curve

The S-N curves are based on the simple relationship between the applied stress ranges,

$S = S_{max} - S_{min}$, and the number of cycles to failure, N. The basic design S-N curve is constructed based on testing and is given by:

$$\log(N) = \log(K_2) - m \log(S) \quad (2\text{-}3)$$

where:

$$\log(K_2) = \log(K_1) - 2\delta \quad (2\text{-}4)$$

N	: Number of cycles to failure for stress range S
K_1	: Constant relating to mean S-N curve (log K1 is the intercept of log N-axis by the mean S-N curve)
δ	: Standard deviation of log (N)
m	: Negative inverse slope of the S-N curve

Experimental S-N curves are defined by their mean fatigue life and standard deviation. The mean S-N curve gives the stress level S at which the structural detail will fail with a probability level of 50 percent after N loading cycles. S-N curves considered in the CSR and other relevant standards are based upon a statistical analysis of appropriate experimental data and are represented by design curves which are constructed two standard deviations below the mean lines. The effect of residual stresses is included in the S-N curves because stress relief is not normally applied to the test specimen.

Under fixed stress amplitude, when the stress range is low enough fatigue fractures will not occur. This stress range level is defined as the fatigue limit. The fatigue limit will normally occur at 10^7 cycles in S-N curves in a non-corrosive environment such as air, and a fatigue analysis may be omitted if the largest local stress range for the actual detail is less than the fatigue limit. In ship structure, due to the random nature of loading and therefore of stress cycle amplitude, no fatigue limit can be considered and second slope is to be defined, ref. Figure 2.

The S-N curve for high cycle fatigue loading in air or for adequately protected environment, e.g. coating and cathodic protection, is characterized by a two slope curve, with negative inverse slopes of typically $m_1 = 3$ and $m_2 = 5$. However, the shift in slope typically occurs at 10^7 cycles for air and typically at 10^6 cycles for cathodic protection, ref. Figure 3. It should also be noted that S-N curves in seawater for free corrosion normally have one inverse slope, m=3.

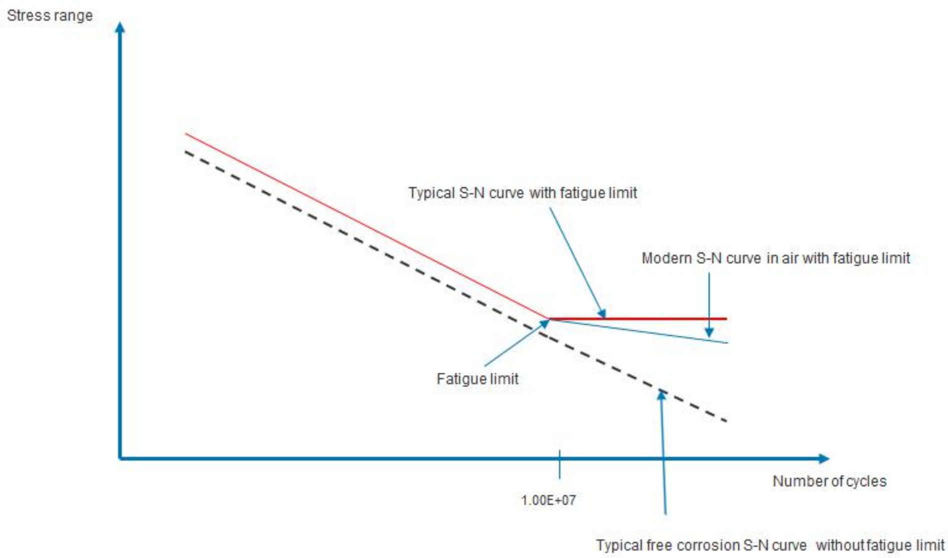


Figure 2 Definition of the fatigue limit

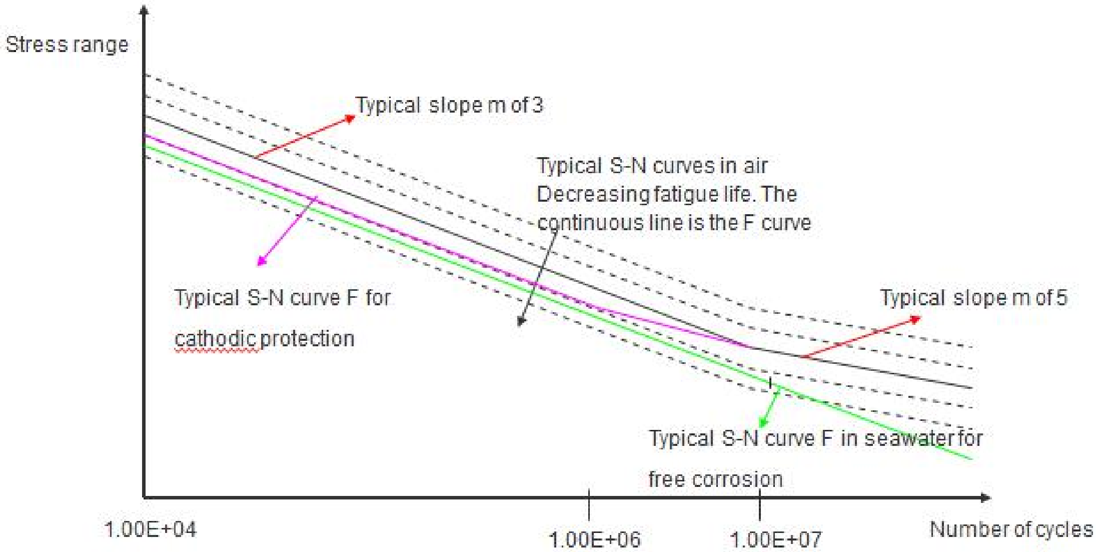


Figure 3 Characteristics of the S-N curve

2.3.3.2 Classes with regards to fatigue strength in welded joints

For practical fatigue design, welded joints are divided into several classes, each with a corresponding design S-N curve. The curves referred to in CSR are S-N curves in air, and offer the structural classes B, C, D, E, F, F2, G, W which in a classical and broad manner can be categorized as follows:

B, C: Used for material without welding. The differentiation between B and C is related to procedures for edge treatment.

B, C, D: Used for continuous welds essentially parallel to the direction of applied stress. The differentiation between B, C, D is related to post weld treatment, welding procedures and application of NDT.

C, D, E, F, F2: Used for transverse butt welds (perpendicular to the direction of applied stress). The differentiation between C, D, E, F and F2 is related to post weld treatment, welding procedures, application of NDT, use of backing and step changes in the weld.

F, F2, G: Used for welded attachments on the surface or edge of a stressed member. The differentiation between F, F2 and G is related to attachment length, distance from attachment to free edges and use of slotted connections.

F, F2, G, W: Used for load-carrying fillet and T butt welds (cruciform joints or T joints). The differentiation between F, F2, G and W is related to weld configuration (full penetration, partial penetration, fillet weld), edge distance, stress direction relative to weld direction.

E, F, F2, G: Used for details in welded girders. The differentiation between F, F2, G and W is related to location and type of welded attachments on girders.

As can be seen from the above, the weld class or category depends on geometry, direction of loading, crack location, fabrication and inspection, ref. also ↾ Figure 4.

Further it can be seen from the above broad classification of welded connections, that class F, F2 and G are the most appropriate categorization to use for bracket connections and end connections of stiffeners and girders in ship structures.

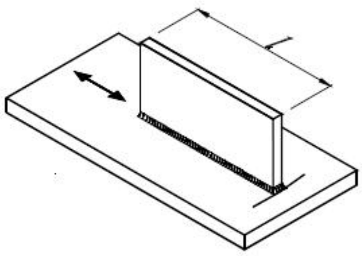
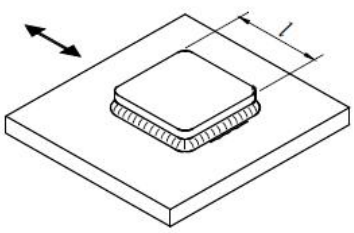
Detail category	*Constructional details*	*Description*	*Requirement*
Notes on potential modes of failure When the weld is parallel to the direction of the applied stress, fatigue cracks normally initiate at the weld ends. When the weld is transverse to direction of stressing, cracks usually initiate at the weld toe; for attachments involving a single, as opposed to a double, weld cracks may also initiate at the weld root. The cracks then propagate into the stressed member. When the welds are on or adjacent to the edge of the stressed member the stress concentration is increased and the fatigue strength is reduced; this is the reason for specifying an "edge distance" in some of this joints (see also note on edge distance in Table A-3).			
	1.  2. 	1. Welded longitudinal attachment 2. Doubling plate welded to a plate.	1. and 2. The detail category is given for: — Edge distance ≥ 10mm — For edge distance < 10 mm the detail category shall be downgraded with one S-N-curve
E	$l \leq 50$ mm		
F	$50 < l \leq 120$ mm		
F1	$120 < l \leq 300$ mm		
F3	$l > 300$ mm		

Figure 4 Typical definition of some weld class categories, ref. /2-3/.

In text books relevant S-N curves can also be found for welded details in seawater with cathodic protection and for welded connections in seawater subject to free corrosion.

Hot spot stress approach is considered to be an efficient engineering methodology for fatigue analysis of welded structures. In CSR, the fatigue strength of welded joints is assessed based on the so called structural hot spot stress range. Hot spot stress is the stress at the weld toe taking into account the stress concentration due to structural discontinuities and presence of welded attachments but disregarding the non-linear stress peak caused by the notch at the weld toe. So for fatigue assessment of welded joints, it is recommended to apply D curve and D_{corr} curve for in air and corrosive environment, respectively, with appropriate hot spot stress. For fatigue assessment of base material at free edge, S-N curves "B" or "C" and "B_{corr}" or "D_{corr}" are used for in-air and corrosive environment, respectively. So the S-N curves supplied by CSR has been reduced from 8 to 3.

The curves referred to in CSR are S-N curves in air and corrosive environment, and offer the structural classes B, C, D, which can be categorized as follows:

B, C: Used for material without welding. The differentiation between B and C is related to procedures for edge treatment.

D: Used for welded joints. Such as welded attachments on the surface or edge of a stressed member, toes, cruciform joints or T joints.

The tabulated form of the S-N curves from the CSR is given in Table 1 while the corresponding S-N curves are given in Figure 5.

Table 1 S-N Curves Characteristics

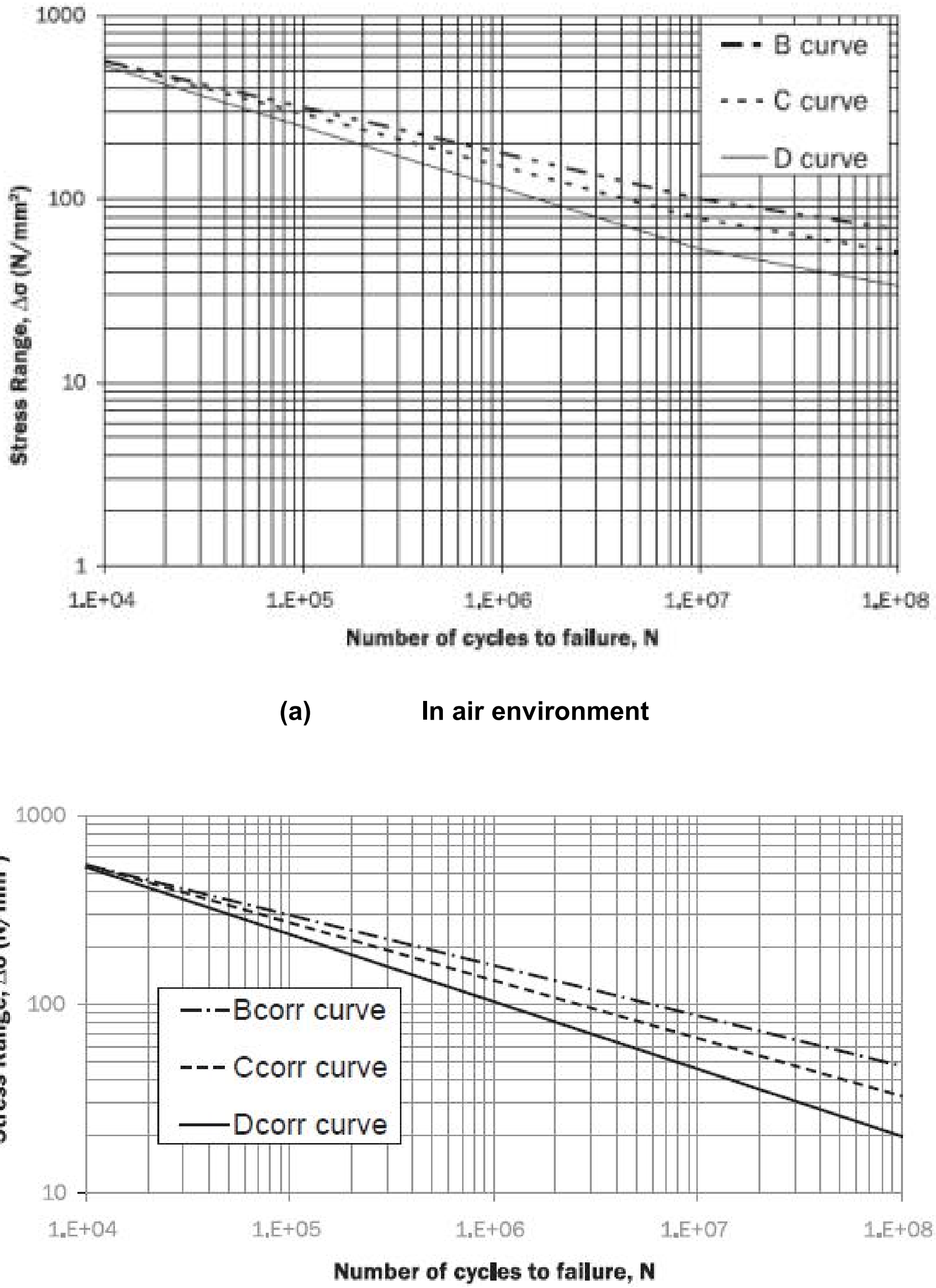
(a) In air environment

Class	K_1		m	Standard deviation δ	K_2	Design stress range at 10^7 cycles	Design stress range at 2×10^6 cycles
	K_1	$\log_{10}K_1$		$\log_{10}\delta$	K_2	$\Delta\sigma_q$ N/mm²	N/mm²
B	2.343E15	15.3697	4.0	0.1821	1.01E15	100.2	149.9
C	1.082E14	14.0342	3.5	0.2041	4.23E13	78.2	123.9
D	3.988E12	12.6007	3.0	0.2095	1.52E12	53.4	91.3

(b) Corrosive environment

Class	K_2	m	Design stress range at 2×10^6 cycles, N/mm^2
B_{corr}	5.05×10^{14}	4.0	126.1
C_{corr}	2.12×10^{13}	3.5	101.6
D_{corr}	7.60×10^{11}	3.0	72.4

The Table 1 provides Basic S-N Curve Data, In-Air and Corrosive environment, from ref./2-7/. S_q is the stress range corresponding to 2×10^6 cycles of the S-N curve, in N/mm².



(a) In air environment

(b) Corrosive environment

Figure 5 Basic design S-N curves, In-Air and corrosive environment, from ref. /2-7/.

2.3.3.3 The stress range principle

In the fatigue assessment performed according to the S-N approach, it is the stress range that shall be applied. The reason for this is that the testing is based on the stress range, partly to pick up the presence of large residual stresses that will increase the mean stress level. Compressive stresses caused by external forces may then effectively act as a tensile stress cycle in the material when added to pre-existing static tensile stresses. Effective stresses acting in the welded joint regions are assumed to fluctuate from yield and downwards, making the mean applied stress an insignificant parameter.

Mean stress correction is accepted as a corrective measure in some standards, because it may be argued that local yielding during peak loads will lead to shake down of residual stresses, making the stress range principle far too conservative especially when the applied stress is primarily compressive. Feedback from service experience of side shell longitudinal stiffeners on single hull oil tankers in the 90s provide some support for this concept.

2.3.3.4 The design S-N curve - two standard deviations

During fatigue testing there will be a scatter of test results that need to be statistically treated in order to develop design S-N curves with inherent safety levels included.

A confidence interval defines the probability that test results will be within given limits. A 95% confidence interval defines the limits within which there is a 95% probability that further test results will be located.

As indicated, the mean S-N curve gives the stress range level S at which the structural detail will fail with a probability level of 50% after N loading cycles. This does not give the desired safety level. The design S-N curves are based on a statistical treatment of test results, and by definition provides a probability of survival of 97.7%. A curve 2 standard deviations below the mean line of test vaues results in a corresponding probability of survival of 97.7%. This means that characteristic fatigue capacity is based on a 2.3% fractile, meaning that the probability of fatigue failure during the design life is 2.3% when the uncertainty only inherent in the S-N curve is included.

Example:

In practical terms this means that for a ship with 100 similar structural details with a calculated fatigue life of 20 years, 2 to 3 of these would be expected to fail within the design life of 20 years.

2.3.4 Cumulative fatigue damage

Fatigue tests that are used as the basis for constructing the S-N curves are normally based on constant amplitude testing. Actions on ships structures are normally caused by variable amplitude loading due to the random nature of the waves. In order to take into account the variable amplitude loading in fatigue assessments, it is assumed that the load spectrum can be divided into equivalent stress blocks, where each stress block contributes to the fatigue damage according to its damage ratio n_i/N_i, The fatigue life for variable amplitude loading may then be calculated by the Palmgren-Miner linear cumulative damage summation rule:

$$D = \sum ni / Ni \quad \leq 1.0 \qquad (2\text{-}5)$$

where:

n_i : Number of stress cycles in block i

N_i : Number of cycles to failure according to the S-N curve for the actual stress range, ref. Figure 6

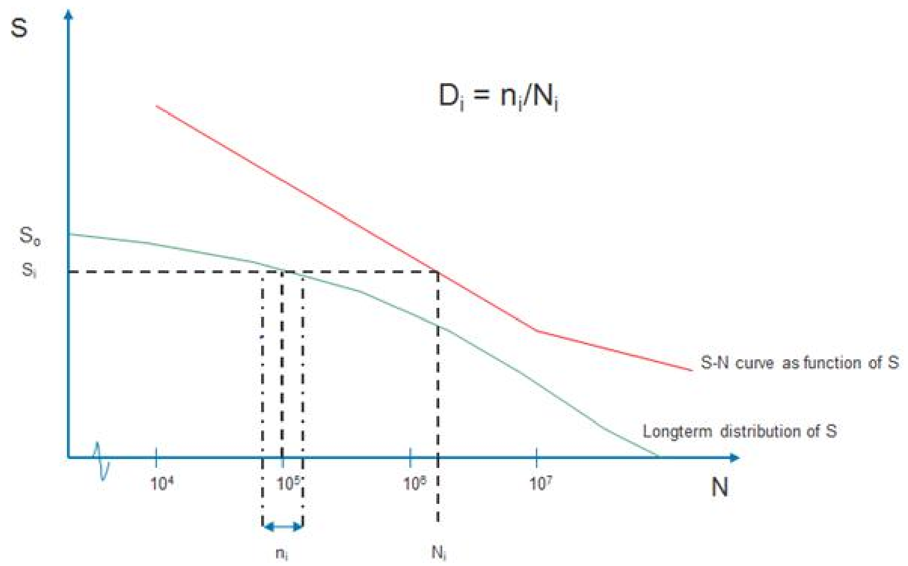


Figure 6 Part damage using a long term stress distribution and an S-N curve

2.3.5 Histogram, Weibull distributions and Scatter diagrams

2.3.5.1 Cumulative damage using histogram

The long term stress range distribution may be expressed by a stress histogram, consisting of a representative number of constant amplitude stress range blocks S_i each with a number of stress repetitions n_i, ref. Figure 6.

Using the S-N curve expression given in (2-3), the following expression can be found for N:

$N = K_2/S^m$ (2- 6)

Expression (2-5) and (2-6) gives the following relation:

$D = \sum n_i / N_i \quad = \quad 1/K_2 \sum n_i(S_i)^m$ (2- 7)

When applying a histogram to express the stress distribution, it is important that the number of stress blocks is large enough to ensure a reasonable numerical accuracy.

When the stress distribution is available in a specified long term or short term distribution (ref. 2.3.5.2 and 2.3.5.3), a closed form fatigue accumulation approach can be used for assessment of the fatigue life.

2.3.5.2 Weibull distributions and closed form fatigue assessment

The Weibull distribution is a probability distribution which is used to approximate the long term stress history for ship structures, that is, the expected number of cycles representing the combined stress ranges due to the hull girder and local bending.

The long term Weibull stress range distribution (here in terms of the complementary distribution) may be presented as a two-parameter Weibull distribution as follows:

$Q(S) = \exp[-(S/q)^h]$ (2- 8)

where:

Q : Probability of exceedance of the stress range S

h : Weibull shape parameter
q : Weibull scale parameter, defined from the stress range level So, see equation (2-10)

A long term distribution of stress ranges, as a function of the Weibull parameter h (the shape parameter), is shown in Figure 7. As can be seen from the figure, an increase in the Weibull shape parameter (h) will increase the stress range within a certain interval of the long term distribution and hence reduce the fatigue life. For a typical S-N F curve in a protected environment (an air S-N curve), the allowable extreme stress range will be reduced by a factor of 0.85, when increasing the h factor from 0.9 to 1.0 (during 10^8 stress cycles). In Figure 7 $\Delta\sigma_o = S_o$ is the maximum stress range (exceeded once out of n_o stress cycles) for a total of n_o stress cycles, while n is the number of stress cycles equal or exceeding $\Delta\sigma$=S.

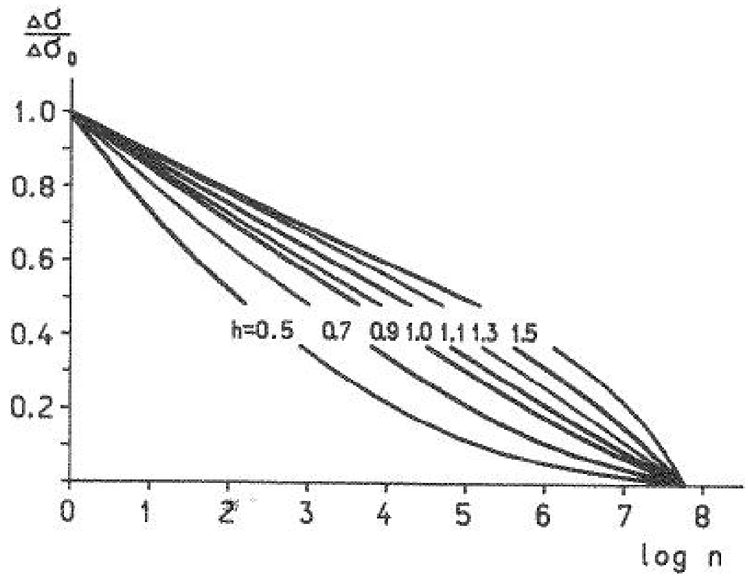


Figure 7 Long term distributions of stress range as a function of the Weibull parameter h (the shape parameter), ref. /2-1/.

For this particular distribution, a closed form expression for equation (2-7) may be derived. If the total number of stress cycles n is expressed by the ships design life T_d and the long term average response zero-crossing frequency ν_o, the following simple closed form expression can be derived for calculating the expected Palmgren-Miner sum (for a one slope S-N curve):

$$D = \sum n_i / N_i \quad = \quad (\nu_o T_d / K_2) \sum p_k \, q_k^m \, \Gamma(1 + m/h_k) \qquad (2\text{-}9)$$

where:

p_k : Fraction of design life in relevant load condition k
h : Weibull stress range shape parameter for load condition k
$\Gamma(1 + m/hk)$: Gamma function (relevant values for the gamma function can be found in text books).
Typical values of the Gamma function for hk = 0.90, 0.95 and 1.0 and m=3, are 9.261, 7.342 and 6.000 respectively.
q_k : Weibull scale parameter for load condition k

The Weibull scale parameter is defined by the stress range level S_o, given by:

$$q_k = S_o/(\ln n_o)^{1/h_k} \qquad (2\text{-}10)$$

where

n_o : Expected number of cycles over the period considered for which the stress range level S_o is defined.

If the stress level S_o is given at a 10^{-8} probability level, the corresponding number of cycles will be 10^8. If the stress level S_o is given at a 10^{-2} probability level, the corresponding number of cycles will be 10^2.

A simplified expression for the zero crossing response frequency for ship structures can be found by:

$$\nu_o = 1/(4 \log(L)) \qquad (2\text{-}11)$$

where :

L : Ship rule length in meters.

Typical Weibull shape parameters h for ship structures can be found in text books or in the CSR(where it is denoted ξ).

In theory, any probability could be chosen if the shape parameter is precise enough.

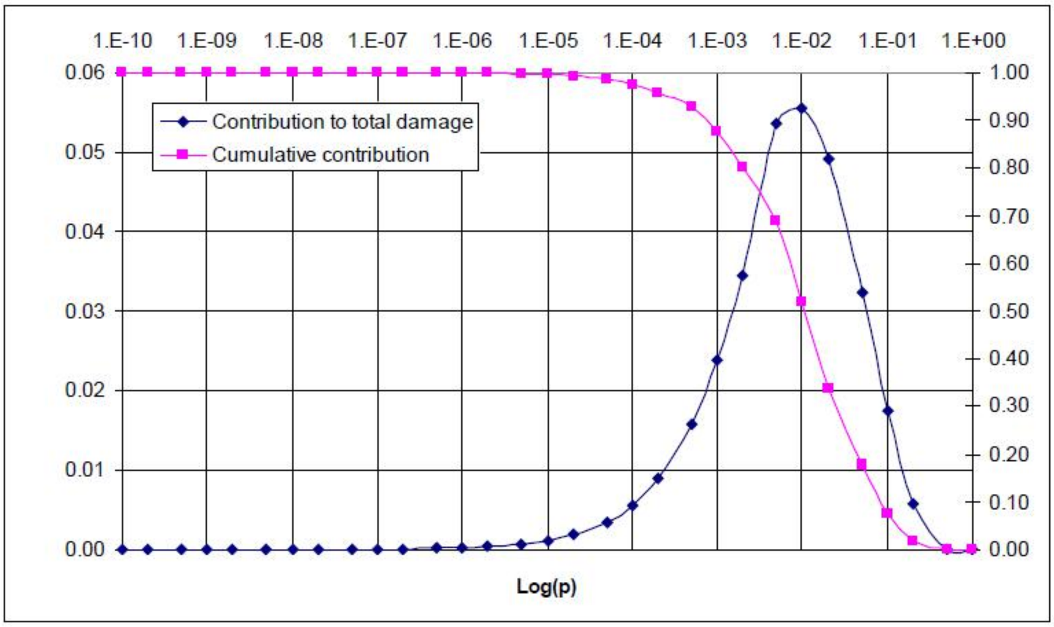
However, if the value that contributes the most to the fatigue damage is better approached, the errors made in the assumption of the shape parameter have less impact on the total fatigue damage, and more than that, it is demonstrated that the impact is minor.

Therefore, in CSR ,the probability level of 10^{-2} has been selected for the determination of scaling factor as it has been identified as the most contributing probability level to the fatigue damage. Based on number of cycles 10^2, shape parameter in CSR is expressed as:

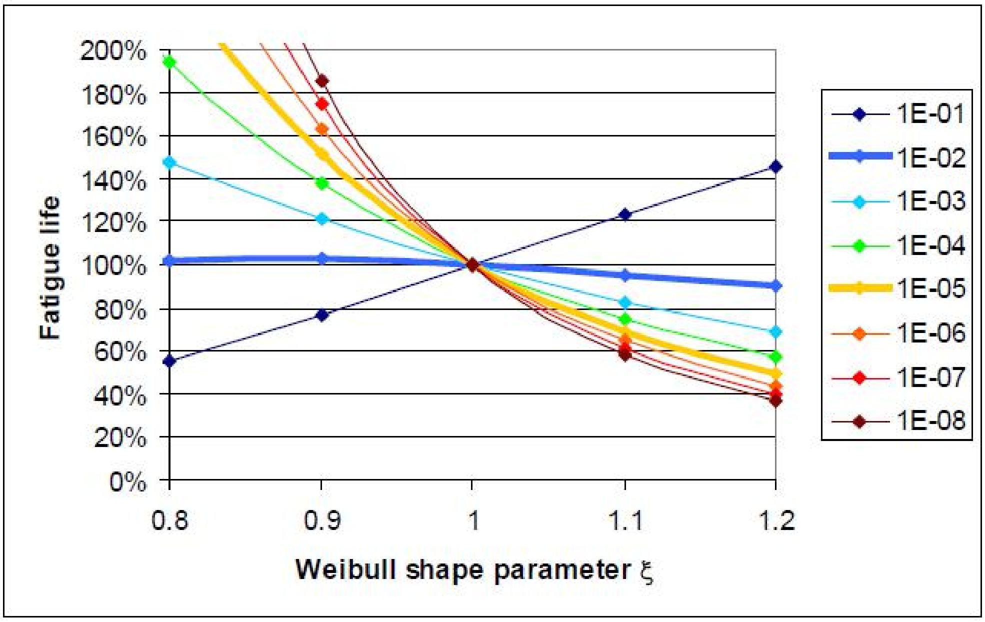
$$h = \xi = 1 \qquad (2\text{–}12)$$

The definition of the loads at 10^{-2} probability level is also based on the EDW approach.

The graph below provides an example of the contribution to the fatigue damage of a certain structural element. Calculations performed for different structural elements and S-N curves have confirmed the results. It can be observed that almost the total damage is obtained up to the probability level of 10^{-5}. However, the most contributing probability level is 10^{-2}.



The graph below shows the influence of the shape parameter on the fatigue life for different choices of scaling factor. It can be observed that the variation of fatigue life is minor for shape parameter varying from 0.8 to 1.2 if the scaling factor is chosen at 10^{-2} probability level.



Expressions similar to equation (2.9) can also be made for a two-sloped S-N curve. Reference is made to relevant textbooks for such expressions.

2.3.5.3 Rayleigh distributions, Scatter diagrams and closed form fatigue assessment

The long term stress range distribution can also be defined through a short term Rayleigh distribution within each short term period calculated based on the probability of encountering different sea states, typically known as a "scatter diagram". Combined with the different loading conditions, and using a one-slope S-N curve, the closed form fatigue damage can then be calculated as, ref. /2-4/:

$$D = \frac{v_0 T_d}{\bar{a}} \Gamma\left(1 + \frac{m}{2}\right) \sum_{n=1}^{N_{load}} p_n \cdot \sum_{i=1, j=1}^{\substack{all\ sea\ states \\ all\ headings}} r_{ijn} \left(2\sqrt{2m_{oijn}}\right)^m \qquad (2\text{-}13)$$

where:

r_{ijn}	:	Relative number of stress cycles in short-term condition
m_{oij}	:	Zero spectral moment of stress response process and can be found as the integral of the stress response spectrum for the respective individual sea state
i	:	Number of headings
j	:	Number of sea states
n	:	Number of loading conditions
$\bar{a}$	:	Same parameter as K_2, which is previously defined in equation (2-4)

A representative scatter diagram for North Atlantic sailing routes is given in Figure 8 below. As can be seen, each short term sea state is represented by an H_s (significant wave height) and T_z (average zero up crossing period) and number of occurrence of the specific sea state. r_{ij} can be calculated based on this occurrence, combined with the probability of heading.

Tz(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	Sum
Hs (m)																	
0.5	1.3	133.7	865.6	1 186.0	634.2	186.3	36.9	5.6	0.7	0.1	0	0	0	0	0	0	3 050
1.5	0	29.3	986.0	4 976.0	7 738.0	5 569.7	2 375.7	703.5	160.7	30.5	5.1	0.8	0.1	0	0	0	22 575
2.5	0	2.2	197.5	2 158.8	6 230.0	7 449.5	4 860.4	2 066.0	644.5	160.2	33.7	6.3	1.1	0.2	0	0	23 810
3.5	0	0.2	34.9	695.5	3 226.5	5 675.0	5 099.1	2 838.0	1 114.4	337.7	84.3	18.2	3.5	0.6	0.1	0	19 128
4.5	0	0	6.0	196.1	1 354.3	3 288.5	3 857.5	2 685.5	1 275.2	455.1	130.9	31.9	6.9	1.3	0.2	0	13 289
5.5	0	0	1.0	51.0	498.4	1 602.9	2 372.7	2 008.3	1 126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8 328
6.5	0	0	0.2	12.6	167.0	690.3	1 257.9	1 268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4 806
7.5	0	0	0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2 586
8.5	0	0	0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1 309
9.5	0	0	0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0	0	0	0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0	0	0	0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0	0	0	0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0	51
13.5	0	0	0	0	0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0	21
14.5	0	0	0	0	0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0	0	8
15.5	0	0	0	0	0	0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0	0	3
16.5	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.1	0.1	0	0	0	1
Sum	1	165	2 091	9 280	19 922	24 879	20 870	12 898	6 245	2 479	837	247	66	16	3	1	100 000

Figure 8 A typical North Atlantic Scatter diagram, ref. /2-4/.

On this basis, a route specific wave scatter diagram which better represent the wave environment of that the vessel operates in and could give a more realistic fatigue life, could be used.

According to IMO GBS requirements, the North Atlantic wave environment given in IACS Rec 34 is to be used as design basis, the aim to cover worldwide trading operations and also to deal with the uncertainty in the future trading pattern of the ship and the corresponding wave conditions that will be encountered, a severe wave environment is used as design basis.

2.3.6 Parameters affecting the fatigue life

2.3.6.1 General

The following parameters are important to the fatigue damage process:

- The number of dynamic stress cycles
- The level of dynamic stress cycles
- The structural configuration/geometry
- The workmanship standard and weld defects (cracks and pores)
- The corrosive environment
- The time spent in unprotected environment for part of the design life
- Surface quality
- The thickness effect
- The mean stress level

As can be seen from equation (2-7), fatigue damage can be expressed as:

$$D = \sum n_i / N_i = (1/ K_2) \sum n_i (KS_{oi})^m \quad (2\text{-}14)$$

and further simplified if the structure is subjected to only a constant nominal stress range S_o during life time, represented by n load cycles:

$$D = (n/ K_2)(KS_o)^m \quad (2\text{-}15)$$

n_i : Number of load cycles related to stress range S_{oi}

K_2 : Constant relating to design S-N curve
K : Stress concentration factor
S_{oi} : Nominal constant stress range for stress block i
m : Negative inverse slope of the S-N curve

It can be seen that the fatigue damage is proportional to number of load cycles. It can further be seen that the fatigue damage is very sensitive to the stress range, *giving a damage rate to the power of m (normally assumed to be 3 for N< 10^7)*. This means that all parameters that will influence the stress range, (KS_o), are very important for the fatigue damage. Such parameters can be:

- Environmental loading, i.e. wave height, wave period and wave meeting angle (influence on So).
- Stress concentrations (influence on K).
- Misalignments (influence on K).
- The workmanship standard, i.e. welding process, undercut (influence on K).
- Weld geometry, i.e. overfill height, weld angle, weld toe radius (influence on K).

2.3.6.2 The workmanship standard and misalignments

Both increasing the weld angle (angle between weld and plate) and decreasing the weld toe radius will tend to lower the S-N curve and hence the fatigue life. Increasing depth of undercut will lower the S-N curve.

Weld parameters are generally considered as part of the statistical variation inherent in the S-N curve, and conservative assumptions about the weld parameters are implied by adopting the design curve.

Misalignments have a very negative influence on fatigue life, and are one of the main causes of low fatigue life in welded connections. Misalignments are not explicitly considered in the S-N curves applied in the CSR and will need to be carefully controlled in way of critical cruciform joint locations during the construction.

Reference to workmanship standard with regards to misalignments is included in the CSR (IACS Rec. 47).

2.3.6.3 Corrosive environment

The corrosive environment is also an important factor with regards to influence on the accumulated fatigue damage.

Generally there are two effects of corrosion on fatigue life.

- The mechanical surface damage due to corrosion pits and
- The increased crack growth rate due to dissolution of metal at the crack tip.

It has been documented through testing in seawater that the accumulated fatigue damage is increased by a factor of 2 to 3 or higher, compared with S-N curves for air, ref. /2-1/, /2-4/ and /2-7/. In addition reduction of the plate thickness due to corrosion will play an important factor on the nominal stress level and hence the fatigue life.

2.3.6.4 The thickness effect

There is a reduction in fatigue life for the same applied nominal stress range if the thickness of the plate is increased. This is called the thickness effect.

The thickness effect is included due to the following reasons:

- An increase in the stress concentration factor at the weld toe, due to larger overfill height
- The local stress field at the crack tip will be more severe in a thick plate than in a thin plate (the stress gradient effect)
- Larger material volume will have greater probability of containing defects
- The steel microstructure of welded thick plates, may have a lesser quality compared to a thin plate

The thickness effect is normally accounted for by modifying the m log(S) term in the S-N curve, by the following expression:

$$\log(N) = \log(K_2) - m\log[S(t/t_r)^k] \qquad (2\text{-}16)$$

where:

t_r : Reference thickness
k : Thickness coefficient

The reference thickness varies normally between 22 and 25 mm in design codes, while the thickness coefficient varies between 0.25 and 0.3.

In the CSR the correction is taken into account for thicknesses larger than 22 mm by the following expression:

$$\log(N) = \log(K_2) - m\log[S(t/22)^n] \qquad (2\text{-}17)$$

n is the thickness exponent provided in CSR Pt 1, Ch 9, Sec 3, [3.3.1], Table 1 and Table 4 respectively for welded and non-welded joints, which to be selected according to the joint category and considered stress direction.

2.3.6.5 The mean stress effect

The mean stress is defined as:

$$S_m = (S_r/2)(1+R)/1-R \qquad (2\text{-}18)$$

where :

R : Stress ratio defined as, ref. (2-7) and Figure 9:
$R = S_{min}/S_{max}$

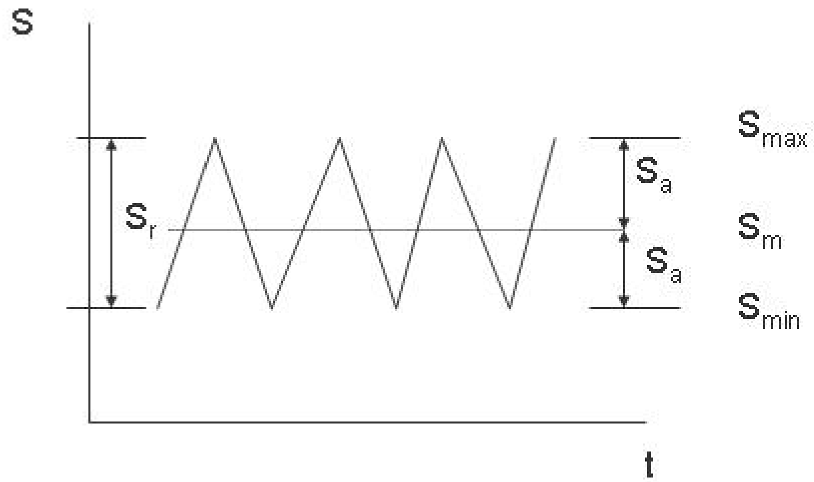


Figure 9 Definition of stress terms

Documented tests have shown that the mean stress level has an influence on the fatigue life. Stress ranges where part of the stress cycle is in compression ($R= \infty$ or $R > 1$), will result in considerably longer fatigue lives than where the stress cycle is completely tensile ($0 \leq R < 1$). However, the presence of large tensile residual stresses will increase the mean stress, such that compensating for the mean stress level in fatigue calculations shall be done with great care. In CSR the influence from welding residual stresses is not explicitly taken into account. However, the total stress range might be reduced depending on whether the mean stress is tensile or compressive. Such a correction will depend on the magnitude of the static load components (combined global and local stress) in the full load condition or the ballast condition.

2.3.7 Evaluation of fatigue life

Fatigue life in S-N tests is usually taken as life until complete fracture has occurred in small specimens or until displacements becomes so large that the load cannot be maintained. In such small specimens there is no possibility for redistribution of stresses during crack growth.

This means that most of the fatigue life is associated with growth of a small crack that grows faster as the crack size increases until fracture through the width or depth of the specimen. For practical purpose these failures are defined as being crack growth through the thickness.

When this failure criterion is transferred into a fatigue crack occurring in a large structure where some redistribution of stress is more likely, this means that this failure criterion corresponds to a crack size that is normally somewhat less than expected from the small specimen tests.

The specific method for calculating fatigue life, for example, in CSR, the expected load history needs to be defined. It is assumed that the load history can be approximated by a two-parameter Weibull distribution. The parameters are the scaling factor and the shape parameter.

The probability level of 10^{-2} has been selected for the determination of the scaling factor, ref to 2.3.5.

In order to obtain fatigue stress range. The two most representative loading conditions are chosen. Oil tankers will normally operate in either fully loaded condition or normal ballast. The fatigue load is applied on the fatigue model , reference fatigue stress range can be calculated basing on simplified stress analysis or finite element analysis.

Simplified stress analysis is used to determine hot spot stress at stiffener end connections. Hot spot stress at stiffener end connections subjected to axial loading due to hull girder bending and local bending due to lateral pressures are calculated based on beam theory combined with tabulated Stress Concentrations Factors.

Fatigue assessment by Finite element stress analysis is to be carried out for critical details where the loading and geometry are more complex. The stress range may be corrected to take into account several effects e.g. thickness effect, mean stress effect ,etc.

The cumulative damage is calculated using the “Palmgren-Miner” linear damage summation

Rule addressed in 2.3.4. Basing on the fatigue stress range, fatigue damage for each loading condition can be calculated.

The fatigue life is calculated from fatigue damage considering all loading conditions .The specific formula is in CSR Pt 1, Ch 9, Sec 3 [5.5].

2.4 Reference stress

Fatigue assessments at the design stage are today normally based on S-N curves where the reference stress should be taken either as nominal stress, hot spot stress or notch stress. Independent of this, all fatigue assessments shall be based on the maximum principal stress range within 45° or 60° of the normal to the weld toe.

A fatigue critical area can be defined as a point in the structure where a fatigue crack may initiate due to stress fluctuation caused by the combined effect of a structural discontinuity and/or the weld geometry.

In CSR, the stress range in both the two principal directions should be assessed with respect to fatigue. Reference is made to I. Lotsberg, "Fatigue design criteria as a function of principal stress direction relative to the weld toe", OMAE 2008.

2.4.1 The nominal stress approach

The nominal stress approach has for a long time been the most commonly practiced and accepted fatigue assessment methodology. The nominal stress is defined as the principal stress at a distance from the discontinuity of the welded attachment or the weld bead itself, where the geometry of the attachment and the weld do not affect the stress level, ref. Figure 10.

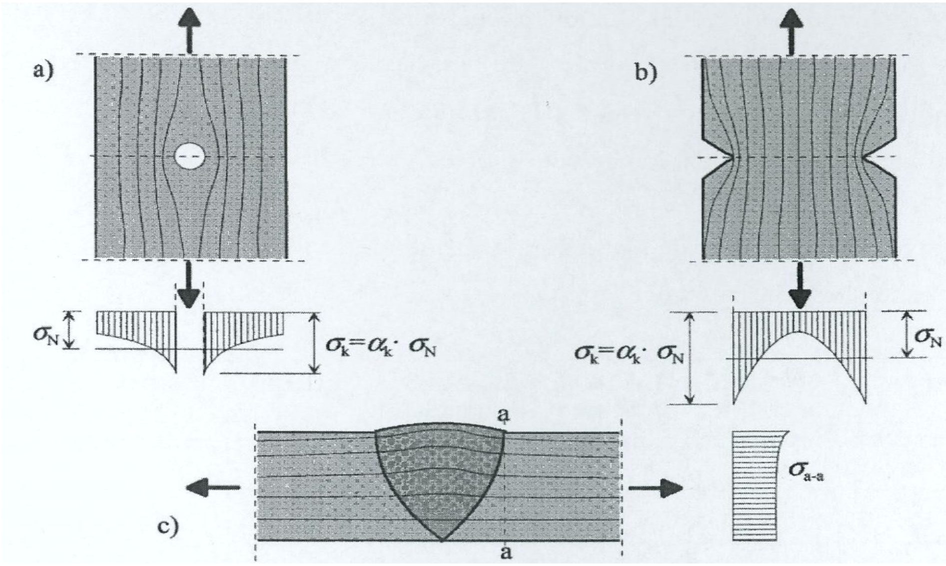


Figure 10 Typical stress distribution

As shown on the Figure 10, the nominal stress level (σ_N or S_n) will appear at a certain distance from the geometrical or weld discontinuity where the stress level is unaffected, ref. /2-6/.

When using the nominal stress approach, the structural details need to be classified and related to a corresponding S-N curve. The related S-N curve takes into account the local stress concentration created by the joint itself and by the weld profile. However, stress concentrations from global geometry e.g. arising from the edge of an opening, misalignments (eccentricities and/or angular mismatch) are not included in the actual S-N curve and must be taken into account if these are expected to contribute significantly to the stress condition.

In Figure 11 an example is taken from a typical structural detail in the side shell. The structural classification is taken from CSR Pt 1, Ch 9, Sec 4, Table 4. For the bracket toe location A, the S-N curve D or D_{corr} shall be applied. Here the effect of the bracket and the weld toe is taken into account in the selection of the stress concentration factor as defined in CSR Pt 1, Ch 9, Sec 4, Table 4. If the longitudinal stiffener is un-symmetrical and the nominal stresses applied are evaluated based on a simple beam analysis, an additional stress concentration factor for un-symmetrical stiffeners on laterally loaded panels needs to be applied.

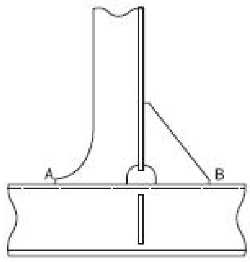
ID	Connection type (2)(3)	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
11		1.28	1.34	1.52	1.67

Figure 11 Typical structural end connection in the side shell, stress concentration factors for calculation of hot spot stresses of longitudinal stiffeners,ref. /2-7/.

In CSR, the simplified stress analysis method is applied to longitudinal stiffener end connections. The disadvantage with this methodology of the nominal stress method in design of some structural configurations is the difficulty of defining nominal stresses, particularly when stress information is obtained by finite element analysis. Another point is it might overestimate the fatigue damage as it does not account for the strengthening of the structure due to the local detail, a bracket for example. In view of this, there has been a growing practice and acceptance of using the hot spot stresses in fatigue design of ship structures.

2.4.2 The hot spot stress approach

In the hot spot stress approach, the geometrical stress at the hotspot are used in the fatigue assessment in combination with a hot-spot fatigue curve, normally taken as S-N curve D, ref. Figure 12.

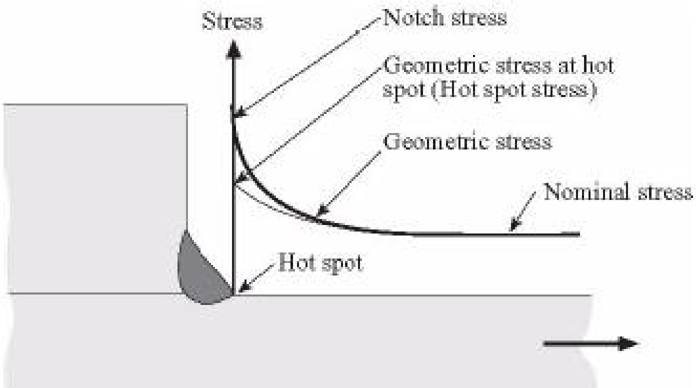


Figure 12 Definition of stress terminology in way of a welded connection, ref. /2-4/.

The geometrical stress is normally found by means of FE analyses and comprises the local stress concentration created by the joint itself (the structural discontinuity) and the stress concentrations from the global geometry. Misalignments (eccentricities and/or angular mismatch) are normally not included in the FE model and must be taken into account in the assessment, or well controlled at the construction stage.

The effect of the weld is taken into account in the selection of the appropriate S-N curve (the hot-spot fatigue curve).

The relation between the nominal stress (S_n) and the geometrical stress (S_g) applied in the hot spot method is given by:

$$S_g = K_g S \qquad (2\text{-}19)$$

where :

K_g : Geometrical stress concentration.

The hot spot stress from a FE analysis shall be derived based on extrapolation of the geometrical stress according to special procedures which can be found in the literature. In addition, the results will also be very dependent upon the choice of the finite element type and size. It should be noted that the hot spot stress fatigue design approach is only applicable to configurations where the potential mode of failure is by fatigue crack growth from the toe of a weld.

In the CSR, the fatigue assessment by finite elements stress analysis method is applied to complex structural connections such as fatigue assessment based on very fine mesh FE for the hopper knuckle (lower and upper) and Connections of transverse bulkhead lower stools to the inner bottom plating in way of double bottom girders.

2.4.3 The notch stress approach

In the notch stress approach, the total stress applied at the hotspot, comprises the geometrical stress concentration and the weld stress concentration

The relation between the nominal stress (S_n) and the notch stress (S_w) applied in the notch stress method is given by:

$$S_w = K_w K_g S_n \qquad (2\text{-}20)$$

Where:

K_w : Weld stress concentration.

Notch stresses can either be calculated by means of parametric formulae or from finite element analyses. Special procedures are anyway required when calculating the notch stresses and the calculated stress shall be linked to dedicated notch stress S-N curves.

In the CSR, the notch stress method is not referred to.

2.5 Stress concentration factors

Stress concentrations occur in structural connections due to the presence of, ref. /2-4/:

- The overall geometry of the detail; Kg
- The local geometry of the weld; Kw
- Eccentricities; Kte
- Angular mismatch; Kt
- Skew bending; Kn
- Effect of relative deformation; Kd

K_{te} and $K_{t\alpha}$ are normally used for plate butt seam connections only, while K_n is normally used for unsymmetrical stiffeners on laterally loaded panels. K_d is a stress factor for bending stress in longitudinal stiffeners caused by relative deformation between supports (i.e. between transverse bulkheads and frames), if the effect is not properly taken care of by FE modelling.

The stress concentration factors can either be calculated by means of parametric formulae or from finite element analyses. Procedures for how to obtain stress concentration factors from

FE analyses can be found in textbooks. It is however important to note the definition of the K-factors and their relation to the S-N curves.

In the notch stress approach, all the above stress concentration factors may be relevant to include in a fatigue assessment.

In the hot spot stress approach, the K_w is included in the selected S-N curve, and shall be omitted. The other stress concentration factors may be relevant.

In the nominal stress approach, the K_w and the K_g are included in the selected S-N curve that better describe the structural detail and shall be omitted. However, a global K_g may be necessary, if indicated in the commentary column of the classification tables for the relevant S-N curves. The other stress concentration factors may be relevant.

Typical values for stress concentration factors are:

- Kg is addressed in 2.5.3 (1.2 to 1.8 for longitudinal end connections) and 2.5.4 (2.5 – 7.0 for a lower hopper knuckle detail)
- Kw is addressed in 2.5.3 (1.5 for a typical bracket end connection).
- Kte is addressed in 2.6.6 (for misalignment in a butt weld).
- Kn is typically in the range 1.2 to 1.5.
- Kd is in CSR stated to be in the range 1.15 to 1.5 or refer to CSR Pt 1, Ch 9, Sec 4, [4.2.6], depending on location and loading condition.

2.5.1 Stress concentrations in welded connections

In ships structures, many of the structural joints are fitted with brackets in order to give better support and an improved load transfer at end connections. However, the brackets will nevertheless introduce a stress concentration due to the weld K_w and a stress concentration K_g due to the shape of the bracket.

A representative structural connection in this category that has been well documented as being prone to cracking is the end connection of side- and bottom longitudinals in way of transverse bulkheads and frames.

2.5.2 Bracket shapes

Brackets will generally improve load transfer between structural elements and reduce stress concentrations. Further, the effective span of a structural element will be reduced and thereby the nominal stress level. However, brackets will to a certain extent also introduce a stress concentration due to the overall geometry of the detail. This can be taken care of by good design.

The following parameters will in general govern the stress concentration:

- The sloping angle (in degrees – a small angle is beneficial)
- The toe height (a small toe height is beneficial)
- The shape (soft or straight) (a soft shape is beneficial)
- Welded attachment length (generally a shorter attachment is better than a long one assuming the same effective span of a stiffener, but a backing bracket which is poorly proportioned may have a negative effect)
- Use of backing bracket (symmetrical bracket attachments in an end connection will be beneficial)

2.5.3 End connections

In CSR, simplified stress analysis is used to determine hot spot stress at stiffener end connections.

Hot spot stress is calculated based on beam theory combined with tabulated Stress Concentrations Factors, SCF.

The tabulated SCF tables are given where stiffener end connection are classified according to configuration and bracket shape, ref. Figure 11.

The classification and the equivalent SCFs adopted in this Rules are based on test data, very fine mesh finite element analysis, experience and engineering judgment performed and agreed upon among the Societies. The SCF values used on the nominal stress to obtain a hot spot stress, together with the hotspot design S-N curve "D" for fatigue assessment is equivalent to use the nominal stress together with the design E-curve, F-curve and F2-curve of UK DEn also referenced in IACS Rec 56 (July 1999).

This means that the following equivalent stress range shall be applied in the fatigue calculations, using the CSR approach:

$$S = K_n K_d K_g S_n \tag{2-21}$$

2.5.4 Knuckles

Knuckles are structural connections with discontinuities that normally will introduce large stress concentrations, due to a change in the stress direction. In CSR, it is required that a hot-spot stress assessment shall be performed for the web–stiffened cruciform joint such as lower hopper knuckle connection. For example,in the lower hopper knuckle connection, stresses initiated from lateral pressure (internal and external) will introduce a transverse bending moment in the double bottom (in the flanges of the double bottom transverse frame). This bending moment will introduce membrane stresses in the inner bottom. These inner bottom stresses will be transferred to the sloped hopper plating. The change in stress direction will introduce an unbalanced stress component, ref. Figure 13. In combination with geometrical eccentricities at the welded connection itself, a large stress concentration will be introduced. The geometrical stress concentration at such a joint will to a great extent depend upon the angle between the inner bottom and the hopper plate, the local plate thicknesses at the joint, effectiveness of support structure such as shape of brackets for welded knuckles; and in the case of a bent knuckle, the radius of the knuckle and the support arrangement in way of the radius.

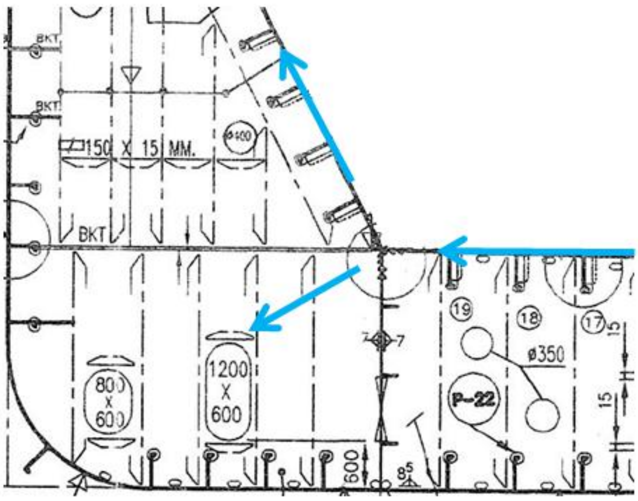


Figure 13 Stress flow in way of a hopper knuckle.

In CSR, it is required that the fatigue assessment shall be performed based on the hot spot stress approach. This means that the stress concentration due to the local geometry of the weld is included in the applicable S-N curve (the D-curve) and that the geometrical stress concentration is picked up by the FE modelling in combination with the hot spot stress approach and the corresponding extrapolation method for the stresses.

The geometrical stress concentration for such connections will normally vary between 2.5 to 7.

2.5.5 Free edges

Fatigue cracks in ship structures will normally be limited to welded connections or to flame cut edges. Only in some rare cases will fatigue cracks be observed in plain uncut material e.g. notches caused by corrosion or wear and tear. The reason for this is that welds and flame cutting provide notches, initial defects and welding residual stresses that will give considerably lower fatigue strength compared to the corresponding plain material. Unless it is relieved or shaken down in service, welding residual stresses will normally be of a magnitude comparable to yield stress and will influence the parent material up to several mm away from the weld.

Free edges around cut outs and manholes with and without edge reinforcement will generally produce geometrical stress concentrations. A typical stress concentration for the free edge of a circular cut out will be in the region of 3. Free edges cut by hand will in addition increase the stress concentration, and should be avoided. Several text books provide guidance and tables related to stress concentration factors for cut outs with and without edge reinforcements. For this reason, it is generally advisable to avoid welding on the edges of openings. Where this is unavoidable e.g. in way of block joint scallops for longitudinal stiffeners, design measures can be taken to mitigate this and some recommendations/requirements are discussed in the CSR.

2.5.6 Description of fatigue mechanism in welded connections

A typical high cycle fatigue failure surface is characterized by a smooth surface with characteristic beach marks (macroscopic progression marks on a fatigue fracture) reflecting the variation in load intensity through interchanging periods of rough and calm weather. If a member is broken off completely due to a fatigue failure, the final fracture surface will appear without beach marking but with a surface characterized by brittle fracture or ductile fracture.

The fatigue life of a machined plate is generally much higher than the fatigue life of a plate with a welded attachment, as illustrated in Figure 14. Fatigue strength of the plate with the welded attachment is as low as 15-20% of base material fatigue strength. The reason for this is that a plate with a welded attachment will negatively influence the fatigue life due to three factors:

- The notch effect due to the attachment and the weld filler metal (stress raiser)
- The presence of non-metallic inclusions or micro-flaws along the fusion line (defects)
- The presence of large tensile residual stresses

The presence of non-metallic inclusions or micro-flaws along the fusion line is the reason why the crack initiation stage is disregarded in the S-N fatigue approach. The uncertainty of the magnitude of tensile residual stresses is the reason why stress correction due to the mean stress effect can only be utilized on a selective rather than general basis. The notch effect due to the attachment and the weld filler metal will influence the hot spot stress level to a power of three or higher.

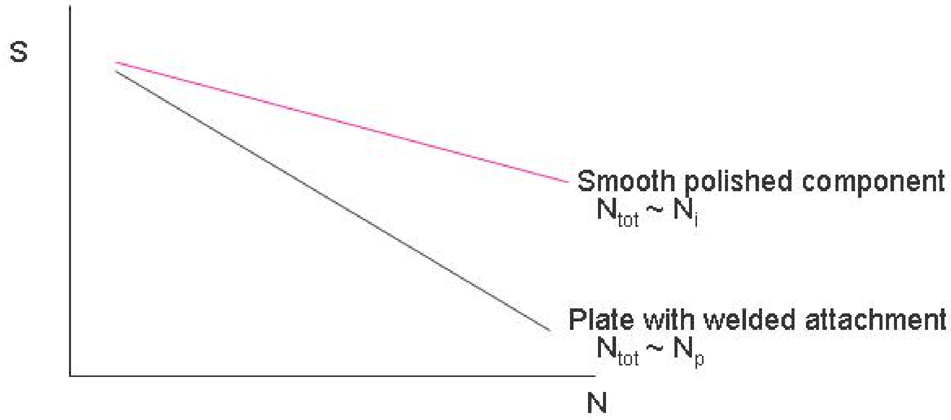


Figure 14 Comparison of a typical S-N for a smooth polished component and a plate with a welded attachment.

2.6 Other Factors influencing fatigue

2.6.1 Fatigue sensitivity

As stated in previous sections, there are lots of factors influencing fatigue life, and as indicated the major parameters influencing fatigue are the characteristics of the S-N curve, number of load cycles and the stress level in way of the welded connection. In this section it will be demonstrated how other factors might influence fatigue life indirectly through the mentioned parameters.

2.6.2 HT steel

Many cases of ships suffering from fatigue damage in side shell structures were reported after the introduction of high tensile steel without proper consideration of fatigue issues in the 1980's and early part of the 1990's.

It has since been understood by the industry that high tensile steel will not offer any improvement on the fatigue strength of a welded joint. The reason for this is that the crack growth speed (phase II) is almost independent of steel strength, and consequently the fatigue strength of welded joints is the same for mild and higher strength steels, in contrast to machined components, where it is demonstrated that the increased strength level has a positive effect on fatigue life. Conversely, as a consequence of the higher working stress permitted by adopting HTS, and the unfavourable tensile mean stress condition, accelerated fatigue damage was observed in way of members such as the side shell stiffeners.

The main purpose of using HTS is to reduce the steel weight by reduction in scantlings. This will also result in a more flexible structure (less rigidity) which may have a negative impact on the fatigue strength. It should however be understood that wider adoption of HTS does not in itself reduce the hull structural integrity from a fatigue point of view, but its use and location in the hull girder must be carefully considered.

The consequence of applying HT steel in a ship structure is that the nominal acceptable stress level is higher compared to mild steel, even if compensated somewhat by the stress reduction factor on yield strength. This is however negative from a fatigue perspective.

Example:

A simply supported HT36 steel profile of HEB260 type with a length of 3000 mm will have the same usage factor as a mild steel profile of HEB 300 type based on yield strength alone

chosen for simple illustration purposes only, i.e. 235 versus 355 N/mm². This means an increase of the nominal stress level with a factor of 1.51.
The difference in steel weight between the two profiles is 117 kg/m versus 93 kg/m, i.e. a reduction in steel weight with a factor of 0.79.
The members are subject to equally distributed loading, and the ratio between the static part of the load and the dynamic part of the load is equal to one.
However, the beam consists of two parts, welded together at the mid span (L/2) by a butt weld and needs therefore to be checked for accumulated fatigue damage. On the basis of these assumptions, the fatigue life of the butt weld at L/2 will be 20 years for the mild steel strength profile, while it will be 6 years for the HTS strength profile, i.e. a reduction of the fatigue life with a factor of 3.3.

For base material free edge, yield correction factor is introduced with beneficial effect on fatigue life in Pt 1, Ch 9, Sec 3, [3.1.3].

2.6.3 Corrosion

Testing has shown that free corrosion in a marine environment reduces the fatigue life significantly for not only machined steel components, but also for welded connections. A reduction factor between 2 and 3 and higher has been reported in the literature, ref. /2-1/, /2-4/ and /2-7/. It has also been demonstrated through testing that the fatigue threshold i.e. stress below which the crack does not grow, is eliminated for specimens in sea water subject to free corrosion (no corrosion protection at all). If cathodic protection is provided as the only corrosion protection, the testing results will be located somewhere between the air and free corrosion results, ref. /2-4/.

A proper corrosion protection system will therefore be an important consideration in order to achieve the desired fatigue life for welded structural connections in ballast- and cargo tanks.

Example:
Based on S-N curve, the following differences in calculated fatigue life can be obtained depending on the corrosion protection (S-N curves for cathodic protection and free corrosion are taken from text books):

- *A given structural connection may have a theoretical design fatigue life of 40 years if it is fitted with proper corrosion protection measures that ensure fully effective protection through the service life.*
- *The same structural connection will have a theoretical fatigue life of 28 years if it is fitted with cathodic protection system with sacrificial anodes.*
- *The same structural connection will have a theoretical fatigue life of 9 if is subjected to free corrosion from the first day (i.e. not fitted with corrosion control measures of any kind).*

If the fatigue life in the example is calculated based on the methodology offered in CSR (based on the assumption that 10 years of a 25 years design fatigue life in an unprotected state, the fatigue damage rate will be about two or three times that in a protected state), the theoretical fatigue life will be 27.5 years. The reason for this less pronounced effect on fatigue life is the assumption that the corrosion protection will be effective for a large duration of the design life with a nominal period when corrosion can have an effect on the fatigue life. However, the validity of this assumption may to a large degree be dependent on the original coating specification (including the surface preparation), the quality of the actual surface preparation, the quality of coating application and the in-service maintenance of the coating and anodes.

2.6.4 Environment

As identified in earlier, the accumulated fatigue damage is proportional to the stress range to the power of 3, or higher for $n > 10^7$.

This means that the fatigue life is very sensitive to prediction of combinations of wave height, wave period and wave encounter angle. Uncertainties in the design scatter diagram or changes in the mentioned parameters due to change in trading routes and operational/navigational procedures affecting the dynamic and static loading of the ship, will have an influence on the calculation of the fatigue life.

An uncertainty in the stress range of +/-10% due to change in the average wave height for the predominant damage sea states, may lead to a +/- 30% variability in calculated fatigue damage.

An uncertainty in the stress range of +/-15% due to change in the average wave height for the predominant damage sea states, may lead to a +/- 50% variability in calculated fatigue damage.

As a consequence, the use of a scatter diagram based on a "world-wide" trade pattern derived from all sea areas traversed on most frequented tanker trade routes for the design of a vessel that will primarily operate in a harsh environment e.g. the North Atlantic or the North Sea, may under predict the fatigue damage by a factor of 2.

That is the reason why in the CSR, the rule requirements are based on a ship trading in the North Atlantic wave environment for its entire design life.

2.6.5 Detail design standard

The selection of sound structural details is essential for achieving a good fatigue life.

A simple example on the effect of the influence of the detail design standard may be the sniping angle of stiffener web to a plate. A typical sniping angle can be 45°, while the preferred sniping angle will be 15° to 30°.

Changing the sloping angle of the stiffener termination from 45° to 30° may decrease the fatigue damage by up to 25%, depending on the loading on the plate e.g. in plane or lateral load.

Another example might be the use of doubler plates for outfitting details. Since the fatigue strength is generally penalised by the length of the welded attachment, by increasing the length of a doubling plate from 50 mm to 150 mm, the fatigue life could be reduced by a factor of 0.73.

A third example might be the shape of an opening in a plate which is characterised by a height h and width w. If the h/w ratio is of unity (h/w=1), this forms a square opening. Normally, in way of the cargo block such openings will be prescribed with rounded corners with a radius r to reduce the stress concentrations. From textbooks (e.g. ref. /2-4/) it can be found that if the r/w relation is changed from 0.35 to 0.20, the fatigue damage might be reduced by a factor of 0.67. This shows the importance of having well designed corners in openings.

A fourth example might be a typical bracket detail on a longitudinal stiffener where the original structural attachment is classified as a G detail. If this can be upgraded to a F2 detail, the allowable stress will be increased by a factor of 1.25. If it can be further upgraded to an F detail, this will increase the allowable stress with a factor of 1.42. This means that the fatigue life can theoretically be improved by a factor of 1.95 and 2.86 respectively in this example.

2.6.6 Alignment

It is almost impossible to have perfect alignment in normal production welding for general ship hull construction. It is therefore assumed that the welded connections on which the design S-N curves are based contain some misalignment. Some design standards indicate that the S-N curves based on a nominal stress approach for welds that are inspected should only be downgraded if the eccentricities are higher than the values given as follows:

- Butt welds: 10% eccentricity (o/t = 0.10)
- Fillet welds: 15% eccentricity (o/t = 0.15) (cruciform joints)

A standard stress concentration formula that might be used due to eccentricities in butt welds is:

$$SCF = 1 + 3(\delta_m - \delta_o)/t \tag{2-22}$$

where:

δ_m	: Eccentricity (misalignment)
t	: Plate thickness
$\delta_o = 0.1t$	: Misalignment inherent in the S-N data for butt welds.

Example:

A typical deck plate thickness on a VLCC may be in the range of 18 to 22 mm. If it is 20 mm, and a total misalignment in abutting plates of 6 mm is measured, this may reduce the fatigue strength of the welded joint. The SCF or K_{te} with the specified misalignment can be estimated by (2-19), as follows:

$$K_{te} = 1 + 3(6 - 2)/20 = 1.6$$

If it is assumed that all fatigue damage will occur for $n < 10^7$ load cycles, the fatigue life will be proportional to the hotspot stress in a power of 3, which gives the following ratios:

Fatigue life with perfect alignment: $F_{life} \sim A(K_{te}S)^3$ *; where* $K_{te} = 1.0$

Fatigue life with misalignment: $F_{life} \sim A(K_{te}S)^3$ *; where* $K_{te} = 1.6$

The fatigue life will be reduced with a factor of $(1/1.6)^3 = 0.24$

It should however be noted that the $\delta_o = 0.1t$ for butt welds and $\delta_o = 0.15$ for fillet welds, in some workmanship standards (among them IACS) are extended to $\delta = 0.15t$ and $\delta = 0.3t$ (or $\delta \leq t/3$) as acceptable maximum construction tolerances. Then the effective eccentricity from equation (2-20) may be used to estimate the applicable stress concentration factor in order to ensure consistency between the construction work and the theoretical fatigue life assessment.

It should be noted that in way of critical fatigue hot spots, such as the bilge hopper knuckle cruciform joints, in the CSR these structural members are to be aligned following the provisions of IACS Recommendation No. 47, Tables 7 or according to the requirements of a recognised fabrication standard that has been accepted by the Society. It should also be recognized that the effect of misalignment is also related to the load path in a joint, such that the effects on some joints will be less than others depending on the loading mode. In practice, as long as the yard's construction standard meets class approval, it is not normally required to consider stress concentration factors due to misalignment beyond what is called for in the class rules.

2.6.7 NDT

It is important that NDT is performed for fatigue sensitive structural details during the construction period in order to monitor the weld performance, Welding defects may have a very large detrimental effect on the fatigue life. Typical welding defects might be:

- Undercut
- Lack of fusion
- Lack of penetration
- Poor welding profile

- Root defect
- Hydrogen cracking
- Solidification cracking

Normally, welding defects should be repaired or ground out. In certain circumstances repair can be difficult or may actually reduce the fatigue life further. The alternatives might then be to do a fracture mechanic evaluation or an S-N fatigue type testing of a structural connection with representative defects included, in order to construct a representative (equivalent) S-N curve.

Applicable NDT methods that can be used in order to detect welding defects might be:

- Liquid penetrant for surface defects
- Magnetic particle for surface defects
- Eddy Current for surface defects (but coating might remain)
- Radiography for embedded defects
- Ultrasonic testing for embedded defects

2.6.8 Mean stress correction

S-N Curves are normally based on a stress ratio R in the range 0.1 to 0.3. Figure 15 is showing a case with R = -1, i.e. with a mean stress equivalent to zero and the maximum and minimum points of the stress range cycle are symmetrical about an axis of zero average stress.

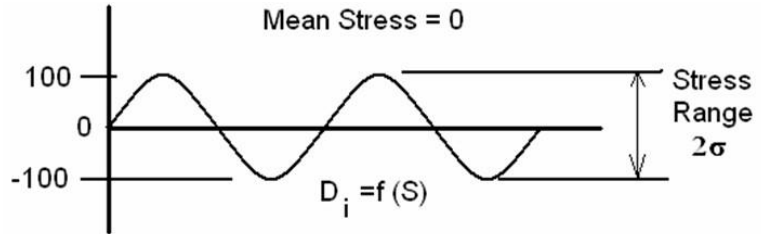


Figure 15 Symmetrical Stress Range

However in some parts of the ship structure the static loads have a predominant effect on the level of average stress. Some longitudinal stiffeners may spend a large part of the design life in compression regardless of the dynamic loads imposed, ref. Figure 16. If some of the stress variation is partly in the compressive side, this will not contribute to fatigue damage to the same extent as variation on the tensile side (if residual welding stresses are shaken down). It is only tensile stress variation that will open the crack and propagate the crack. The overall result of this is that the effective stress range that is experienced may be reduced.

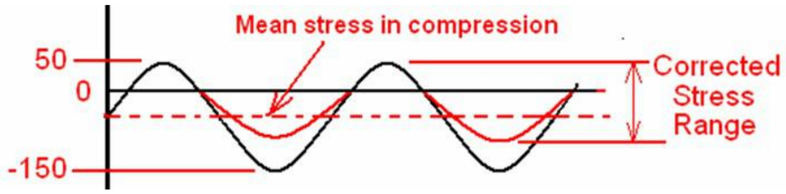


Figure 16 Compressive Mean Stress Affect on the Stress Range

The mean stress effect is therefore applied to reduce the predicted stress range for relevant longitudinal stiffeners. The mean stress correction is different for different standards, and in CSR it is included in Pt 1, Ch 9, Sec 3, [3.2]. Its effect is most noticeable in the fatigue damage for bottom and side shell predicted in the full load condition. In this condition the dominant compressive bending stress in the flange of the shell stiffener in way of the supports is due to lateral load from the external hydrostatic pressure at scantling draught.

2.6.9 Uncertainties in fatigue analyses

The theoretical calculated fatigue life of a ship structure is normally based on a long term stress distribution, which combined with an S-N curve and a Palmgren-Miner summation (in open or closed form) will give an expected theoretical fatigue life. Normally, no load or material factors are considered, but the uncertainty in the S/N curves is taken into account by using the design S-N curve, i.e. the two standard deviation curve.

The structural integrity will then normally be monitored during the service life by means of inspections, maintenance and repair.

However, the fatigue lives calculated according to the current standard engineering practice are subject to other influencing uncertainties. These can very roughly be divided into three main categories:

- Modelling of the marine environment, ship response and slowly varying loads
- Modelling of the structure (FEM representation)
- Modelling of the structural capacity

In addition to the above items, other uncertainties having an effect on the fatigue life might be imperfections introduced during the fabrication process (misalignments, welding defects etc.) and the Palmgren-Miner cumulative damage hypothesis. For ageing structures, uncertainties will also be introduced by corrosion mechanisms and other degrading or ageing effects.

Uncertainties related to modelling of the marine environment, ship response and slowly varying loads can be divided into several parameters. Some of these are:

- Wave heights
- Wave periods
- Sailing routes and corresponding scatter diagrams and wave spectrums
- Effect of forward speed
- Wave theories
- Wave encounter angle (heading)
- Roll motion prediction (radius of gyration and GM)
- Roll damping
- Non-linear effects (e.g. representation of external pressure)
- Loading condition
- Phasing between global and local response
- Springing/whipping
- Sloshing
- Low cycle fatigue and combination with high cycle fatigue
- Combination of load effects

Uncertainties related to modelling of structure can be divided into several areas. Some of these are:

- Structural analysis type
- Calculation of stress concentration factors
- Relative deflections
- Double hull bending
- Hot spot extrapolation method
- Stress direction
- Analysis methodology (simplified or advanced)

- Global FE to local FE modelling and load transfer
- Structural simplifications in the FE modelling
- Boundary conditions
- Non-linear effects

Uncertainties related to modelling of the structural capacity can be divided into several areas. Some of these are:

- Scatter in S-N data
- Miner sum accumulation hypothesis
- Effect of corrosion on fatigue behaviour
- Effect of corrosion on scantlings
- Selection of appropriate S-N curve
- Definition of failure
- Thickness effect
- Mean stress effect
- Residual stress effect

Most of the above uncertainties are indirectly taken into account in fatigue assessments by a sound selection of relevant parameters giving an overall conservative estimate that is generally supported by industry experience. This is especially true for certain parameters used as basis for constructing the S-N curves. The results due to the above uncertainties may in some circumstances result in observable differences between the theoretical fatigue life and what may actually be experienced in service.

3 Scope of CSR fatigue Strength Assessment

3.1 Introduction

The CSR define a minimum strength standard for classification of oil tanker structures. These Rules require design verification of fatigue aspects to be carried out in accordance with CSR, CSR Pt 1, Ch 9..

The CSR scantling criteria for fatigue are based on an idealization of operating profile and structural response of "standard" oil tanker designs. The idealization is sufficiently representative of typical oil tanker operation to be used reliably to design new ships to a common strength standard. Parameters are included in the Rules which can adequately take account of typical variations in "standard" tankers design.

Experience from a wide range of tanker operations shows that the structural performance of a particular design depends on the operational profile of the ship; including voyage pattern, variations of types of cargo carried as well as frequency of ballast operations. Since it is impractical to take all possible variations of these factors into account using simplified deterministic calculations, there are certain limitations of the CSR approach which may influence ship specification of some unique oil tanker types.

This chapter focuses on assumptions within the CSR fatigue criteria which are linked directly to operational matters. Information is included on the circumstances when departures from these assumptions may need to be investigated further in relation to the specification of certain new building projects. The chapter does not challenge the correctness of the theoretical modeling which is considered to be a practical and appropriate design methodology in relation to standard oil tankers.

The emphasis of the chapter is on discussion of the limitations that these simplifying assumptions may have on non-standard designs based on known experience gained by TSCF with such designs

3.2 Scope of fatigue analysis

3.2.1 Coverage

Fatigue strength is ensured in CSR by the use of:

- Direct fatigue assessment where fatigue life is calculate by:
    - Simplified stress analysis (mandatory Rule assessment).
    - Finite element stress analysis (mandatory Rule assessment).
    - Screening fatigue assessment (if the screening criteria is not met then Finite element stress analysis is required).
- Detail design standards where fatigue strength is ensured by good fatigue design (if the detail design standard is not followed then Finite element stress analysis is required).

Mandatory items in the CSR subject to numerical fatigue strength requirements are:

- End connections of stiffeners within the cargo region that are effective in longitudinal strength. An explicit rule criteria, simplified stress analysis, based on fatigue theory using a hot stress approach is provided in CSR Pt 1, Ch 9, Sec 2, [1] and Sec 4;
- Critical structural details in Table2 are to be assessed for fatigue by very fine mesh analysis irrespective of their compliance with the design standard due to its higher risk of fatigue failure reflecting past experience.

Table 2 Structural details to be assessed by very fine mesh analysis

No	Critical detail	Applicability
1	Welded lower hopper knuckle connection (intersection of hopper sloping plate, inner bottom plate, longitudinal girder, floor and transverse web) at the most critical frame location. (1)	One cargo tank (4)
2	Radiused lower hopper knuckle connection (intersection of knuckled inner bottom plate, longitudinal girder, floor and transverse web) at the most critical frame location. (1)	One cargo tank (4)
3	Welded upper knuckle connection (intersection of hopper sloping plate, inner hull longitudinal bulkhead, transverse web and side stringer) where the angle between hopper plate and inner hull longitudinal bulkhead is less than 130 deg, at the most critical frame location. (1)	One cargo tank (4)
4	Connections of transverse bulkhead lower stools to the inner bottom plating in way of double bottom girders. (2) (3)	One cargo tank (4)

(1) The most critical frame position is generally, but not necessarily, located closest to the mid length of the hold. Where a swash bulkhead is fitted, this is generally located closest to the mid length between the swash bulkhead and the oil-tight bulkhead.
(2) Stool connections at each end of the hold are to be checked unless these are symmetrical about mid-hold.
(3) Position at the mid breadth location of the largest hold.
(4) Cargo hold located closest to the midship.

A few other fatigue prone areas are highlighted in the Rules as areas for recommended detailed design improvements as shown in Figure 17 to Figure 20, critical structural details in Table3 for which fatigue assessment by very fine mesh analysis can be omitted if their design is in accordance with detail design standard given in CSR Pt 1， Ch 9, Sec 6, otherwise, fatigue assessment should be carried out.

Table 3 Structural details to be assessed by very fine mesh analysis if not designed in accordance with detail design standard

No	Critical detail	Corresponding detail design Standard	Applicability
1	Radiused upper hopper knuckle connection(intersection of knuckled inner side plate, side girder and transverse web) at the most critical frame location. (1)	CSR, Pt1,Ch 9, Sec 6, [4]	One cargo tank(4)
2	Corrugations of transverse bulkheads	CSR, Pt1,Ch 9, Sec 6, [6]	One cargo tank(4)

	to lower stool or inner bottom plating connection. (2) (3)	and Ch 9, Sec 6,[7]	
3	Cruciform heel connections between side stringers in double side and transverse bulkhead horizontal stringers, for the stringer closest to the mid depth and for the uppermost one.	CSR, Pt1,Ch 9, Sec 6, [5]	One cargo tank(4)
4	Cut out for longitudinal stiffeners in web-frame without web stiffener connection.	CSR, Pt1,Ch 9, Sec 6,[2.1]	One cargo tank(4)
5	Scallops in way of block joints on strength deck close to mid hold (and down to 0.1D from deck corner).	CSR, Pt1,Ch 9, Sec 6, [3]	One cargo tank(4)

(1) The most critical frame position is generally, but not necessarily, located closest to the mid length of the hold. Where a swash bulkhead is fitted, this is generally located closest to the mid length between the swash bulkhead and the oil-tight bulkhead.
(2) Stool connections at each end of the hold are to be checked unless these are symmetrical about mid-hold.
(3) Position at the mid breadth location of the largest hold in the considered transverse section.
(4) Cargo hold located closest to the midship.

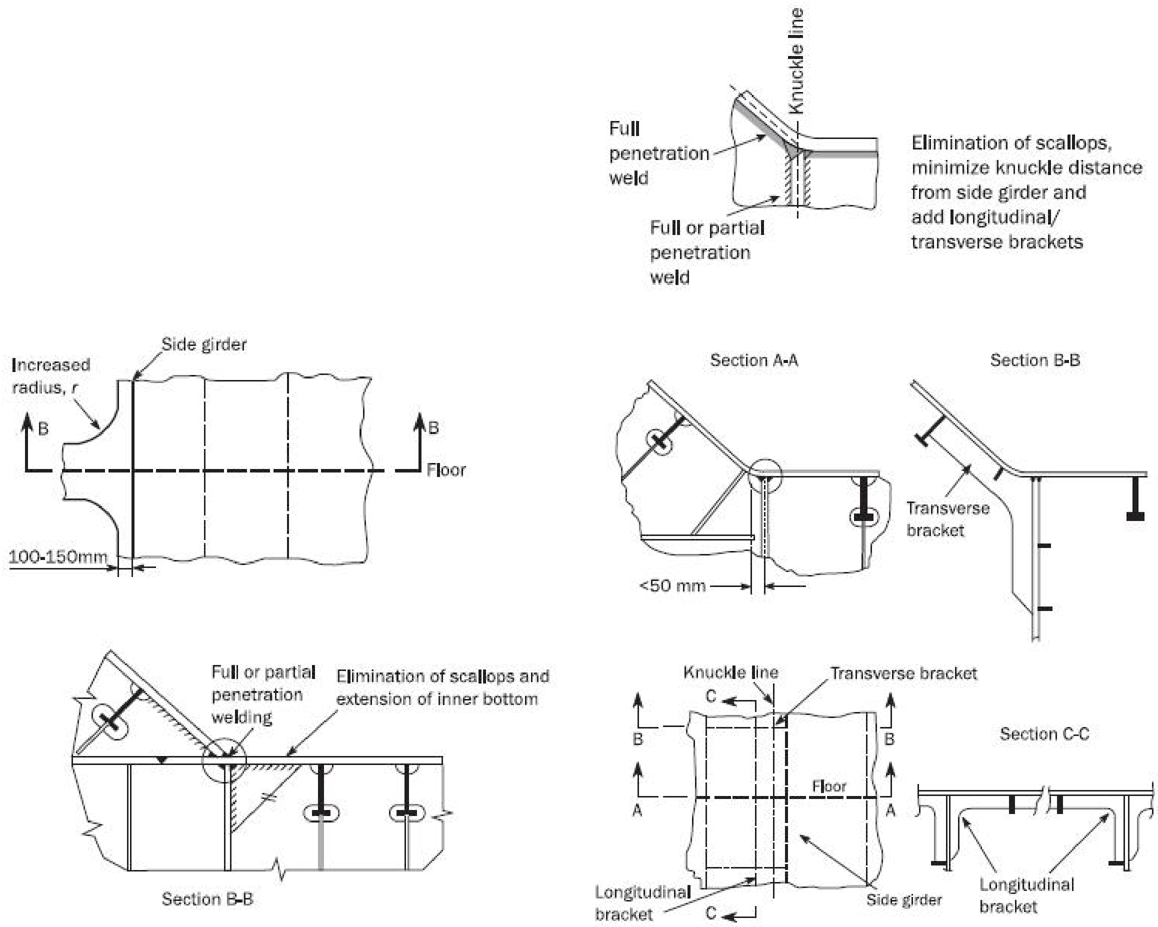


Figure 17 Locations where detail design improvement is recommended in CSR

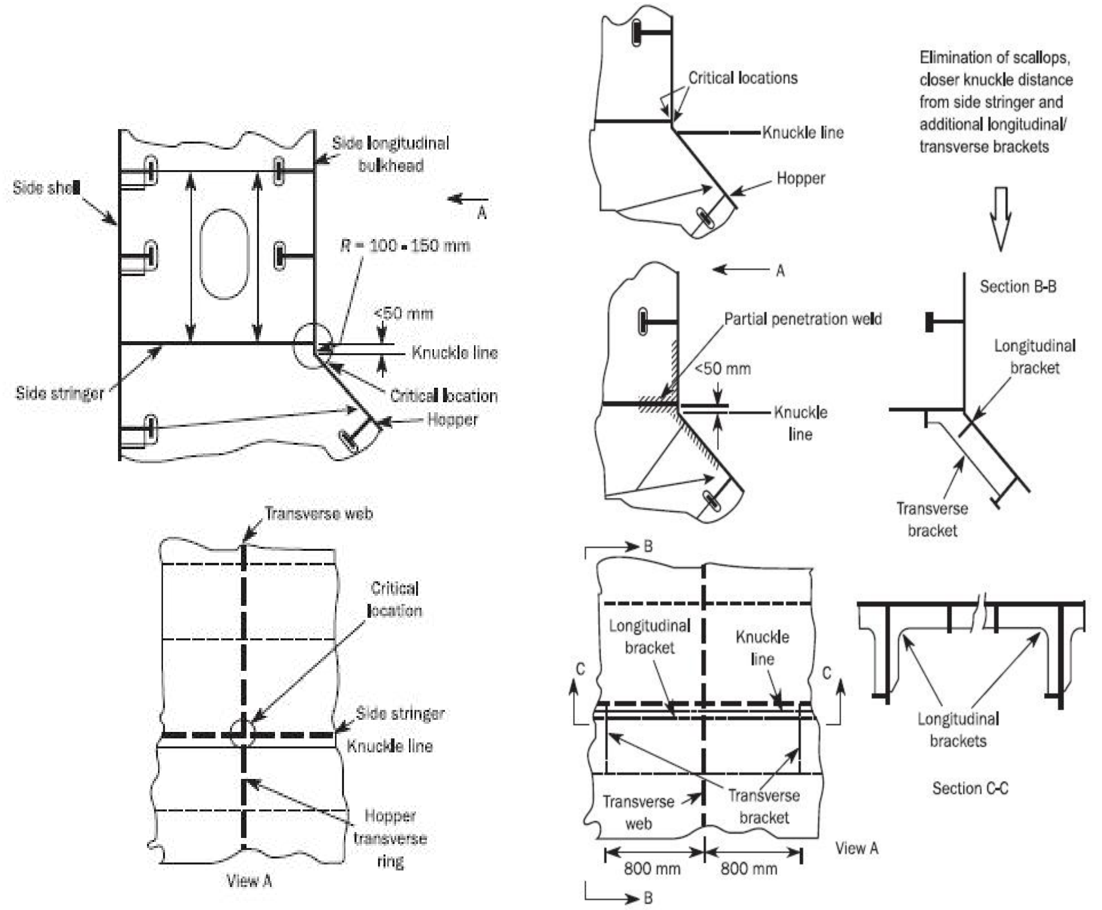


Figure 18 Locations where detail design improvement is recommended in CSR

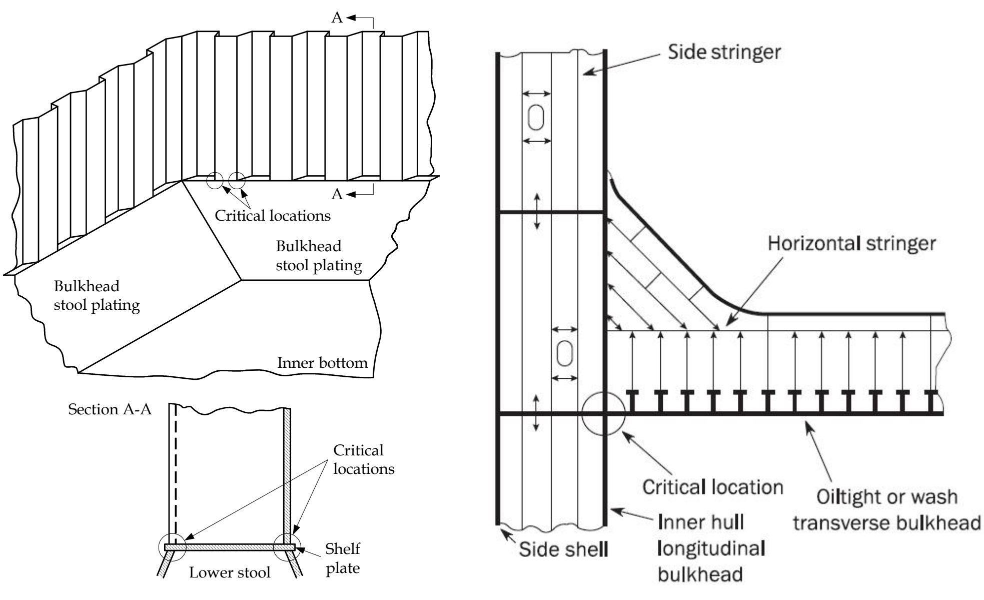


Figure 19 Locations where detail design improvement is recommended in CSR

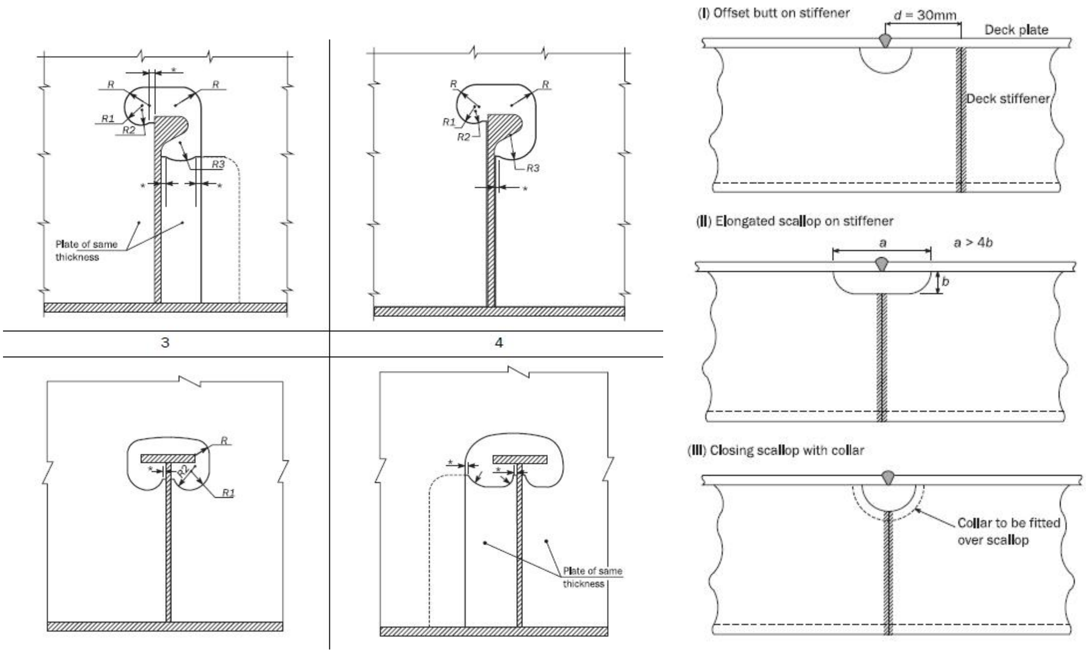


Figure 20 Locations where detail design improvement is recommended in CSR

In addition ,the structural details listed in Table 4 for which FE fine mesh models have been analysed according to yielding requirements given in CSR Pt 1， Sec 3 are to be assessed using the screening fatigue procedure as given in CSR Pt 1， Ch 9,Sec 5, [6] or to be assessed by very fine mesh analysis according to CSR Pt 1， Ch 9,Sec 5, [1] to CSR Pt 1， Ch 9, Sec 5, [4].

Table 4 Structural details for screening fatigue assessment

No	Critical detail	Applicability
1	Bracket toe of transverse web frame	For details assessed by fine mesh analysis according to CSR, Pt1,Ch 7, Sec 3, [3.2.1]
2	Toe of horizontal stringer	For details assessed by fine mesh analysis according to CSR, Pt1,Ch 7, Sec 3, [3.2.1]

In addition to the fatigue related Rules, there are other Rule requirements which may contribute to an improved fatigue life of critical structural details. However these are not directly related to the fatigue design life of 25 years. These are:

- Local fine mesh analysis yield stress check of critical locations as identified by means of screening criteria in the coarse mesh model (CSR Pt1, Ch 7, Sec 3, [3]).
- Mandatory fine mesh analysis of one deck, double bottom longitudinal and adjoining transverse bulkhead vertical stiffener to examine stress concentration in way of transverse bulkhead location (CSR Pt1, Ch 7, Sec 3, [2.1.1])

- Some longitudinal end connections require mandatory adoption of soft heel where the design stress exceeds 80% of the stress criteria for strength check. (CSR Pt1, Ch 3, Sec 6, [5.1.5])
- Where a lower stool is not fitted to a transverse or longitudinal corrugated bulkhead, the maximum permissible stresses are to be reduced by 10%. This reduction is applicable both yielding and buckling check (CSR Pt1, Ch 7, Sec 3, [6.2.2])

3.2.2 CSR fatigue net thickness approach

The fatigue calculations are based on a net scantling approach using a simplified corrosion model.

For simplicity, the stress range calculations are based on a section properties corresponding to a reference level of corrosion corresponding to the “average” state of the ship structure during its design life. The hull girder stresses for simplified stress analysis are to be corrected by multiplying the calculated stress by 0.95.Local bending stress range due to lateral pressure is calculated from section properties with 50% of the corrosion margin deducted from the new-building scantlings. This models the effect of localized higher rates of corrosion affecting the local structural response.

The values of corrosion margin vary depending on the structural item and are derived from statistical analysis of Classification in service inspection records.

When the FE hold model, based on the corrosion model deducting $0.5t_c$ from the gross thickness, used for yielding and buckling assessment, is used for fatigue assessment, the stresses are to be reduced by multiplying with a factor of 0.95.

3.2.3 CSR fatigue analysis approach

For both the weld joints and secondary member end connection fatigue assessments the calculation of stress ranges follow a similar approach. The background to this approach and its main limitation is discussed in 3.2.6.

CSR fatigue addresses load effects of wave induced loads and is therefore understood to model fatigue as a high cycle phenomena. Whilst high cycle fatigue is the primary source of fatigue damage in double hull oil tankers, in a small number of special cases, low cycle fatigue due to other factors such as more frequent loading/unloading may require a more detailed consideration.

3.2.4 CSR Screening fatigue analysis approach

The screening procedure assesses fatigue strength as described in CSR Pt1,Ch 9, Sec 3, [3]. The fatigue damage is based on hot spot stress at weld toe of specified structural details obtained by multiplying the quasi-nominal stresses obtained from available fine mesh finite element model by tabulated stress magnification factor (η) of the classified detail, CSR Pt1,Ch 9, Sec 5, [6.1.2]. All correction factors describe in CSR Pt1, Ch 9, Sec 3 should also be accounted in the screening assessment. Structural details in Table 4 that do not comply with the screening fatigue criteria should be checked with respect to fatigue strength assessment using a very fine mesh finite element model as described in CSR Pt1, Ch 9, Sec 5.

The screening fatigue procedure includes the following three phases:

Phase 1: Calculation of fatigue stress.

Stresses are calculated at the stress read out point from the fine mesh element analysis with elements size of 50 × 50 mm, according to CSR Pt1, Ch 7, Sec 3 for all fatigue load cases defined in CSR Pt1,Ch 9,Sec 1, [7], for all loading conditions. Stresses to be used are element average membrane components stress defined in CSR Pt1,Ch 9,Sec 5 [6.2.3]. Hot- spot surface stress components are calculated for each load case ‘i1’ and ‘i2’ from the stresses multiplied by the stress magnification factor η, taken as:

- $\sigma_{HS,\, i1(j)} = \eta\ \sigma_{S,\, i1(j)}$
- $\sigma_{HS,\, i2(j)} = \eta\ \sigma_{S,\, i2(j)}$

Hot spot principal surface stress ranges are the difference of hot spot stress components obtained for each load case ‘i1’ and ‘i2’. Fatigue stress ranges for welded joints are determined from hot spot principal surface stress ranges with correction factor for mean stress and thickness effect.

where:

$\sigma_{S,\, i1(j)}$: Stress calculated from the fine mesh analysis in load case ‘i1’ of loading condition (j) defined in CSR Pt1, Ch 9,Sec 5 [6.2].

$\sigma_{S,\, i2(j)}$: Stress calculated from the fine mesh analysis in load case ‘i2’ of loading condition (j) defined in CSR Pt1, Ch 9,Sec 5 [6.2].

η : Stress magnification factor given in Table 5.

Table 5 Stress magnification factors

Ship type	Structural detail category	Stress magnification factor
Oil tanker	Toe of stringer	2.45
	Bracket toe of transverse web frame	1.65

Phase 2: Selection of S-N curve.

The S-N curve D defined in CSR Pt1,Ch 9, Sec 3, [4] is to be used with the fatigue stress range of weld toe in screening fatigue procedure.

Phase 3: Calculation of fatigue damage and fatigue life

Structural details that do not comply with the acceptance criteria are to be checked with respect to fatigue strength using a very fine mesh finite element analysis as described in CSR Pt1, Ch 9, Sec 5.

3.2.5 CSR fatigue detail design standard

Detail design standards given in CSR Pt1,Ch 9, Sec 6 are provided to ensure improved fatigue performance of critical structural details which is as following:

- Stiffener-frame connection
- Scallops in way of block joints
- Hopper knuckle connection
- Horizontal stringer heel
- Bulkhead connection to lower and upper stool
- Bulkhead connection to inner bottom
- Hatch corner

Detail design standard provides welding requirement at critical structural details in order to prevent the following types of fatigue failure:

- Fatigue cracks initiating from the weld toe into the base material.
- Fatigue cracks initiating from the weld root and propagating into the plate section under the weld.
- Fatigue cracks initiating from the weld root and propagating through the weld throat.

- Fatigue cracks initiating from surface irregularity or notch at the free edge into the base material

A few structural details defined in Table 3 are required to be in line with recommended detailed design, Alternative detail design configurations may be accepted subject to demonstration of satisfactory fatigue performance, otherwise, fatigue assessment should be carried out.

3.2.6 CSR fatigue load combinations approach

3.2.6.1 Longitudinal end connections -Simplified Stress Analysis

Hot spot stress ranges are calculated for two load cases representing full load and normal ballast load conditions respectively. Each load case combines four characteristic dynamic loads: vertical hull girder loads; horizontal hull girder loads; external wave loads and tank inertial loads. The characteristic loads are calculated based on draught and metacentric height values of the actual loading conditions at mid voyage i.e. half bunker, in the preliminary trim and stability booklet. The CSR formulas correspond to a 10^{-2} probability of exceedance and have been calibrated with direct calculations for five sizes of oil tanker.

For each characteristic load a corresponding stress range is calculated as described in CSR Pt1, Ch 9. The combination of the four stress ranges is made using load combination factors which consider the phasing of the different load components. The load combination factors vary for different structural members and position on the vessel structure. Implicit in this approach is that for net dynamic loads the loading pattern for full load condition has all cargo tanks full and all ballast tanks empty. Conversely, for normal ballast condition the cargo tanks are assumed all empty and ballast tanks all full.

The fatigue damage is calculated for each load case and summated in accordance with Palmgren-Miner's law.

3.2.6.2 Welded Joints – Finite Elements Stress Analysis

Stress ranges are calculated using FE Models for the two load cases of full load and normal ballast. Each load case uses combination of two characteristic dynamic loads: external wave loads and tank inertial loads. The characteristic loads are calculated using the same formula used for the simplified stress analysis approach.

The combination of the stress ranges is made using specific fixed load combination factors which consider the phasing of the different load components. See CSR Pt1, Ch 4, Sec 8, [5] and Pt1, Ch 9, Sec 5, [3] or [4].

The fatigue damage is calculated for each loading conditions and summated in accordance with Palmgren-Miner's law.

The theoretical approach is summarized in Table 6 .

Table 6 Technical summary of CSR fatigue assessment methodology

	Simplified Stress Analysis	**Finite Elements Stress Analysis**
Objective Structural Location	Longitudinal end connections	Welded joints
Design Life, Years	25 years	
Assumed life at sea	85%	
Reference Stress	Obtained by multiplying the nominal stress by a Stress Concentration Factor (SCF), according to Pt1, Ch 9, Sec 4, [5] or directly by a very fine mesh FE analysis, according to Pt1,Ch 9, Sec 5, [3] and Pt1,Ch 9, Sec 5, [4]	Obtained either using very fine or fine mesh FE analysis, as required in Pt1, Ch 9, Sec 5 or using analytical calculation based on beam theory, as required in Pt1,Ch 9, Sec 4
Damage Model	Linear cumulative using Palmgren-Miner's Rule	
Number of loading patterns used	2	2
Number of loading conditions used	2	2
S-N Curves	Based on Den(1990)and HSE(1995),details as follows: UK DEn, "Offshore installations: guidance on design, construction and certification", 4th edition, January 1990 HSE, "Offshore installations: guidance on design, construction and certification", 4th edition, February 1995	
S-N Curve Joint Classification	For fatigue assessment of welded joints exposed to in-air environment, S-N curve D as defined in Table 2 is to be used. For corrosive environment, S-N curve Dcorr as defined in Table 3 is to be used. For fatigue assessment of base material at free edge exposed to in-air environment, S-N curves B or C as defined in Table 2 are to be used. For corrosive environment, S-N curves Bcorr or Ccorr as defined in Table 3 are to be used.	
S-N Curve Selection Criteria	Survival probability of 97.7% corresponding to two standard deviations from mean.	

Approximation of long term stress distribution	Modified Weibull probability density parameter	
Low cycle fatigue coverage	None	None
Mean Stress Effect	Included. The mean stress correction factor on stress range in CSR is a further development of the two procedures applied in CSR Oil Tankers and CSR Bulk Carriers.	
Thickness Effect	Included	

3.3 Ship operational profile

In this section, answers are provided to the frequently asked questions about fatigue issues.

3.3.1 Design Life and Assumed Time at Sea

3.3.1.1 Question 1: Is 85% for time at sea realistic?

The CSR make a single assumption of utilization of all types and sizes of tankers covered by the Rules. Table 7 includes some example utilizations for different voyage lengths using quite optimistic allowances for vessel productivity in time charter trading. Time spent at sea for sport charter tonnage will generally be less than for time charter's.

Table 7 Example utilisation ratios for seagoing tankers

Typical Voyage Length (nautical miles)	Voyage Days at Sea @ 12 knots	Approx. Minimum Voyages per Year	Case A Utilization At sea	Case B Utilization At sea	Case C Utilization At sea
8,000	56	6	0.91	0.96	-
4,000	28	13	0.80	0.91	0.95
2,000	14	26	-	0.82	0.89
1,000	7	52	-	0.64	0.79
500	3	105	-	-	0.58

Notes:

1) Case A 4.0 days loading/unloading per round trip + 0.75 days per port entry. E.g. VLCC
2) Case B 1.5 days loading/unloading per round trip + 0.5 days per port entry e.g. Aframax
3) Case C 0.75 days loading/unloading per round trip + 0.35 days per port entry e.g. MR
4) One day per annum dry docking assumed (i.e. 5 days per five year survey cycle)

Table 7 shows that medium size tankers on long haul trades are more likely to spend a large proportion of time at sea.

In general 85% is considered reasonable. Specific operation profiles may require special considerations

3.3.1.2 Question 2a: What if more time is spent at sea?

In relation to dynamic loads, the assumption of time spent at sea may generally be disregarded as an issue for an Owner's specification for most oil tankers.

In special cases where there is reason to believe the time spent in harbour may be significantly reduced e.g. shuttle tankers, the effect is easily quantified since for a given stress range the fatigue life is directly proportional to the time at sea.

A simple way of addressing this issue is to specify a longer design fatigue life.

3.3.1.3 Question 2b: What if less time is spent at sea?

Less time at sea is not an issue for high cycle fatigue, and the Rules do not permit any reduction of fatigue cycles in any case. Therefore in terms of fatigue strength, the Rule assumption should be conservative for the locations required to be assessed.

3.3.2 Trade Routes

3.3.2.1 Question 3: How does the CSR wave environment compare to that used in Pre-CSR?

The CSR uses an idealized wave environment referred to here as "North Atlantic with equal probability of headings" (NAEPH). This idealized wave environment is based on documented wave statistics corresponding to sea conditions in the North Atlantic which are generally acknowledged to be the most severe (See 8).

The wave environment is derived assuming the tanker design has equal probability of headings in accordance with IACS Recommendation 34 Standard Wave Data.

It should be noted that CSR NAEPH is more onerous than the Pre-CSR class society basic fatigue standards for worldwide trading which were generally derived from combination of wave statistics derived from a larger group of sea areas.

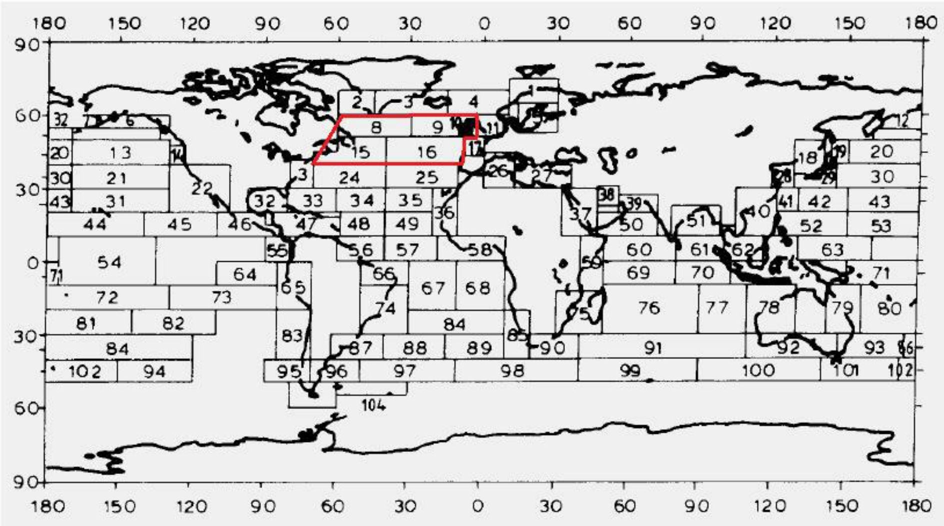


Figure 21 Marsden Areas used for IACS NAEPH Wave Environment

At the same time, it is noteworthy that the CSR NAEPH standard may be less onerous than some IACS member "North Atlantic" wave environments, in particular those based on stochastic analysis for tankers sailing on a specific trade across the North Atlantic between USA and Europe. For such trades the predominant wave direction in the Northern North Atlantic coincides with the trade route. As a consequence, the ship would spend a larger proportion of time with seas close to a bow or stern heading and therefore experience relatively higher magnitudes of vertical wave bending moments. Furthermore there are also differences in the assumption of speed reduction in heavy weather between different Class Societies' proprietary approaches.

3.3.2.2 Question 4: Can scantlings be reduced if the ship operates outside the North Atlantic?

No. Ships operating in less severe wave environments are not allowed to derive any reduction in scantlings for doing so, because the intention of the CSR is to produce robust ships for worldwide trading.

3.3.2.3 Question 5: Are the CSR assumptions of wave environment reliable for all trade routes?

The assumptions of equal probability of heading and speed reduction in CSR are considered to be generally conservative and may normally be disregarded as an issue for owner's specification.

However for some specialized or new trade routes a detailed investigation of wave environment may be required and Classification Societies can advise on the exact requirements.

Examples of such trades are:

- US to Mongstad or US to Europe
- West Africa to West Coast of US via Cape Horn.
- US west coast to Alaska
- Specific trading routes in the Southern Pacific

3.3.3 Loading conditions

The CSR fatigue model assumes a simplified trading pattern. The design is assumed to spend all of it's time at sea in either fully loaded (homogeneous load condition) or normal ballast condition.

Half of the at sea time is assumed to be cargo carrying in a homogenious condition and half is assumed to be in ballast resulting in a net time allocation of the 25 year design life of:

- Time in harbour 15.0%
- Time in ballast 42.5%
- Time loaded with oil cargo 42.5%

Such a pattern is considered representative for most crude oil trades averaged over an extended period of time.

3.3.3.1 Question 6: CSR only uses two loading patterns. Is this valid for all tanker types?

Where significant time is envisaged to be spent in part loading conditions this may have a significant effect on the fatigue performance of some details.

However the CSR fatigue methodology is not intended for investigations of such conditions because the load combination factors used in the fatigue analysis are only applicable to the two basic loading conditions. The procedure required needs to account for the impact of time variation of loading condition, drafts and hull girder bending moments on overall fatigue performance. Such a procedure will need to take account of the fatigue damage from multiple load cases and variation of environmental conditions in the time domain. Ref. section 5.2.5.

3.3.3.2 Question 7: Can design draught and metacentric height be optimized to minimize impact of the requirements?

The load calculation for determination of the stress ranges is based on the actual draughts and metacentre shown in the preliminary loading conditions.

The definition of the homogeneous load condition included in CSR Pt1, Ch 1, Sec 4, [3.1.5] means that some variation of cargo specific gravity (S.G.) is permitted between different designs for the purposes of establishing the loaded draught. However as noted in 3.3.5.1 the cargo S.G. used for determination of the inertial loads is fixed.

The predicted fatigue life of longitudinal end connections of side shell is sensitive to variation in the design draughts. These sensitivities depend on ship size and project specific parameters. For illustrative purposes Table 8 shows how the fatigue life varies with draught for a specific project. Where the draught used in the homogeneous loading condition is significantly different from the scantling draught, the effect of changing draught on the fatigue calculations should be considered in the fatigue calculations.

Table 8 Example of sensitivity of predicted fatigue life to change of draught for a specific VLCC design

	Maximum and Minimum % Change in fatigue life compared to original draught	
Stiffener Location	**10% Reduction in ballast Draught**	**10% Increase in Loaded Draught**
Bottom Shell	-6%/ 0%	-6% / 0%
Side Shell Below Ballast T	0%/ +7%	-10%/+5%
Side Shell Ballast T-Loaded T	0% /+7%	-25%/-11%
Side Shell Top of Wave	+1%	-37%/-25%
Side Shell above wave zone	+1%	-26%/-10%
Main Deck	0%/ +1%	-2%/ +0%
Inner Bottom	-1%/ +1%	-1%/ +1%
Hopper	0%/ +5%	0%/ +2%
Inner Hull	0%/ +3%	0%/ +1%
Longitudinal Bulkhead	-1%/ +1%	-1%/ +1%

3.3.4 Effect of predominant still water loads – "Mean stress" effect

In the assessment of weld joints, CSR Pt1, Ch 9, Sec 3, [3.2] specifies that a mean stress correction is applied.

The calculation of mean stress is explicitly stated in CSR Pt1, Ch 9, Sec 3, [3.2.2] to[3.2.4] .

3.3.4.1 Question 8: Are still water bending moments taken into account in the fatigue assessment?

As noted above SWBM is taken into account as input to the mean stress correction for assessment of longitudinal end connections. The hull girder static stress for full load is based on the SWBM for the full load condition which is normally a sagging condition. The hull girder static stress for ballast is based on the SWBM for the normal ballast load condition which is generally close to the design hogging SWBM.

3.3.4.2 Question 9: Which longitudinal end connections are affected by the mean stress correction?

Where the full load condition is a modest sagging condition, the effect is most significant to the full load component of the predicted fatigue damage for bottom and side shell. In this condition the dominant compressive bending stress in the flange of the shell stiffener is due to lateral load from the external hydrostatic pressure at scantling draught.

For designs with large full load sagging SWBM's the correction also impacts the upper side shell and deck structures.

In the ballast condition the bottom longitudinal may also be affected by the correction depending on the size of the hogging moment.

3.3.4.3 Question 10: Can the designer optimize the still water bending moments to increase the fatigue life?

Yes, Permissible still water bending moment is a design parameter to be decided by designer. This can be optimized since rule minimum is very small.

It can be seen from Table 9 that the fatigue life of end connections can be sensitive to variation of SWBM.

Table 9 Sensitivity of predicted fatigue life to change of SWBM

	Maximum and Minimum % Change in fatigue life compared to original SWBM	
Stiffener Location	25% reduction in SWBM	
	Sag	Hog
Bottom Shell	0%	-12%/0%
Side Shell Below Ballast T	0% / +3%	0% / +3%
Side Shell Ballast T-Loaded T	-4%/ +2%	-4%/ +2%
Side Shell Top of Wave	-5%	-5%
Side Shell above wave zone	-4%	-4%
Main Deck	-3%/ -4%	-1%/ 0%
Inner Bottom	0%	0%
Hopper	0%	0%
Inner Hull	-4%/ 0%	-4%/ 0%
Longl. Bulkhead	-5%/ 0%	-2%/ 0%

3.3.5 Effect of Cargo

The cargo inertial load calculation is based on a fixed cargo specific gravity of 0.9. Refer to Sec. 5.2.5 for higher specific gravity.

For simplicity CSR assumes that there is no dynamic lateral pressure load acting on the deck longitudinals when calculating the fatigue life because the dynamic hull girder stress range will be dominant.

The actual dynamic pressure acting on the deck longitudinals are:

- Intermittent dynamic load due to green sea loading
- Dynamic load due to cargo inertial load
- Inert gas pressure

3.3.5.1 Question 10: What happens if a low or high S.G. cargo is being carried?

Where the design cargo S.G. is less than 0.9, the minimum value of 0.9 is always to be used in the Rule assessment.

Where the design cargo S.G. exceeds 0.9, 0.9 or the maximum S.G. of homogeneous full load design draught, which is greater, is to be used in the Rule assessment. However , higher cargo density for fatigue evaluation for ships intended to carry high density cargo in part load conditions on a regular basis is an owner's extra. Such owner's extra is not covered by the Rules, and need not be considered when evaluating fatigue strength unless specified in the design documentation". Refer also to Sec. 5.2.5 for higher specific gravity.

3.3.5.2 Question 11: Are there cases where dynamic local loads should be taken into account on the deck?

Where part cargoes are to be regularly carried e.g. some product carriers, some investigation of likely dynamic loads on the deck may need to be carried out. The Classification society should be able to advice on this.

For most typical designs, this is not expected to be necessary; but for some designs fitted with corrugated bulkheads without an upper stool, particular attention need to be paid to the connection between the bulkhead and the deck longitudinal stiffeners. Dynamic pressure acting on the bulkhead under a differential loading pattern i.e. one side empty, will induce sizeable local bending moments on the deck longitudinals which are not considered in the CSR fatigue loads. Adequate support need to be provided, verified by additional class procedures as necessary.

3.3.5.3 Question 12: At what level could inert gas pressure have an influence on fatigue life?

CSR does not explicitly account for variation of inert gas pressure because the long cycle period compared to wave load period would effectively render this a static load.

Even if the inert gas pressure has no influence on the stress range the mean stress will be affected by the value of the PV valve setting pressure. It is noted that this mean stress level may have direct influence on the fatigue life of structural details subject to this pressure; however the effect is expected to be small.

Where increased inert gas pressure results in increased scantlings of the deck longitudinals, there will be an effect on the fatigue life.

3.3.5.4 Question 13: What happens if a sour crude or high corrosive cargo is being carried?

CSR takes no account of the type of oil carried. If a particular cargo is identified as being particularly corrosive then additional corrosion protection measures should be taken. It should be noted that this issue is not considered to be solely or specifically fatigue related.

3.3.6 Effect of Ballast

The main fatigue critical structural components affected by the rate of corrosion in ballast tanks are:

- Lower and upper hopper knuckles
- End connections of side shell and bottom longitudinal stiffeners
- End connections of inner bottom longitudinal stiffeners in way of oil tight transverse bulkheads

Rates of corrosion in ballast tank spaces are fundamentally influenced by the corrosion protection scheme. Ship owners should therefore consider the need to upgrade the protective coating and cathodic protection scheme chosen for particular project on a case by case basis.

3.4 Structural arrangement and response

3.4.1 Structural arrangements

The CSR were developed considering standard tanker designs and there are therefore implicit assumptions built into the Rules regarding structural arrangement such as:

- Primary member spacing
- Secondary member spacing
- Number of bulkheads
- Number of cross ties
- Arrangement of deck transverses

Primary member spacing is discussed in 3.4.3.1

Secondary member spacing is not normally an area of concern.

The number of bulkheads is not a major issue.

The CSR Rules do not cover VLCC designs without cross ties.

The CSR Rules envisage a continuous ring of web frame structure. Designs departing from this would need to be examined in detail by the Classification Society.

3.4.2 Scope of assumed standard connections for secondary member end connections

The CSR fatigue assessment of longitudinal stiffeners is limited to the analysis of the two common hot spot locations associated with a web stiffener end connection. These critical hot spots are located on the top surface of the face plate of the stiffener as shown at points A and B in Figure 22.

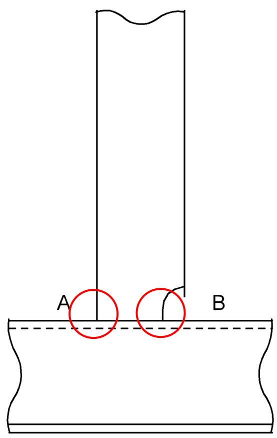


Figure 22 Critical hot spot locations on longitudinal stiffeners

Tables of common end connection details are included in CSR Pt1, Ch 9, Sec 4, Table 4. For each detail, this table provides the relative stress concentration factor for the particular detail.

3.4.2.1 Question 14: What if a detail is proposed which is not in CSR Pt1, Ch 9, Sec 4, Table 4 of the Rules ?

The CSR require that upon agreement by the Society, the geometrical stress concentration factors for alternative designs are to be calculated by a very fine mesh FE analysis according to the requirements given in CSR, Ch 9, Sec 4, [5.3].

3.4.2.2 Question 15: How are pillarless stiffeners treated?

In the case that a connection is proposed without a web stiffener (so called pillar-less connections) there are no hot spots on the flange of the stiffener. For this type of connection, the critical hot spot stress locations tend to be at the connection of the primary member web to the stiffener as shown in Figure 23.

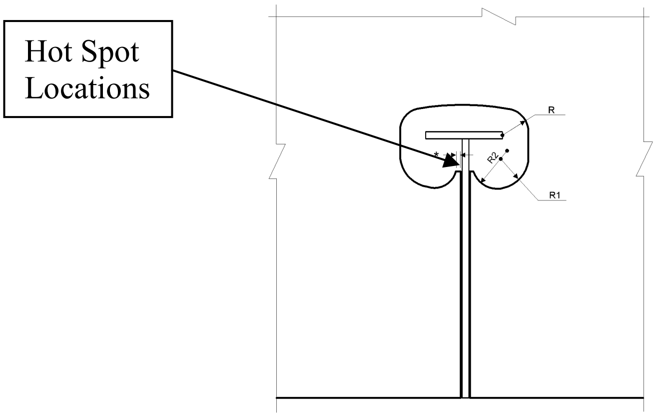


Figure 23 Critical hot spot locations for a longitudinal without pillar stiffener

To assess the fatigue life in way of such hot spots requires the stresses on the primary member web to be obtained. However, in lieu of numerical assessments, the CSR consider it sufficient to prescribe improved detail design standards as a means of fatigue control in way of the critical areas for this type of hot spots. For the purposes of CSR the fatigue life of pillar-less stiffeners is calculated based on the assumption that a nominal hot spot exists on the flange. Designs with overlapped connection / attachments see CSR Pt1, Ch 9, Sec 4, [5.2.3]. Details where web stiffeners are omitted or not connected to the longitudinal stiffener flange see [5.2.4] (See CSR Pt1, Ch 9, Sec 6, [2] and Table 1).

3.4.2.3 Question 16: What if an alternative detailed design of pillar-less stiffener connection is proposed?

Should alternative cut-out details be proposed, a comparative finite element analysis is to be carried out. The extent of the finite element analysis for this will be agreed by the Classification Society. While the CSR do not explicitly state if the comparative finite element analysis will be required as part of a fatigue analysis, it is the understanding that the intention of the Rules will be met as long as equivalent or improved stress concentration factors can be demonstrated.

3.4.3 Structural Flexibility (Relationship with FEM/zoom up analysis)

In addition to the local deformation caused by application of pressure loading, the overall response of the primary structure induces additional stress in way of the stiffener end connections due to relative deflection of adjacent web frames. For practical purposes this has been shown to be negligible except for locations in way of transverse or swash bulkheads where the relative rigidity compared to adjacent frames is large.

The CSR accounts for the effect of relative deflection in two ways

A set of standard stress concentration factors is used to multiply the stress range at each bulkhead location. This varies from 1.15 to 1.5 depending on the position around the transverse section(See CSR Pt1, Ch 9, Sec 4, [4.2.4] and Table 2).

Other parts of the CSR are intended to ensure that departures from the standard tanker design assumptions are adequately investigated.

This includes a mandatory zoom up fine mesh analysis of the bottom/inner bottom longitudinal connection to transverse bulkhead floor connection and stress reduction in way of secondary member end connections.

3.4.3.1 Question 16: Is the CSR approach to structural flexibility reliable for all designs?

The approach is considered robust for double bottom structures of current crude oil and product carrier designs. These feature primary member spacings generally within the ranges shown in Table 10 .

Size	**Typical Primary Member [m]**
Handy	2.7-3.6
Panamax	3.0-3.9
Aframax	4.0- 4.4
Suezmax	4.0-5.0
VLCC	5.0-6.0

Table 10 Typical range of primary member spacings on standard tanker designs

Should the primary member spacing for a particular tanker size be exceeded then the Classification Society should be requested to give guidance on the additional deflection analysis of double bottom and side structures required to be carried out.

3.4.4 Hopper Connections

As noted in section 3.2.1, the scope of CSR analysis of hopper connections is applicable both to the welded and radiused configuration. Where a bent type hopper knuckles is proposed ,the procedure in principal is the same as that applied on the welded knuckle, but the plate angle correction factor and the reduction of bending stress as applied for welded knuckle defined in CSR Pt1, Ch 9, Sec5 [4.2.2] are not to be applied for the bent hopper knuckle type.

3.5 Construction Standards and Residual Stresses

This section describes the CSR Rule assumptions/requirements on construction standards and residual stresses. Recommendations for reducing uncertainties related to these factors are included in 5.

3.5.1 Construction standards

In order to realize the design fatigue life, attention to the quality of production in critical areas is essential. To some extent this is reflected in CSR as in the examples below.

Note 2 of CSR Pt1, Ch 9, Sec 4, Table 4 of the CSR fatigue requirements penalizes longitudinal end connections which are not designed with at least an 8 mm offset between the welded attachment such as web stiffener and tripping bracket and the edge of the longitudinal face bar. The penalty is that a lower fatigue classification is used. This concept is to ensure a sufficient clearance between the weld toe and the plate edge, thus reducing the risk of introducing an undercut or weld spatter on the edge which could lead to premature fatigue cracking. Flat bar type longitudinal stiffeners, though comparatively rare on modern tankers, will automatically attract this penalty.

Enhanced alignment standards for hopper knuckle connections, transverse bulkhead horizontal stringer heel and transverse and longitudinal corrugated bulkhead connection to lower stool are included in CSR from CSR Pt1, Ch 9, Sec 6(Table 3, 4, 6, 8, 9, 11, 13). Further enhancements are also referred to such as mandatory partial penetration welding in way of the hot spot areas, as well as the adoption of weld dressing to improve actual fatigue life.

Elsewhere enhancements to the quality of production at critical locations are in accordance with the individual classification society's requirements, which will generally conform to a national shipbuilding quality standard or IACS Recommendation 47.

3.5.2 Residual stresses

As with most non-CSR fatigue assessment procedures, residual stresses are not explicitly addressed in the requirements. Some allowance for the effects of such stresses are catered for within the S-N curves, and it is accepted that S-N curves (developed under constant amplitude testing) are safe to use for design purposes.

Large tensile residual stresses (up to yield) may be present in the hot spot in the as-welded condition. Hence, in theory, an external load that causes partly compressive stress variation will inflict an entirely cyclic tensile stress response when superimposed on large static residual tensile stresses. In ship structures, it is however normally accepted that shake down effects will take place almost as soon as it becomes operational, due to tank testing, loading and un-loading and due to transit in heavy weather. This load variation will tend to shake down the residual stresses and also provide a practical reason for the acceptance of the mean stress correction as stated in 3.3.4.

3.6 Other Assumptions

3.6.1 Vibration

Cyclic loading from main engine or propeller induced vibratory forces are not considered in the Rule formulations.

For certain vessels operating in certain trades, hull girder vibration caused by wave loading may introduce uncertainties related to fatigue loading. The contribution from vibration caused by springing and whipping are implicitly considered in the present Rule formulations as described in CSR Pt 1, Ch 3, Sec 5 [2.4.1] and justified in TB Report "Hull Girder Vibration"..

3.6.2 Thermal loads

Consideration of thermally-induced stresses is not explicitly included in the CSR fatigue analysis loads.

Where carriage of hot cargoes is envisaged the Classification society can advise on the need to consider its impact on fatigue, if any.

3.6.3 Other considerations

Impact loads are not explicitly included in the CSR fatigue, because the frequency of such loads is relatively low.

4 Pre-CSR Service Experience

4.1 Introduction

In this chapter typical experience from previous generations of vessels will be looked into and it will be shown if and how these have been specifically dealt with in the CSR with regard to fatigue. The chosen details have mainly been taken from the 'Guidance Manual for Tanker Structures'/4-1/ (Single hull designs) and 'Guidelines for the Inspection and Maintenance of Double Hull Tanker Structures'/4-2/ although illustrations showing the typical details have also been taken from other sources.

The examples which are shown for single hull structures have been included because they are considered relevant also for double hull designs.

It should be noted that it is a general requirement in CSR to design and construct tankers to achieve 25 years fatigue life, as defined in the CSR. Reference is also made to Chapter 5 of this Guidance Note for fatigue enhancement.

Some of the details shown below are covered by the same CSR chapters and repetitions will therefore be found. In addition to CSR requirements concerning specific details, the individual classification societies have their own practice and acceptance criteria based on their own experience.

4.2 Secondary member end connections

4.2.1 General

Fatigue cracks of secondary member end connections were frequently observed in single hull oil tankers during the 80's and 90's and such damage experience has been incorporated in updated classification rules to assess the fatigue strength of secondary member end connections. While these feedbacks have also been incorporated to the fatigue assessment of double hull tankers, several fatigue crack damages have still been observed at secondary member end connections. As the causes of damage depend on the position of the secondary member and the stress combination due to local bending and hull girder bending, typical examples of fatigue damages at different locations are introduced separately in this section.

Although the wave environmental condition and minimum design fatigue life were not uniform amongst all classification societies, now in the CSR, prescriptive rule requirements to achieve 25 years fatigue life in North Atlantic wave environment are applied to secondary member end connectionsas given in CSR Pt1,Ch9 Sec2 1.1.1 and the specific locations defined in CSR Pt1, Ch9 Sec4 1.1.2.

4.2.2 Deck

4.2.2.1 Deck longitudinals to vertical stiffeners on transverse bulkhead

Figure 24 Deck longitudinal bracket connection to bulkhead stiffener

Contributing factors to damage:

- High stress concentration factor due to toe height and bracket stiffness, hull girder stresses are dominant.
- Load effects from the transverse bulkhead
- Picture on the left would seem to indicate zero clearance between the weld toe and the face edge, which in the CSR the stress concentration factor listed in the table(CSR Pt1, Ch9, Sec 4, Table 4) is to be multiplied by a factor of 1.12.
- Picture on the right would seem to indicate HP bulbs. While the edge condition is considered better than that for a rolled angle profile, this could warrant an additional penalty factor of 1.12 to the stress concentration in the CSR if the edge clearance criteria is not met.

4.2.2.2 Equipment on deck

Figure 25 Pedestal support and deckhouse

These items are not covered by CSR. Individual classification societies practice and rules may apply. They also may be covered by additional class notations available from the various classification societies. Reference is also made to the publication TSCF IP001/2011 'Outfitting related structural defects' which is posted on the TSCF web site (www.tscforum.org).

Contributing factors to damage:

- Stress concentration factor high due to lack of soft brackets

- Misalignment with support below deck.

4.2.2.3 Connection between deck longitudinals and local girder support

Crack at the connection between deck longitudinal and girder support under crane pedestal is one of the typical damages in deck.

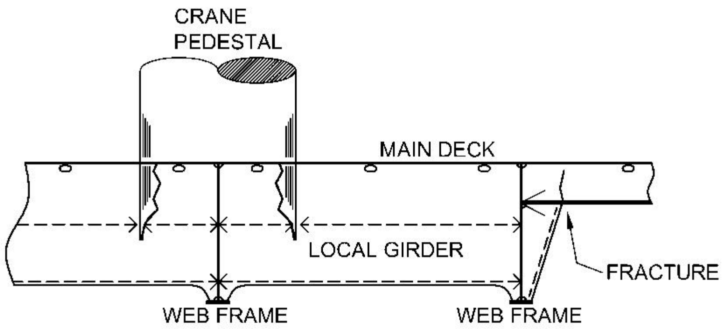


Figure 26 Inserted local support girder

These items are not covered by CSR.

Contributing factors to damage:

- Lack of continuity or poor connection of the longitudinal member
- Large stress concentration factor due to large change in stiffness
- Secondary bending effects caused by transitions between flexible and stiff structural elements

4.2.3 Side shell

4.2.3.1 Side longitudinals at web frames

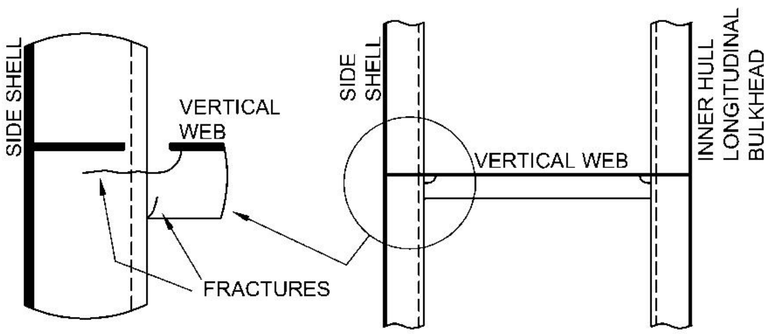


Figure 27 End connections of longitudinals

End connections of side longitudinals are covered by CSR.

Contributing factors to damage in these locations are:

- Asymmetrical connection of flat bar stiffener resulting in high peak stresses at the heel of the stiffener
- High stress concentration factor due to sharp corners
- High dynamic wave pressure loads on ship side coupled with high tensile static stress
- Higher tensile steel indirectly leading to higher dynamic working stress level in side longitudinal

- Higher tensile steel indirectly leading to higher strain in way of notches which could also accelerate coating fatigue in way.
- Insufficient connection and weld area for transfer of shear load between longitudinal to web of primary support members

4.2.3.2 Side longitudinals at transverse bulkheads

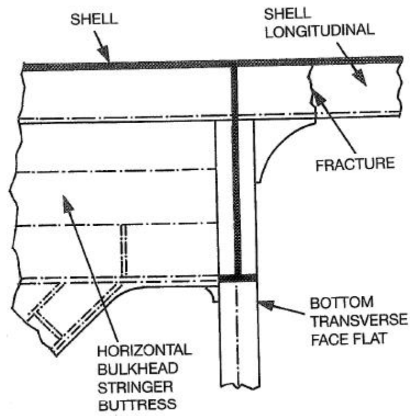


Figure 28 Stringer to side longitudinal connection

Similar damage may be found at side longitudinal connections to stringers in double side structures.

Contributing factors to damage:

- Under-designed end bracket
- Higher tensile steel/higher dynamic stress level in side longitudinal
- Deflection of the adjacent transverse web frame under load
- High dynamic loads on ship side
- Poor/Defective return fillet welding in way of and around attachment toes where stresses are high
- Asymmetric longitudinal resulting in additional torsional stresses

4.2.3.3 Web frames in way of side longitudinals

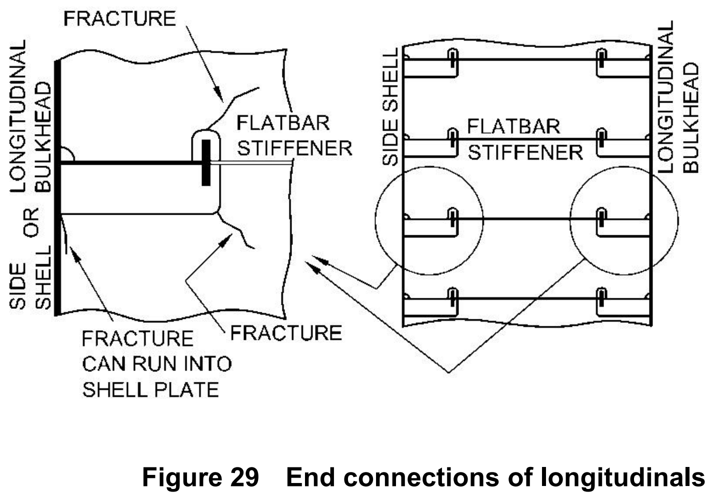


Figure 29 End connections of longitudinals

Details of the web frames in way of cut outs for longitudinals are not covered by explicit fatigue check in CSR. Individual classification societies practice and rules may apply.

Contributing factors to damage:

- Asymmetrical connection of flat bar stiffener resulting in high peak stresses at the heel of the stiffener
- Insufficient connection and weld area for transfer of shear load between longitudinal to web of primary support members
- Poor/Defective return fillet welding in way of and around connection edges where stresses are high
- High localized corrosion at areas of stress concentration such as flat bar stiffener connections, corners of cut-out for the longitudinal and connection of web to shell at cut-outs which might have been caused by a combination of poor edge and surface preparation, inadequate coating specification/quality of application, and strain from more flexible joints leading to premature coating breakdown.
- High shear stress in the web at the transverse
- High dynamic loads on ship side

4.2.4 Bottom and Inner bottom

4.2.4.1 Bottom and inner bottom longitudinals at web frames/floors

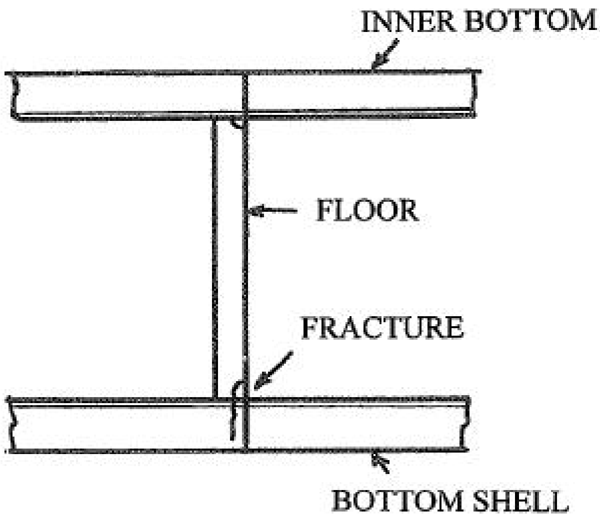


Figure 30 End connections of longitudinals

End connections of bottom longitudinals are covered by CSR.

Contributing factors to damage:

- Asymmetrical connection of flat bar stiffener resulting in high peak stresses at the heel of the stiffener
- Combination of high local and longitudinal dynamic stresses
- Inadequate clearance between welded attachment and edge of face member (picture on left side of Figure 30)

4.2.4.2 Bottom and inner bottom longitudinals at transverse bulkheads

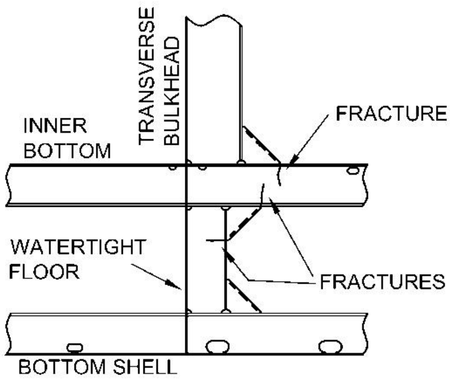


Figure 31 Plane transverse bulkhead to double bottom

Crack at inner bottom and on floor stiffener may not be adequately covered by CSR fatigue checks and prescriptive requirements. However, required fine mesh stress check should normally ensure satisfactory detail design in this area. Crack on face plate of inner bottom longitudinal should be adequately covered by CSR fatigue checks.

Contributing factors to damage:

- Asymmetrical connection of bracket in association with a backing bracket which is omitted or too small
- Relative deflection of the adjacent floor to transverse bulkhead
- Inadequate size and “softness” of the brackets
- High stresses in the longitudinals and the floor stiffener

4.2.4.3 Floors in way of bottom and inner bottom longitudinals

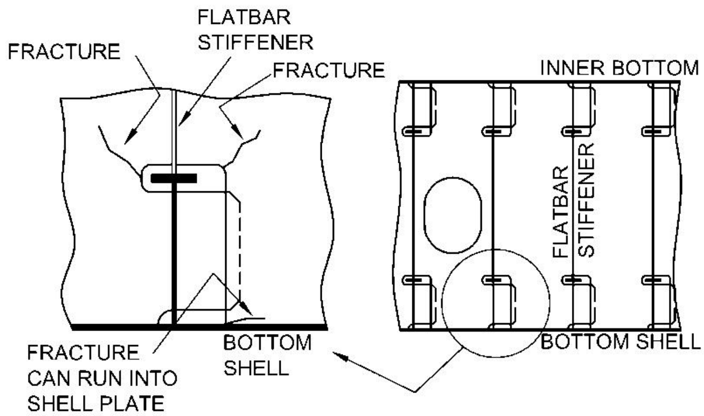


Figure 32 End connections of longitudinals

Details of the web frames in way of cut outs for longitudinals are not covered by explicit fatigue checks in the CSR. Individual classification societies practice and rules may apply.

Contributing factors to damage:

- Insufficient connection and weld area for transfer of shear load between longitudinal and web of primary support members

- High shear stress in the web at the transverse
- Dynamic loads on bottom
- High localized corrosion at areas of stress concentration such as flat bar stiffener connections, corners of cut-out for the longitudinal and connection of web to shell at cut-outs which might have been caused by a combination of poor edge and surface preparation, inadequate coating specification/quality of application, and strain from more flexible joints leading to premature coating breakdown.

4.2.4.4 Details at suction wells

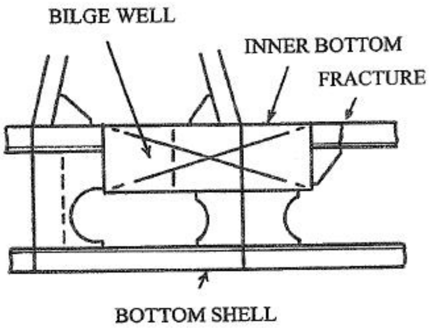


Figure 33 Details at suction wells

Details of the bilge wells related to the connection to longitudinals and bulkhead structure are not covered by the CSR. Individual classification societies practice and rules may apply.

Contributing factors to damage:

- Lack of continuity or poor connection of the longitudinal member
- Stress concentration due to unsuitable bracket shape
- Asymmetrical sectional shape of inner bottom longitudinal

4.2.5 Hopper and inner skin

4.2.5.1 Longitudinals at web frames/floors and transverse bulkheads

CSR requirements are in CSR Pt1, Ch9 Sec02 1.1.1 and the specific locations defined in CSR Pt1, Ch9 Sec04 1.1.2S.

4.2.5.2 Web frames in way of longitudinals

Figure 34 End connections of longitudinals

Details of the web frames in way of cut outs for longitudinals are not explicitly covered by the CSR fatigue check. Individual classification societies practice and rules may apply.

Contributing factors to damage:

- Insufficient area of connection of longitudinal to web
- High shear stress in the web at the transverse

4.2.6 Longitudinal bulkheads

4.2.6.1 Web frames in way of longitudinals

Details of the web frames in the connection to longitudinals are not covered by the CSR. Individual classification societies practice and rules may apply.

4.3 Transverse Bulkheads

4.3.1 General

Transverse bulkheads are normally designed by either vertically stiffened plane bulkhead or corrugated bulkhead in case of double hull oil tankers. It is well known that each design has following critical points mainly by local deflection and related stress concentration.

- Vertically stiffened plane bulkhead:
    - Connection of transverse bulkhead vertical stiffener to inner bottom plate, see 3.2.6.2
    - Connection of transverse bulkhead and inner hull longitudinal bulkhead in way of horizontal stringers. See 4.3.7.
- Corrugated bulkhead:
    - Connection between corrugated bulkhead and inner bottom plate
    - Connection between corrugated bulkhead and upper deck plate
    - Connection between corrugated bulkhead and lower stool plate
    - Connection between corrugated bulkhead and upper stool plate
    - Connection between lower stool plate and inner bottom plate

The typical examples of damages are shown in 4.3.2 – 4.3.5.

No explicit fatigue check for this critical location is required or provided in the CSR. High cycle fatigue check alone may not be adequate for assessment of transverse bulkhead structures.

Contributing factors to damage:

- Local stress concentration
- Lack of supporting structure
- Misalignment

To cover these possible causes, detail fine mesh stress analysis and prescriptive arrangement of supporting structures are additionally required, depending on the position, in the CSR. Detail fine mesh stress assessment and prescriptive arrangement are now applied to indirectly enhance the fatigue strength.

4.3.2 Connections between inner bottom and transverse bulkhead stools

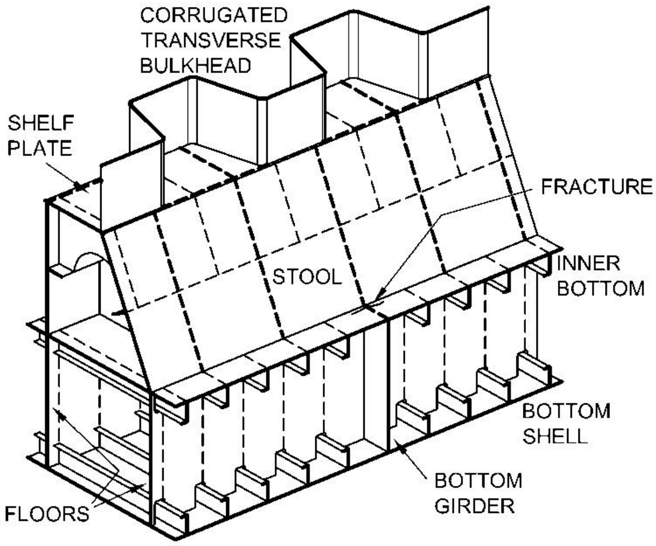


Figure 35 Lower stool connection to inner bottom

Connection of transverse bulkhead lower stools to the inner bottom plating in way of double bottom girders is location for fatigue assessment by very fine mesh in CSR. High cycle fatigue check using homogeneous full load condition alone may not be sufficient for assessment of transverse bulkhead structures especially for ships that frequently trade with one-side-full/other-side-empty condition in open waters. CSR includes prescriptive requirements and recommendations in order to improve the detailed design, are found in CSR Pt2, Ch2, Sec 3, [2]. These recommendations include the following:

The stool sides are to be located in line with floors in the double bottom, the internal webs or diaphragms are to be aligned with structure below. Other details affecting fatigue are not covered by CSR. Individual classification societies practice and rules may apply.

Contributing factors to damage:

- Misalignment between stool side plating and floor and /or stool webs and girders of double bottom
- Insufficient thickness of floor compared to stool thickness
- Scallops, cut-outs, air holes reducing too much the connection area and presenting crack initiation points
- Weld details and dimensions
- Lamellar tearing of inner bottom plating

4.3.3 Connection between corrugated bulkhead and stool

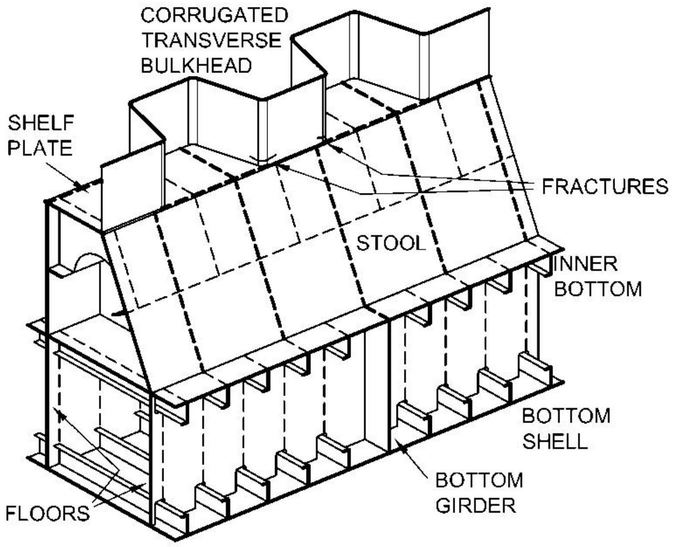


Figure 36 Corrugation connection to lower stool

Connection of transverse bulkhead lower stools to the inner bottom plating in way of double bottom girders is location for fatigue assessment by very fine mesh in CSR-BC&OT.CSR includes prescriptive requirements and recommendations. These are found in CSR Pt1, Ch3, Sec 6, [10.4], CSR Pt2, Ch2, Sec 3, [2], CSR Pt1, Ch7, Sec 3, [4.8] and CSR Pt1, Ch9, Sec 6, [6].They include a general requirement that the global strength of the corrugated bulkhead and attachments to surrounding structure is to be verified by the cargo tank FEM model. Corrugated bulkhead connections to stool top including shelf plate are included.

The following requirements apply in general:

- Cargo hold analyses and fine mesh analyses for yielding
- Prescriptive requirement for yielding & buckling
- Recommended standard details and focus areas

Contributing factors to damage:

- Stress concentration due to unsupported corrugation web
- High through thickness stress, lamellar tearing
- Weld details and dimensions
- Misalignment
- Insufficient thickness of stool side plating in relation to corrugation flange thickness

4.3.4 Corrugated bulkhead connections to deck without upper stool

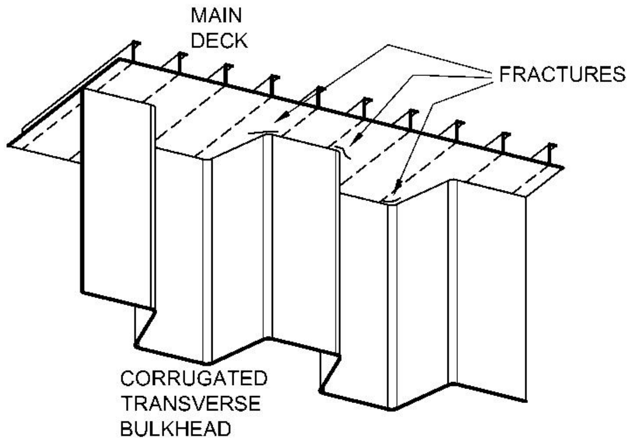


Figure 37 Corrugated bulkhead connection to deck

No explicit fatigue check for this critical location is required or provided in the CSR. High cycle fatigue check using homogeneous full load condition alone is not appropriate for assessment of transverse bulkhead structures especially for ships that frequently trade with one-side-full/other-side-empty condition in open waters.

CSR requirements are found in CSR Pt1, Ch3, Sec 6, [10.4], they include a general requirement that the global strength of the bulkhead and attachments to surrounding structure is to be verified by the cargo tank FEM model.

Cracks may appear in the deck/bulkhead plating at the weld to the deck plating.

Contributing factors to damage:

- Stress concentration due to unsupported corrugation web
- Weld details and dimensions
- Misalignment between face of corrugation and web above
- Cut-outs and scallops or air holes increasing the stress in the web

4.3.5 Inner bottom plating at corrugated bulkheads without lower stool

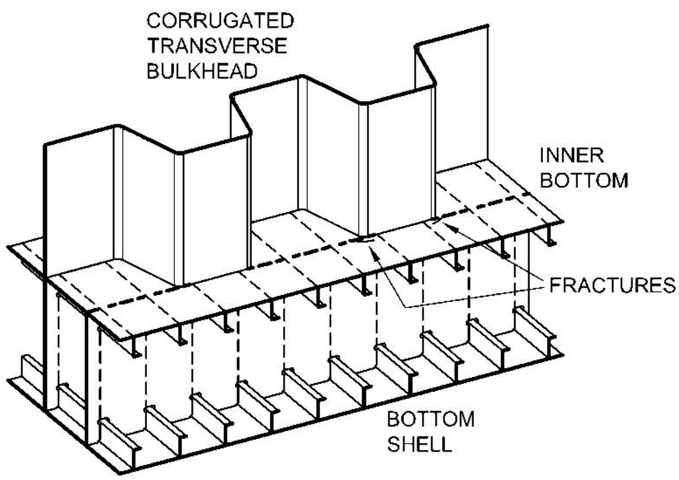


Figure 38 Corrugated bulkhead connection to inner bottom

No explicit fatigue check for this critical location is required or provided in the CSR. High cycle fatigue check using homogeneous full load condition alone may not be adequate for assessment of transverse bulkhead structures especially for ships that frequently trade with one-side-full/other-side-empty condition in open waters.

CSR requirements are found in CSR Pt1, Ch3, Sec 6, [10.4], CSR Pt2, Ch2, Sec 3, [2], CSR Pt1, Ch7, Sec 3, [4.8] and CSR Pt1, Ch9, Sec 6, [6]

They include a general requirement that the global strength of the corrugated bulkhead and attachments to surrounding structure is to be verified by the cargo tank FEM model. Corrugated bulkhead connections to stool top including shelf plate are included.

The following requirements apply in general:

- Cargo hold analyses and fine mesh analyses for yielding
- Prescriptive requirement for yielding & buckling
- Recommended standard details and focus areas

Contributing factors to damage:

- Stress concentration due to unsupported corrugation web
- High through thickness stress, lamellar tearing
- Insufficient through thickness properties of the inner bottom plate
- Weld details and dimensions
- Misalignment between face of corrugation and floor underneath
- Cut-outs and scallops or air holes increasing the stress in the floor

4.3.6 Connection between stool shelf plate and inner side stringer

This is not covered in particular, for stringer connections, see 4.3.7.

4.3.7 Transverse bulkhead stringer to double side structure

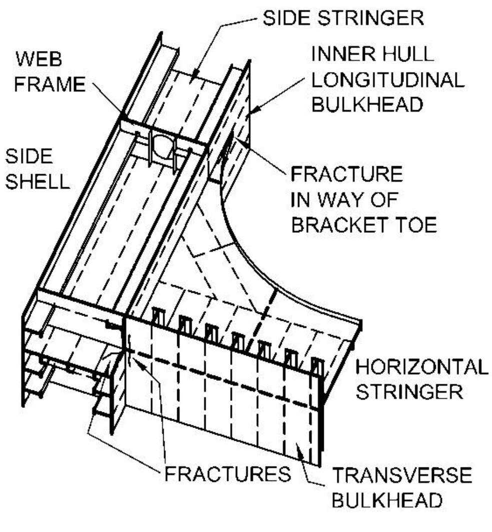


Figure 39 Transverse bulkhead stringer connection

No explicit fatigue check for this critical location is required or provided in the CSR.

CSR recommendations for detailed design improvement are found in CSR Pt1, Ch9, Sec 6, [5] and Table 9, CSR Pt1, Ch7, Sec 3, [4.6]Transverse bulkhead stringer connection to inner hull, toe and heel:

Standard details (Recommendation), including proposed bracket in the heel

Cargo hold analyses and fine mesh analyses for yielding

Fracture type 1, Contributing factors to damage:

- Misalignment between bracket end and side girder in side tank

Fracture type 2, Contributing factors to damage:

- Stress concentration / square corner
- High loads transferred from side stringer to transverse bulkhead

4.4 Primary Members

4.4.1 General

Connection between primary members (e.g. hopper knuckle, cross tie end) and end termination of primary member (e.g. bracket toe) are well known as critical points of fatigue strength. Typical damages in double hull tankers are shown in 4.4.2

Fatigue checks for these locations in CSR are limited to the lower hopper knuckle. For other locations only strength (yielding checks) are carried out by fine mesh analysis.

4.4.2 Transverse Web Frames

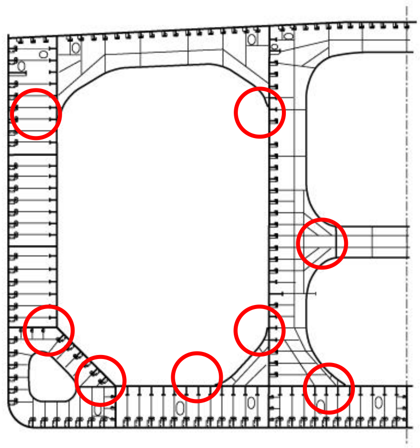


Figure 40 Locations of high stresses

4.4.2.1 Bracket connections

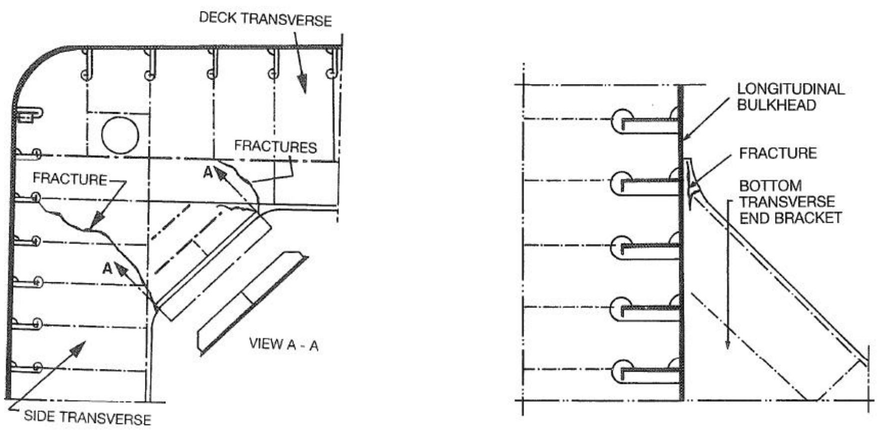


Figure 41 Web frame brackets

No explicit fatigue check for this critical location is required or provided in the CSR.

CSR requirements are found in CSR Pt1, Ch7, Sec 3, [4.5] and include cargo hold analyses and fine mesh analyses for yielding.

Contributing factors to damage:

- Stress concentration at bracket face plate sniped end
- Defective weld or material at the face plate snipe/around bracket toe
- Bracket face plate in way of toe with insufficient taper
- Localized corrosion at bracket toe
- Insufficient bracket size/high nominal stress

4.4.2.2 Cross tie connections

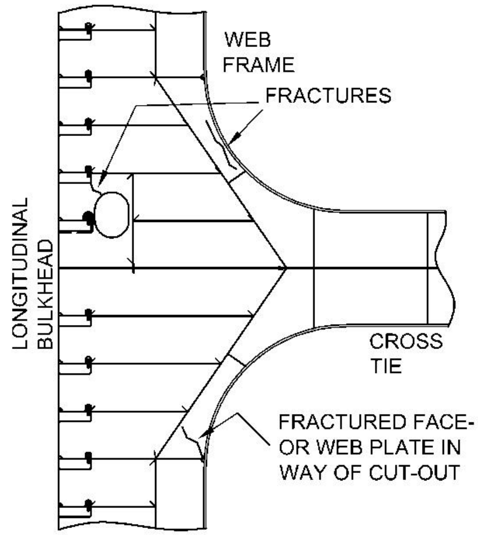


Figure 42 Cross tie connection

Fractures in face plate are not covered by an explicit fatigue check in CSR.

CSR requirements are found in CSR Pt1, Ch8, Sec 4, [5] and comprise prescriptive buckling and FE analyses for yielding and buckling

Contributing factors to damage:

- Face plate radius in way of cross-tie too small leading to high stress under bending of vertical web and cross-tie
- Stress concentration at notches in web plate
- Localized corrosion of web plate leading to panel flexing and fractures
- Inadequate panel stiffening of web plate
- Butt weld seams located too close to the radius

4.4.2.3 Hopper knuckle

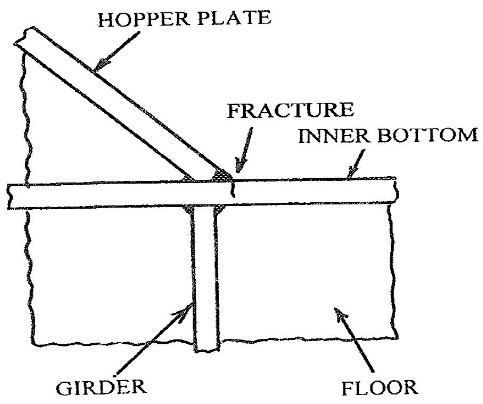


Figure 43 Hopper knuckle

Fatigue check is explicitly required and a quantitative procedure for the lower welded knuckle is included in the CSR.

CSR requirements are found in CSR Pt1, Ch9, Sec 6, [4] and include as follows.

- Yielding fine mesh for upper hopper knuckle
- Mandatory fatigue analyses for welded type lower knuckle
- Prescriptive design standard for radiused type, mandatory fatigue analyses for different design

Contributing factors to damage:

- Local stress affected by design parameters e.g. depth of inner bottom, size of hopper, width of tank, spacing of primary members and corresponding scantlings.
- Stress concentration at juncture of hopper plate to inner bottom, including angle of hopper plate, arrangement of scarfing bracket outboard of the side girder, support at the knuckle point (for radiused knuckles offset from the side girder)
- Insufficient and/or poor quality welding connection, including leg length, weld toe flank angle and weld toe undercut.
- Misalignment between hopper plate, inner bottom and girder

4.4.2.4 Other knuckles

CSR Pt1, Ch3, Sec 6, [2.2.1]Reinforcement at knuckles by closely spaced carlings.

5 Recommendations to Enhance Fatigue Performance

5.1 Introduction

There are many assumptions inherent within the CSR fatigue analysis with regards to vessel structural arrangement, trade route, loading cycles, material, welding, alignment, etc. These assumptions, together with a conservative approach regarding the probability of failure of a connection, enable a simplified fatigue analysis to be applied to the large majority of modern oil tanker designs being built and in establishing a common base-line design fatigue standard for these ships. However, it could introduce possible inaccuracies in the predicted fatigue lives of an individual vessel, particularly if it is of an unconventional form or designed, constructed, loaded, operated and maintained in a manner that differs significantly from the assumptions adopted during Rule development.

This section describes a number of additional measures which can be taken to increase the reliability of the fatigue prediction and enhance the fatigue life of a vessel. The descriptions are intentionally brief and so further guidance on each section should be sought from the Classification Society when considering enhancing a vessel's fatigue life.

5.2 Analysis

The fatigue life of a structural element or connection is highly dependent upon the stress range applied. Therefore the fatigue life can be significantly improved by reducing this stress range. This can be achieved through an increased section modulus of individual stiffeners, in the case of local loads, or the midship section, in the case of global loads.

5.2.1 Specified Fatigue Life

The CSR require that the vessel be designed and constructed to achieve a fatigue life of at least 25 years when exposed to a North Atlantic wave environment. A simple way to build more confidence in the fatigue life of a vessel and mitigate the effect of the uncertainties in the assumptions on the fatigue life is to specify a longer required fatigue life (e.g. 30 years) whilst maintaining all the other assumptions used by the CSR. A notation indicating this extended fatigue life is typically offered by the Classification Society.

5.2.2 Level of Fatigue Analysis

The fatigue analysis required by the CSR is a simplified analysis which makes a number of assumptions as described in earlier sections. To require comprehensive fatigue assessment of all potential hotspots would obviously be impractical so the analysis is selectively applied to a number of hot spots based mainly on experience and current class practice, and not applied to some other fatigue prone locations within a vessel design such as transverse bulkhead stinger connections.

If a vessel's design or operation is sufficiently outside what has been assumed in the CSR, or a more reliable calculation of fatigue life is required for a structure than what is required or provided by the CSR, then a higher level of fatigue analysis may be carried out.

Typically called a hotspot stress spectral fatigue analysis it may include:

- A fine mesh finite element model of the structure of interest

- Application of a larger number of operational loading conditions
- Direct analysis of external hydrodynamic pressure, vessel motions and associated tank content's accelerations (inertia loads), based on sailing routes or scatter diagrams
- Calculation of cyclical loads on structure
- Summation of stress cycles and calculation of resulting fatigue life.

The greater detail with which the structure is modeled makes it easier to identify where the hotspots are located with a higher reliability in the stress state at these hotspots and therefore how the fatigue life of the structure can be improved.

CSR requires that the lower welded hopper knuckle connection be assessed using a fine mesh fatigue method using simplified loads which is understood to have been validated against the individual spectral methods employed by the class societies charged with the development. It is recommended that the following additional connections may also be analyzed by the spectral approach to supplement the Rule in consultation with the Class Society:

- Lower knuckle connection of the radiused configuration
- Additional highly stressed welds in the lower knuckle area, only the longitudinal weld in the knuckle is considered by CSR
- Upper knuckle connection whether welded or radiused (intersection of hopper sloping plate, longitudinal bulkhead, transverse web and side stringer).
- Transverse bulkhead lower stool connection to inner bottom.
- Transverse bulkhead upper stool connection to deck.
- Corrugated transverse bulkhead to lower stool or inner bottom.
- Corrugated transverse bulkhead to upper stool or deck.
- Transverse oil-tight and wash bulkhead horizontal stringer heel connection to inner hull, for the stringer closest to mid-depth and uppermost (OTBHD only).
- Selected cut outs for longitudinal stiffeners in web-frame without web stiffener connection e.g. in areas of high primary member shear and high lateral pressure.
- Scallops in way of block joints on strength deck close to mid hold.

5.2.3 Low Cycle Fatigue

Low cycle fatigue occurs where high stress ranges involving yielding at hot spots are applied for a relatively low number of cycles. Typical locations for low cycle fatigue damage include the transverse bulkhead and support structures on vessels performing a large number of loading and offloading cycles (e.g. shuttle tankers, product carriers, FPSOs, lightering vessels). In these cases the differential heads across the transverse bulkheads, as the individual cargo and ballast tanks are loaded and unloaded, generate large cyclic stresses in the transverse bulkhead structure. In the case of lightering vessels and shuttle tankers these differential heads can be exacerbated by pitching and rolling motions of the vessel (see Figure 44 below):

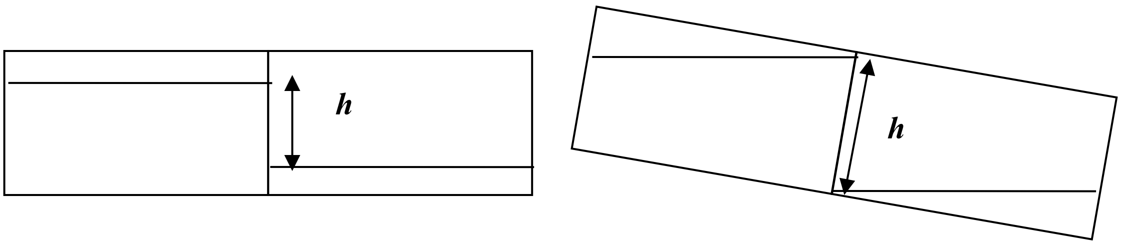


Figure 44 Effect of vessel pitching on differential head

The simplified fatigue analysis required by the CSR does not examine low cycle fatigue and so additional spectral fatigue analysis using a finite element model of the structure is required. Recommendations for equivalent stress levels and related S-N curves to be used and combination of high cycle and low cycle effects in the fatigue assessment should be clarified with the respective classification society.

5.2.4 Trade Routes

As described in section 3.3.2.1 the CSR assumes a vessel will trade solely on a North Atlantic route when calculating fatigue life. This is a more onerous trade route than many Class Societies had applied as their default route prior to the introduction of the CSR and therefore should be a conservative approach for most vessels.

However there are some trade routes that are more injurious in terms of fatigue than the North Atlantic route, for example the northern and southern extents of the Pacific. Shuttle tankers working solely in the northern North Atlantic may also experience a more onerous environment than that assumed by the CSR. This is because CSR’s definition of North Atlantic includes Marsden squares 8, 9, 15 and 16 and assumes equal probability of all wave headings whereas the Shuttle Tanker may be operating almost continually in Marsden square 9 for example and predominantly in head and stern seas.

It is therefore important to consider the vessel’s likely trading pattern at the design stage to identify whether a specific trade route with prevailing wave headings should be specially analyzed in addition to the CSR default.

5.2.5 Loading Conditions

The CSR simplified analysis looks at only the fully loaded and ballast conditions. In the case of product and chemical tankers for example a significant proportion of their time will be spent with partial cargoes. These vessels will therefore be operating in loading conditions which may be more or less onerous, from a fatigue point of view, than the ballast and fully loaded conditions. For these vessel types consideration should be given to including a larger number of loading conditions in the fatigue analysis than required by CSR.

5.2.6 Hull Vibration

Recent investigations have revealed that global vibration of the hull girder can have a significant effect on fatigue damage for certain ship types in certain operational conditions for certain trade routes. The global vibration of the hull girder can originate in two ways, often referred as Springing and Whipping. Springing is the vibration of the hull structure due to resonance with the wave environment. Whipping is the vibration induced from wave impacts/slamming. The effects of Springing or Whipping are not included in the CSR fatigue assessment methodology.

Fatigue damage due to vibration can contribute considerably to the total fatigue damage, depending on vessel geometry, hull girder properties, loading, speed, heading, trading routes and damping. Consideration should be given to the vessel's likely trade routes when compared to the North Atlantic trade routes used for design purposes. The Classification Society should be consulted regarding the impact of Springing and Whipping on a vessel's fatigue life if the North Atlantic scatter diagram is considered non- conservative when compared with the vessel's likely trade routes or where these routes indicate a high probability of Springing or Whipping occurrence.

Other possible excitation sources for vibration in structural details include the propeller and slow running diesel engines.

5.2.7 Use of High Tensile (HT) Steel

Steel having a specified minimum yield stress of 235 N/mm^2 is regarded as normal strength hull structural steel. Steel having a higher specified minimum yield stress is regarded as higher strength hull structural steel (HT). The higher yield stress allows thinner plate to be used thereby reducing lightship weight and newbuild cost. However, whilst HT steel has a higher yield stress than normal strength steel it does not possess better fatigue properties in welded structures. Therefore as the steel is experiencing larger stresses than normal steel, it will endure fewer cycles before fatigue failure occurs.

HT steel corrodes at the same speed as normal steel and so if the HT steel is thinner initially it will lose a relatively larger proportion of its thickness each year due to corrosion. This will then increase the stresses with the HT steel faster than in the normal steel further reducing the relative fatigue performance of HT steel to normal steel.

Where HT steel is being used in areas of cyclic loading the above problems can be mitigated through a combination of effective coating systems (to reduce corrosion), specifying an increased thickness (to lower stresses) which is effective up to a point because of the thickness penalty, careful design of structural details, weld enhancements (grinding, peening etc., ref. 5.4.1) and requiring a more detailed fatigue analysis (e.g. spectral).

5.2.8 Hull Outfitting

Deck outfit items, such as pipe run supports, manifold drip trays, deck stores and access manholes, attached to or penetrating the deck can act as stress raisers, significantly decreasing the fatigue life of main deck welds. For example the fatigue life of a main deck weld can be halved if an access manhole or doubling pad is located within 100mm of the deck weld seam.

The precise location of outfit items is not normally known at the design phase and so it is often up to the site team building the ship to ensure that penetrations and pads are kept clear of deck seams. However, requirements can be included in a build specification to limit the creation of these stress raisers, e.g. 'penetrations for access manholes and pads for deck outfit to be kept at least 100mm clear of any deck weld seams'. Documentation related to location and details of outfitting on deck should be submitted by shipyard to the owner at an early stage of the design phase.

5.2.9 Corrosion Protection

Whether a structural element is protected from its environment has an impact on its fatigue life. The corrosive atmosphere found in ballast and cargo tanks will result in a reduction in steel thickness of an unprotected element, an associated increase in stress and thus a reduction in fatigue life.

In CSR, during the 25 year design life, it is assumed that corrosion protection is partially effective, i.e. that joints in way of water ballast, oil cargo hold and fuel oil holds, are efficiently protected against corrosion during a certain amount of time and during the remaining part of the design life, they are exposed to corrosive environment because the corrosion protection is more questionable. During the effective corrosion protection period, the steel surface is protected from the corrosive environment. Then, the steel may be considered to be as in dry air condition. In this case, the fatigue strength may be assessed with the S-N curves in-air, Pt 1, Ch 9, Sec 3, [4.1.4] for the effective corrosion protection. During the remaining life when the joint is subjected to corrosive environment, fatigue strength may be assessed with the S-N curves in corrosive environment, Pt 1, Ch 9, Sec 3, [4.1.5]. Then, design life may be divided into one interval with protected environment condition and one interval with unprotected environment condition. Each of these intervals is divided into different loading conditions depending on each ship's type.

5.3 Enhanced Details Design

5.3.1 Weld improvement

It is typical to find fatigue defects initiating at the toes of welds, often due to a stress concentration resulting from poor weld profile in this area. This poor profile can be removed through post weld treatment. It is generally recommended that such post fabrication improvement methods be reserved as an additional or remedial measure to enhance fatigue life, and that emphasis should be given to having good basic scantlings and good detail design.

However it is recognized that such weld improvement methods used in combination with scantlings improvements offers a more practical approach in way of some locations, such as angled cruciform joints, than by scantlings improvement alone e.g. by fitting very thick inserts, or where effectiveness of detail design improvement may be limited.

The CSR require the calculated fatigue life in way of the hopper knuckle joint to be at least 17 years determined without any consideration of the weld improvement effects. It also requires weld improvement to be applied in way of the hopper knuckle joint irrespective of calculated fatigue life to improve the reliability.

Weld improvement is also required in way of the cruciform joint between the inner-hull longitudinal bulkhead and the oil-tight transverse bulkhead at the heel of the bulkhead horizontal girder where a backing bracket is not fitted.

The CSR do not however permit any benefit to be claimed from such improvement in way of longitudinal stiffeners based on the premise that practical improvement can and should be achieved by scantlings and detail design consideration.

Several post weld treatment methods that will increase the fatigue life are available. The most common methods are:

5.3.1.1 Weld Profiling by Machining and Grinding

Weld profiling is a weld geometry modification and defect removal improvement method where the weld face is machined and given a concave shape by profile grinding. The stress concentration is reduced and potential harmful defects are removed. Weld profiling will have an influence on the hot spot stress, dependent upon the grinded weld radius, the angle between weld and parent plate and the plate thickness. This approach will need to be considered with care to ensure that there is sufficient initial weld thickness such that the profiled weld area satisfies the throat thickness requirement and sufficiently long weld leg length such that the profiled weld does not form an indented groove which attracts stress.

5.3.1.2 Weld Toe Grinding

Weld toe grinding should normally only be applied on full penetration welds, if applied on partial penetration welds, the final fatigue life of the complete weld joint including weld root should also be confirmed by fatigue calculations.

Weld toe grinding is normally performed by using a rotary ball shaped burr with a diameter in the range of 10-14 mm. The grinding needs to be performed so the weld toe and the plate display a shallow concave shape. The depth of the grinding should normally be 0.5 mm below any visible undercut, the minimum needed in order to remove toe defects caused by the welding process. Care should be exercised not to over-grind. The primary aim is to remove or reduce the size of the weld toe flaws and to reduce the local stress concentration due to the weld toe flank angle. Correctly applied weld toe grinding has been demonstrated in laboratory conditions to improve the fatigue life by a factor between 2 and 3.5, depending on the yield stress; but for CSR approval purposes, the improvement factor cannot be taken above 2.

5.3.1.3 Welds Machined Flush

Excessive weld reinforcement (i.e. weld cap) can act as a stress concentration and reduce the fatigue life of a weld. IACS Guidelines and Recommendation 47 recommend that the height of the weld cap is limited to not greater than 6mm.

Machining a butt weld flush with the plate surface will give a better S-N class due to removal of the stress concentration caused by the weld overfill. The surface should also be proven free from defects through NDT. A typical D class butt weld may then be reclassified to a C class butt weld. Such measures are sometimes required in way of butt weld terminations on a plate edge in conjunction with smooth grinding of the corners and on the cut surface of the plate.

5.3.1.4 TIG Dressing

TIG dressing is a weld toe re-melting method using tungsten inert gas (TIG) where the welding toe is re-melted in order to give a smooth transition between the plate and the weld and where also non-metallic contaminants such as slag intrusions are melted and removed. TIG dressing will increase the fatigue life by a factor between 2 and 3.5, depending on the yield stress.

5.3.1.5 Hammer,Ultrasonic and Needle Peening

Hammer, ultrasonic and needle Peening is a residual stress method where it is necessary not only to remove tensile stresses but also to introduce compressive stresses of sufficient magnitude in fatigue critical areas in order to obtain improvements in fatigue strength. Peening techniques use manually operated portable equipment to create a residual compressive stress in the weld toe and a smooth transition between the weld toe and parent material. The imposed compressive stress results in subsequent cyclical stressing of the weld toe having some part within the compressive range, which will not contribute to fatigue damage. In addition, the resulting concave shape at the weld toe reduces the stress concentration in the toe region. Peening methods may increase the fatigue life by a factor between 2 and 3.5, depending on the yield stress.

It should be noted that the improvement methods referred to above are only relevant to fatigue failures initiating from the weld toe. Peening methods will normally give improved fatigue performance in the high cycle region, while the effect in the low cycle region is regarded as minor. It is also important to notice that the method should be avoided in areas with high compressive stresses, because the residual stress field set up, can be neutralized and destroyed. Peening is not recognized as a weld improvement method by CSR.

5.3.1.6 Combination of Weld Improvement Methods

Compounding two or more weld improvement methods can give very large improvements in fatigue strength. This can be used in situations when extra fatigue strength is needed to avoid extensive re-design when a damaged structure is to be repaired.

5.3.2 Structural Enhancement

Careful detail design can greatly improve the fatigue life of a connection. The following are some suggestions:

5.3.2.1 Keyhole shaped Heel scallops and Backing Brackets

Where a soft-nosed bracket has been used to improve the fatigue life of a connection it can result in the heel of the bracket becoming the fatigue hotspot. The fatigue life of the bracket heel can then be improved through the adoption of a keyhole shaped scallop or the fitting of a backing bracket (see Figure 45). The use of keyhole heels on longitudinal stiffeners below the loaded waterline is now relatively common as is the use of backing brackets at the connection of longitudinal stiffeners to transverse bulkheads. However, backing brackets can also be used at the connection of stringers to transverse bulkheads and in way of lower hopper connections to inner bottoms. In the latter applications with the back brackets becoming load carrying members, care should be taken to ensure proper bracket sizing and edge preparation such that fatigue cracks will not initiate on the bracket edge.

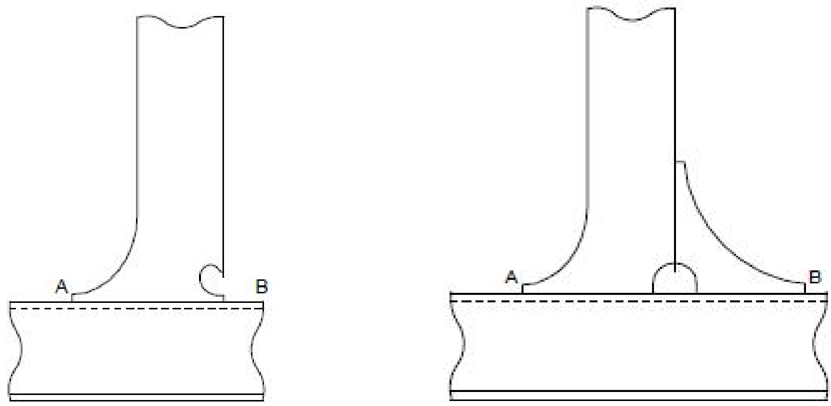


Figure 45 Examples of keyhole type heel connection (left) and backing bracket (right)

5.3.2.2 Symmetrical Stiffeners

The fatigue life of an attachment welded to the face of a longitudinal stiffener can be increased by the use of a symmetrical profile instead of an asymmetrical profile (see Figure 46) assuming both have the same Rule section modulus. When subjected to lateral loading, the rotated neutral axes will mean an asymmetrical stiffener experiences a larger stress in the short side of the flange when compared with a symmetrical stiffener and thus a shorter fatigue life.

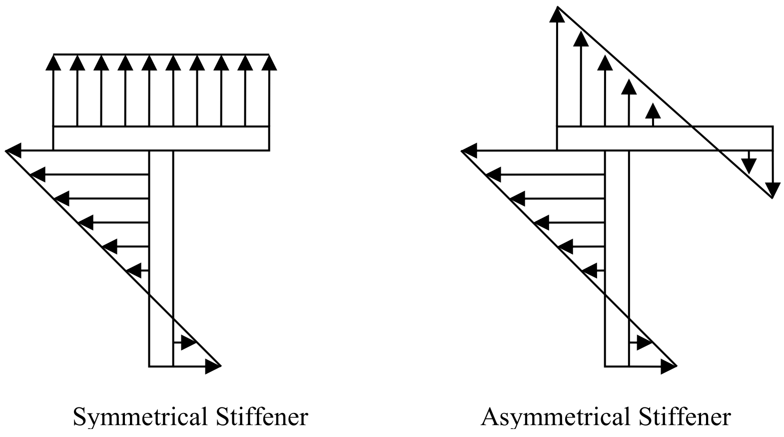


Figure 46 Stress Distribution of a Symmetrical and Asymmetrical Member

5.3.2.3 Continuity of Structure

Continuity of structure is important when trying to maximize the fatigue life of a vessel. Care should be taken to ensure gradually tapered thickness and cross sectional area transitions and scarphing of structure.

5.3.2.4 Slots, Scallops and Drain Holes

Care should be taken when designing and locating scallops and drain holes, areas of high stress should be avoided. Where scallops are unavoidable for the construction of the ship, they should be as small as possible and closed with a collar in way of areas of high stresses. Scallops and drain holes should be kept clear of fatigue critical cruciform joints and toes of pillar stiffener connections and tripping brackets. Where this is unavoidable the opening should be closed with a pad (See Figure 47 below). Requirements for air and drain holes and scallops are included in the CSR Pt1, Ch 3, Sec 6, [6.1].

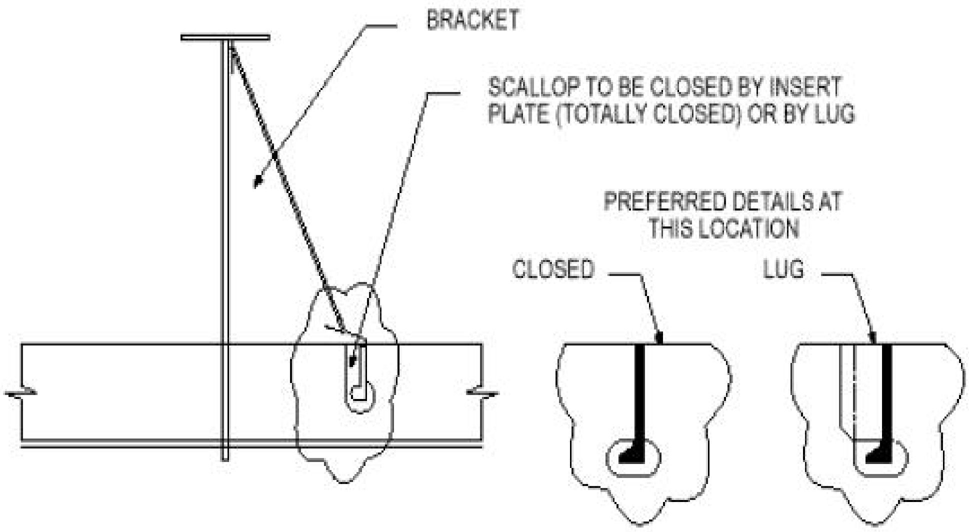


Figure 47 Scallops and drain holes in this location should be avoided or closed.

Two kinds of end connections between longitudinal stiffeners and transverse frames are normally offered for ship structures. These are:

- Connections where web stiffeners are fitted and welded to the longitudinal face plate

- Connections where web stiffeners are not fitted or not welded to the longitudinal face plate.

However, in the latter case, sniped buckling stiffeners are normally welded to the web plates, but typically 50-100 mm offset to the longitudinal penetration, or oriented differently.

Connections where web stiffeners are welded to the longitudinal face plate are often fitted with an additional bracket or a soft nose termination and are commonly offered by shipyards today.

An end connection without a web stiffener will normally, for identical scantlings, introduce a higher nominal end bending moment and shear force to a longitudinal subjected to lateral pressure, due to a longer effective span. As the effective supporting area between the longitudinal and the web frame also is reduced when the web stiffener is disconnected from the longitudinal face, the load transferred between the longitudinal web and the transverse member in shear will increase. Great care should therefore be given to the design of the cut out in the web frame, and the corresponding shear area in order to control the stress level and the corresponding hot spots. CSR has therefore introduced recommendation for design of end connections of longitudinals, for designs where web stiffeners are not connected to the face, ref. Figure 49.

For end connections where web stiffeners are connected to the face, ref. Figure 48, hotspots for cracks developing at the welded connection between the stiffener toe or heel and the longitudinal (or alternatively between the bracket toe or heel and the longitudinal) are deemed more likely and critical than those at the scallop (in the circumference of the cut out or at the collar plates).

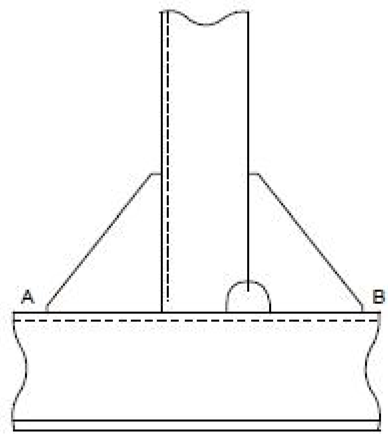


Figure 48 End connection with web stiffener (and brackets) included

For end connections where web stiffeners are not connected to the longitudinal face, ref. Figure 49, the location of the hotspots will be changed and will normally be introduced in way of the scallop (in the circumference of the cut out or at the collar plates). Hot spots may also be introduced at the end connection of the offset web stiffener. In such cases it may increase confidence by doing a supplementary fatigue check of the scallop hot spots and at the end connections of the eccentric web stiffeners in way of joints with high lateral loads e.g. wetted side, despite that the CSR has made the fitting of cut-outs with enhanced shape virtually a requirement for such connections at such areas.

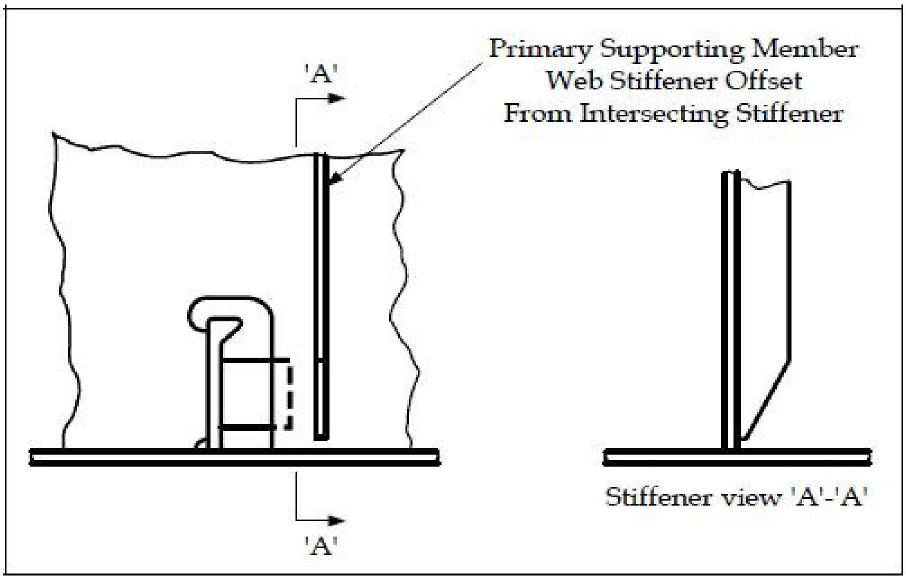


Figure 49 End connection with offset web stiffeners

Location and shape of slots/scallops will have a great influence on fatigue life for such connections. In general, slots/scallops should be avoided in areas with high cyclic stresses. However, in circumstances where this cannot be avoided, great care should be given to the local design as indicated in Figure 50.

For the same reason CSR also gives recommendation to design of welded connection for deck stiffeners in way of block joints. In general scallops will introduce a stress concentration, and CSR recommends one of the following options to remove or reduce the hot spots, ref. Figure 51:

- Offset between the deck butt weld and the corresponding scallop and the butt on the deck stiffener
- Elongation of the scallop on the stiffener (will reduce the stress concentration in the scallop)
- Close the scallop by means of a collar

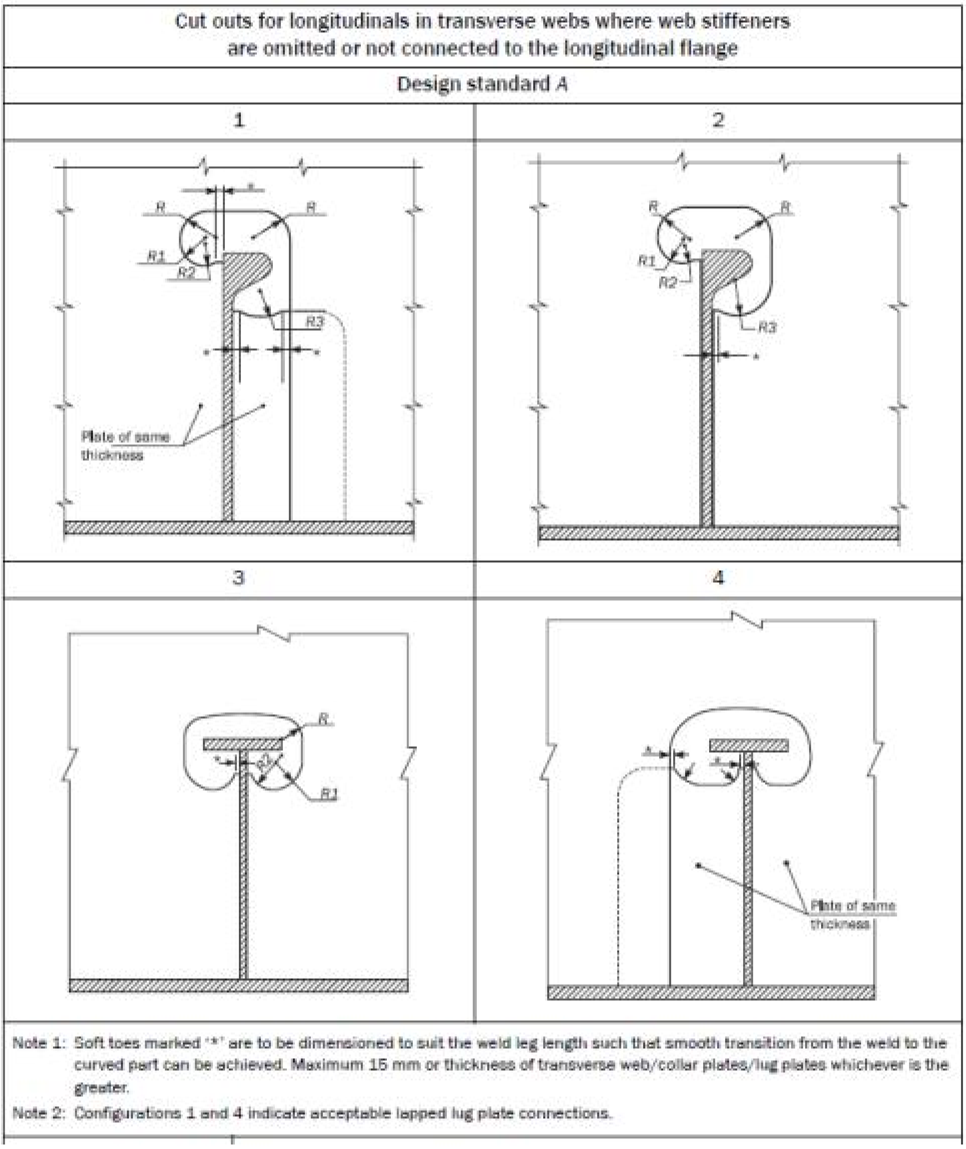


Figure 50 Design of cut-outs in cases where web stiffeners are omitted.

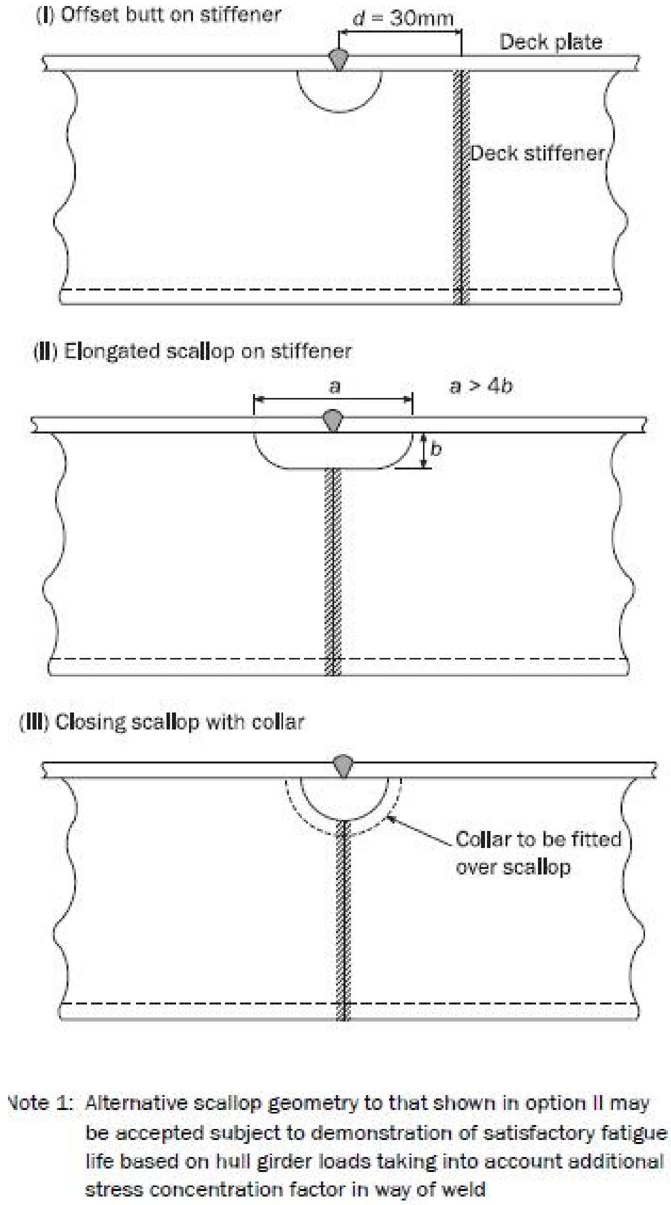


Figure 51 Welding of deck stiffeners in way of block joints.

5.3.2.5 Full Penetration Welding

A simple method of improving the fatigue life of a "load carrying" welded joint is to specify full penetration welding. The full penetration weld provides a more uniform stress flow and removes the possibility of crack initiation at the weld root. When combined with weld toe grinding this can typically increase the fatigue life when compared with a double continuous fillet weld by a factor of two.

Another advantage of using full penetration welding instead of double continuous or partial penetration is that it allows the final weld to be examined using Ultrasonic Testing. This enables sub-surface defects to be identified and repaired before they initiate a crack in service.

Full penetration welding will normally be a class requirement in way of load bearing joints susceptible to root cracking and deep penetration welding will generally be specified in way of less susceptible load bearing joints, but suggestions for additional locations where full penetration welds may be considered include:

- Hopper knuckles in way of primary support members
- BHD Stool knuckles in way of girders
- ILBHD/OTBHD joint in way of BHD horizontal girder heel
- Transverse frame bracket toes
- Stringer bracket toes
- Ends of bilge keels
- Deck penetrations

5.3.2.6 Alignment

Fatigue life calculations for some welded connections, such as butt joints and cruciform joints, assume a certain level of misalignment is present. If the degree of misalignment can be reduced the rotation of the weld under load is reduced and fatigue life is increased. For example the IACS Shipbuilding and Repair Quality Standard recommend an alignment of t/3 or better for a cruciform joint, where t is the thinner member. Some class procedures also specify an upper value of, say, 5mm in way of critical joints.

It is generally recommended that buttering (correction of misalignments by use of welding beads) at misalignments is avoided

5.3.2.7 Knuckles

Where a discontinuity exists it is recommended that a supporting stiffener or bracket is provided as per Figure 52 below. Knuckles in areas of high stress should be well supported, preferably by continuous stiffeners along the knuckle line. The CSR have requirements for the maximum distance between the knuckle and supporting member. The stress concentration factor due to the knuckle will be reduced as the distance between them is reduced.

Typical location of knuckles are inner side, hopper and top wing tank panels of double hull tankers outside the parallel midship area. In some cases knuckles of different structural members (e.g. stringers and panels) are crossing each other and causing complicated connections where great care should be taken to ensure acceptable stress levels.

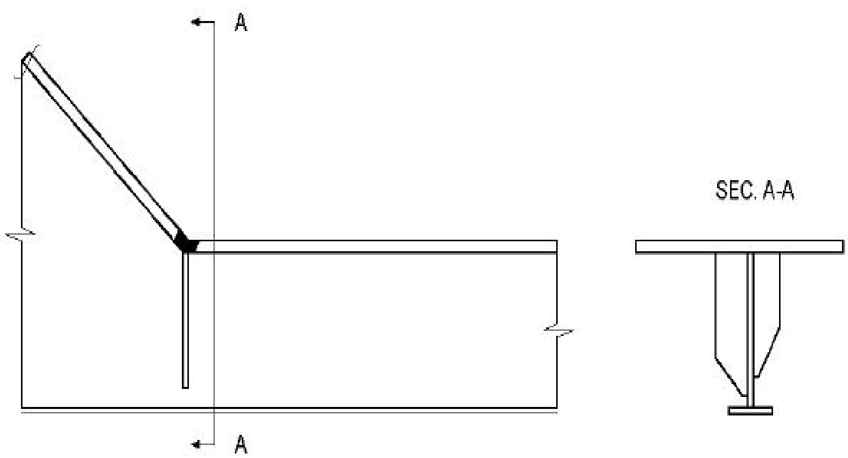


Figure 52 Supporting bracket provided at discontinuity

5.4 Non Destructive Testing (NDT)

Typical fatigue crack initiators include weld defects such as lack of sidewall fusion, lack of inter-run fusion, lack of penetration, cold lap, etc.. Many of these defects can be detected using differing forms of NDT, the type of NDT used depending on the nature of the defect and whether it is surface-breaking or sub-surface. For sub-surface defects UT is the preferred option. However UT is not suitable for fillet welds and so here Magnetic Particle Inspection (MPI) may be used.

It is generally recommended to increase the extent of NDT during the newbuilding stage, beyond the minimum requirements of the Classification societies. Such additional NDT should be performed in relevant high dynamically stressed and crack prone areas, making due reference to the Rule and additional fatigue calculations where available, which may typically include locations such as:

- Hopper knuckles
- BHD Stool knuckles in way of girders
- Stringer terminations/brackets/heels
- Transverse frame terminations/brackets
- Cross tie terminations/brackets
- Attachments/penetrations in the hull envelope
- Ends of bilge keels
- Selected longitudinal stiffeners end connections to transverse frames and bulkheads
- Areas where weld improvement methods have been applied should be subjected to 100% NDT (MPI) to ensure that there are no remaining/new surface defects.

Appendix 1 - References

References Ch 1

CSR

CSR Background documents

TSCF manuals

References Ch2

/2-1/ Fatigue Handbook; A.Almar-Næss, Tapir 1985

/2-2/ Fatigue Life Analyses of Welded Structures; Tom Lassen and Naman Recho; ISTE 2006

/2-3/ DNV-RP-C203 Fatigue design of Offshore Steel Structures; 2010

/2-4/ DNV Classification Note 30.7 Fatigue Assessment of Ship Structures 2010

/2-5/ ABS The Criteria to Adapt SafeHull system to FPSO Applications; 2004

/2-6/ Rechnerishe Eermüdungsnachweise für gescheisste Bauteile; Peter Knödel, 2006

/2-7/ IACS: Common Structural Rules for Bulk Carriers and Oil Tankers

/2-8/ Presentation: Utmattingsstyrke – dominerende faktorer ved sprekkvekst; 2009. Prof. P.J. Haagensen, NTNU, Norway.

References Ch 3

IACS Recommendation 34

IACS CSR Background Document Section 7

References Ch 4

/4-1/ TSCF Guidance Manual for Tanker Structures, 1997

/4-2/ TSCF Guidelines for the Inspection and Maintenance of Double Hull Tanker Structures, 1995

Appendix 2 - Additional Class Notations (Valid 2016) – Fatigue

ABS:

ABS offers an optional fatigue notation for tankers with a design fatigue life in excess of the 25 years required by CSR. 5C-1-1/1.2 of the Steel Vessel Rules outlined the requirement. Note that the passage has been modified to reflect the change from 20 to 25 years that accompanied the adoption of the CSR:

Vessels designed and built to the requirements in this Chapter are intended to have a structural fatigue life of not less than 25 years. Where a vessel's design calls for a fatigue life in excess of the minimum design fatigue life of 25 years, the optional class notation FL (year) will be assigned at the request of the applicant. This optional notation is eligible, provided the excess design fatigue life is verified to be in compliance with the criteria in Appendix 1 of Part 5C, Chapter 1 of the Steel Vessel Rules, “Fatigue Strength Assessment of Tankers”. Only one design fatigue life value is published for the entire structural system. Where differing design fatigue life values are intended for different structural elements within the vessel, the (year) refers to the least of the varying target lives. The 'design fatigue life' refers to the target value set by the applicant, not the value calculated in the analysis.

The notation FL (year) denotes the design fatigue life assessed according to Appendix 1 is greater than the minimum design fatigue life of 25 years. The (year) refers to the fatigue life equal to 30 years or more (in 5-year increments) as specified by the applicant. The fatigue life will be identified in the Record by the notation FL (year); e.g., FL(30) if the minimum design fatigue life assessed is 30 years.

Where a spectral fatigue analysis is performed satisfactorily in accordance with an acceptable procedure and criteria, and the vessel is built in accordance with plans approved on the basis of the results of such analysis, the vessel will be distinguished in the Record by the notation SFA (year). The notation, SFA (year), denotes that the designated fatigue life value is greater than the minimum design fatigue life of 25 years or greater. The (year) refers to the designated fatigue life equal to 30 years or more (in 5-year increments) as specified by the applicant.

BV:

The fatigue requirements are defined in the BV Rules.

The requirements apply for ships with a length equal to or greater than 170m for non CSR ships, and for container ships of length greater than 150m. Fatigue methodlogy in BV Rules is based on the hot spot stress approach.

In addition, Bureau Veritas published in September 2016 new Guidance note NI 611 – Guidelines for fatigue assessment of steel ships and offshore units, which gather state of the art methodology for fatigue assessment.

The following topics are detailed to allow to perform fatigue calculation on any type of unit with a wide variety of possible approaches:

- Load definition: rule based (reference load at given probability level), Spectral or time domain calculation, including intermittent wetting correction
- Reference stress for fatigue calculation: different methods are detailed, from hot spot stress analytical approach for longitudinal stiffeners or tubular joints, to FEA stresses for both welded (hot spot stress) or non-welded (local nominal stress) joints

- Specific section defines a methodology to evaluate reference stress for root cracking assessment
- S-N curves are given considering different environment: in-air, under free corrosion and under corrosion with cathodic protection. For each type of detail (plated joints, cut edges, tubular joints) and corresponding reference stress.
  In addition, specific guidance is detailed for the definition of design S-N curves obtained from fatigue testing.
- The different factors affecting the fatigue life are detailed, such as thickness effect, effect of material yield strength, misalignment, mean stress and workmanship and the methodology for taking those effect into account is detailed, by correction on the S-N curve parameters in view of fatigue damage calculation
- Fatigue damage calculation is then based on cumulative damage using Miner's sum principle
- A procedure for performing fatigue assessment based on crack propagation is also given
- In addition, a detailed appendix provides the state of the art methodology for fatigue calculation performed with direct hydro-structure calculations, either spectral or time domain simulations. This may be used for Spectral fatigue calculation of for springing calculations using time domain simulations.

The structural details which are to be checked for fatigue are defined in tables (BV Rules Pt B, Ch 11, Sec 2 & Pt D, as relevant), depending on the ship type and on the hull area where the details are located.

With respect to the method to be adopted to calculate the stresses acting on structural members, the details for which the fatigue check is to be carried out may be grouped in 2 categories:

- Details where the stresses are to be calculated through a three dimensional structural model (e.g. connections between primary supporting members)
- Details located at ends of ordinary stiffeners, for which an isolated structural model can be adopted (simplified analysis).

The fatigue criteria are based on a cumulative damage ratio estimated from the hot spot stresses calculated in net scantling, for several load cases and loading conditions associated with a given reference probability for loads depending on the ship type.

The Rules consider a fatigue design life of 20 years. However an additional class notation has been implemented to allow a fatigue check over those 20 years design life.

The additional class notation VeriSTAR-HULL is completed by FAT and may be completed by xx years, with xx having values between 25 and 40, when a fatigue assessment has been carried out on selected structural details showing that their evaluated design fatigue life is not less than xx years.

The additional class notation VeriSTAR-HULLFAT xx years may be assigned to ships of less than 170 m in length, subject to special consideration.

CCS:

Class Notation: Compass (F)

This notation is assigned to the design details on a vessel which have been checked using China Classification Stru-Safety Solutions software. The notation is defined in Rules for classification of sea-going steel ships Part 1, Chapter 2, Appendix 1, Table E and Guidelines for fatigue strength of ship structure outlined the requirement separately.

Rules for classification of sea-going steel ships:

For ships the design of which has been checked using China Classification Stru-Safety Solutions software, one or more of the following suffixes R, D and F are to be added. Meanings of the suffixes are as follows:

F: For ships of which hull structure fatigue assessment has been performed using the hull structure fatigue calculation program (FATIGUE) of hull structure and safety solution (China Classification Stru-Safety Solutions).

Technical requirements to be complied with are in the Software for hull structure and safety solution (China Classification Stru-Safety Solutions).

Guidelines for fatigue strength of ship structure:

1.1.4 The class notation COMPASS (F) may be assigned to classed ships complying with the assessment requirements of the Guidelines.

1.2.2 The fatigue strength assessment for oil tankers with CSR class notation is to be carried out in accordance with relevant provisions of PART NINE of Rules for Classification of Sea-Going Steel Ships.

1.2.3 The fatigue strength assessment for bulk carriers with CSR class notation is to be carried out in accordance with relevant provisions of PART NINE of Rules for Classification of Sea-Going Steel Ships.

DNVGL:

The method and procedures for fatigue assessment is given in the guideline DNVGL-CG-0129, *Fatigue assessment of ship structure*.

For oil tanker and chemical tankers with length between 90 m and 150 m, fatigue assessment is mandatory. The fatigue strength calculations shall be carried out for at least the following locations:

- Longitudinal stiffener end connections in midship area
- Lower hopper knuckle connections forming boundary of the inner skin amidships

The fatigue loads are at 10^{-2} level based on the Equivalent Design Wave concept similar to CSR. The minimum fatigue target is 25 years based on the World Wide scatter diagram unless otherwise specified.

For tankers of length 150 m or more, CSR applies.

In case of additional fatigue assessment is requested, the class notations Plus, CSA(FLS1), CSA(FLS2), CSA(1) or CSA(2) may be used. The fatigue strength evaluation shall be carried out based on the target fatigue life and service area specified by the CSR (150m ≤ L) or the relevant notation for the type of tanker in question (90m ≤ L < 150m).

Class Notation: Plus covers additional requirements for the fatigue life of hull structural details. The fatigue assessment is based on the rule loads given in CSR (150m ≤ L) or in the DNV GL rules Pt.3 Ch.4 (L < 150m). The Plus notation is intended for vessels operating in harsh areas and includes extended scope of fatigue strength verification for hull structural details.

The effect of low cycle fatigue shall be included in the assessment for details subjected to large stress variations during loading and unloading operations.

The following details in the cargo area shall be considered in the fatigue strength assessment in addition to those required for other class notations, see also guideline DNVGL-CG-0152, *Plus*:

- Longitudinal stiffener-frame connections located in the bottom, inner bottom, side and inner side including connected web stiffener, cut out and collar plate.

- Deck plating in way of stress concentrations from openings, scallops, pipe penetrations and attachments
- Bottom and side shell plating connection to frames and stiffeners
- Stringer heels and toes where relevant

Plus may be combined with any of the Computational Ship Analysis (CSA) notations. Details being scope for both CSA and Plus shall be checked in accordance with the requirements of CSA, i.e. with direct loads and not rule loads. Details being defined as scope for Plus and not for CSA, e.g. longitudinal stiffener - web frame connections, shall be checked in accordance with the requirements of Plus, i.e. with rule loads.

Class Notations: CSA(FLS1), CSA(FLS2), CSA(1) and CSA(2) are based on directly calculated loads, i.e. Computational Ship Analysis (CSA). These notations are based on direct calculations of the wave loads and finite element calculations of the full ship model and extended fatigue control, see also guidelines DNVGL-CG-0130, *Wave load analysis* and DNVGL-CG-0127, *Finite element analysis.*

The loading conditions for fatigue strength assessment shall be based on ballast and full load and part load conditions. Sea keeping and hydrodynamic load analysis shall be carried out using 3-D potential theory, with possibility of forward speed. Non-linear theory shall be used for design waves for ULS assessment, where non-linear effects are considered important. Response amplitude operators (RAOs, transfer functions) and time histories for motions and loads shall be calculated. The inertia loads and external and internal pressures calculated in the hydrodynamic analysis shall be directly transferred to the global FE structural model.

A Stochastic (spectral) fatigue analysis is performed for longitudinals/plating and other critical locations within the cargo hold area.

CSA(FLS1) fatigue scope is full stochastic analysis of the following details:

- Lower hopper knuckle amidships, foremost hold and aftmost hold
- Upper hopper knuckle amidships, foremost hold and aftmost hold
- Stringer heels and toes amidships, foremost hold and aftmost hold

CSA(FLS2) fatigue scope is:

- End connections of longitudinals assessed with component stochastic method based on tabulated stress concentration factors
- Bottom and side shell plating connection to stiffener and frames, with component stochastic method
- Strength deck plating i.w.o. openings and attachments, full stochastic analysis
- Scope as defined for CSA(FLS1)

CSA(1) has the same fatigue scope as CSA(FLS1) and CSA(2) has the same fatigue scope as CSA(FLS2). In addition to the fatigue assessment CSA(1) and CSA(2) also include an ultimate strength analysis related to yield and buckling capacity and hull girder strength.

KR:

Class Notation : SeaTrust (FSA1, FSA2, FSA3)

These notations are defined in Annex 3-3 of Part 3 hull structure, “Guidance for the fatigue strength assessment of ship structures”. Ships with CSR notation are to be complied with Part 13 of rules for the classification of steel ships, “Common structural rules for bulk carriers and oil tankers”.

The structural members to be assessed for fatigue strength are selected considering the structural system of the ship, and importance, functions, etc. of the members. Following details shall be considered and additional fatigue assessment may be required for other locations where deemed necessary by KR.

- Connection of longitudinal stiffeners with web frames and transverse bulkhead in bottom, inner bottom, side shell, inner skin and upper deck
- Primary members such as hopper knuckle connection, connections of transverse bulkhead to inner bottom, toe of horizontal stringer, bracket toe of transverse web frame
- Large openings

The following Class Notations are assigned based on the corresponding assessment methods:

- SeaTrust(FSA1) uses a simplified approach based on beam theory and tabulated stress concentration factors to evaluate the fatigue strength of the longitudinal end connection.
- SeaTrust(FSA2) is based on hold FEA to determine hot spot stress at weld toe of specified structural details.
- SeaTrust(FSA3) is applied to new type of ships or ships requiring more precise fatigue strength assessment. Spectral fatigue analysis or transfer function method apply to global FEA for fatigue analysis.

LR:

Class Notation: ShipRight (FDA plus).

Assignment of this notation denotes that the design details on a vessel have been based on LR’s spectral analysis based fatigue procedures. For ships with CSR Notation such fatigue analysis will be carried out in addition to the basic fatigue analysis within CSR. The “FDA plus” notation is intended for application where the Owner or Builder wishes to take additional measures to ensure the risk of fatigue failure is minimised.

The fatigue requirement of the “FDA plus” notation is different to the basic class assessment in these aspects:

- The scope of calculations can be increased with respect to structures to be assessed
- The ship responses and wave loads will be derived from hydrodynamics calculations
- The wave conditions encountered by the ship will be derived from analysis of trading routes, ship’s speed and heading using global wave scatter diagrams, or specified equal probability all headings for specified sea areas e.g. per IACS Recommendation 34.
- The number of design stress cycles will be determined based on the wave conditions encountered by the ship.
- The total fatigue damage will be calculated as the sum of short term fatigue damages sustained in each encountered wave condition.

The minimum design fatigue life associated with assignment of “FDA plus” notation to ships approved in accordance with IACS Common Structural Rules depends on the wave environment specified as follows:

1. Minimum 25 years fatigue life using the North Atlantic wave environment
2. Owner’s specified years of fatigue life (minimum 25 years) using the Fatigue wave environment (worldwide) trading pattern for the ship type, and
3. Owner’s specified years of fatigue life (minimum 25 years) using Owner's specified trading pattern

It also has the flexibility to investigate additional loading patterns, loading conditions, cargo specific gravity, low cycle effects etc. as necessary.

“FDA plus” include spectral fatigue analysis of stiffener/frame connections as well as critical primary structure elements. The design load conditions include the ballast, full load as standard and part loading conditions should the intended operation require this.

As an essential complement to the fatigue assessment whether or not the ShipRight (FDA plus) notation is requested, the ShipRight (CM) notation (Construction Monitoring) is a requirement for oil tankers complying with the CSR. This notation will ensure a higher level of construction tolerance in way of the fatigue critical joints at the plan approval stage and a higher level of confidence during the construction stage.

NK:

"Notation: PS-FA (PrimeShip-Fatigue Assessment)

This means ship's fatigue strength assessment has been carried out on the structural details of areas where stress is concentrated, such as joints of longitudinals, and transverse members; girder members connecting side shell plating or bulkheads; and discontinuous structures according to the procedures given by the Society's Guidelines for Fatigue Strength Assessment.

Notation: PS-TA (PrimeShip-Total Assessment)

This means ship's comprehensive fatigue assessment together with the yielding strength assessment and the buckling strength assessment has been carried out using design loads obtained by direct load analysis according to the procedures given by the Society's Guidelines for Fatigue Strength Assessment.

Additional abbreviation may be attached if special design conditions are requested to be considered additionally."

RINA:

For ships other than CSR vessels, according to RINA Rules fatigue requirements are mandatory for ships greater of 150 m in length and are based on the notch stress approach.

The structural details to be subjected to fatigue checks are defined in RINA Rules, Pt.B, Ch.12, Sec.2; mainly the details are grouped taking into account the ship type and their location.

Two main categories of details where fatigue checks are required are identified in the rules:

- Details where the stress range is to be calculated by means of a three dimensional FEM model (e.g. connection of inner bottom with hopper tank sloping plates)
- Details of end connections of ordinary stiffeners to primary supporting member where a simplified approach considering beam theory and tabulated stress concentration factors is deemed acceptable

The requirements are based on a minimum requested fatigue life of 20 years.

In case where a higher fatigue life is requested the additional class notation “FATIGUE LIFE (Y)” may be assigned. (Y) is the required fatigue life in years according to the yard/owner request and in general is to be greater than 20 years; for ships with service notations bulk carrier ESP CSR or oil tanker ESP CSR, (Y) is to be greater than 25 years. The fatigue calculations are carried out using RINA software LH2D and LH3D.