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Comparative Fatigue Behavior of Structural Details of VLCC's

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ABSTRACT

The paper deals with the comparison of the fatigue behaviour of a typical structural detail of crude oil tankers, made either of mild steel or of higher tensile steel. Calculations are based on the use of S-N curves and Miner cumulative damage rule.

The analysis aims at calibrating the procedure for assessment of fatigue strength set up by Bureau Veritas.

To conclude, the paper gives recommendations for further research to validate or improve the preliminary results of the fatigue analysis.

1. GENERAL

Among the factors which contribute to the structural failures observed on ships in service, fatigue may be considered as one of the most significant.

Though fatigue does not generally result in catastrophic failures, its impact on the cost of ship maintenance is important due to frequent and costly repair works.

Experience shows that fatigue cracking is occurring on inadequate structural details due either to improper design for the loads expected in service or to bad workmanship.

In the recent years, research works carried out to optimize ship structures have resulted in extensive use of higher tensile steels, not only for longitudinal deck and bottom structures but also for transverse structures such as web frames and transverse bulkheads.

Since fatigue properties of welded structures are not improved with increased yield stress, the use of higher tensile steels has been questioned by the shipping community, arguing that shorter life may be anticipated, all the more as corrosion margins have been simultaneously reduced.

This paper aims at comparing the theoretical fatigue behaviour of a typical structural detail of a Suez max tanker, made either of mild steel or of higher tensile steel.

To carry out this comparative study, the connection of tripping brackets of bottom transverses to longitudinals has been selected (see Fig. 1).

Fatigue behaviour of structural details is affected by many factors, such as :

- geometry of the members or weld details producing stress concentrations,
- loading (static loads, wave induced loads, impact loads, thermal loads, residual stresses, etc.),
- materials and welding procedures,
- workmanship,
- environmental conditions,
- corrosion rate.

Only some of them are considered in the present analysis, in particular :

- geometry of the members,
- loading, and
- materials.

At that stage, neither influence of environmental conditions nor that of corrosion rates is examined.

The method used is based on S-N curves and application of the Miner cumulative damage rule.

2. DETERMINATION OF THE CAPACITY OF THE STRUCTURE

2.1. The fatigue strength of welded joints is characterized by S-N curves which give, for a probability level of rupture p, the relationship between cyclic stresses and the number of cycles to rupture.

Experimental S-N curves show existence of a fatigue limit below which the number of cycles to rupture is infinite. Marine structures are subjected to random loads exceeding this fatigue limit, which enables initial cracks to grow and propagate while the fatigue limit decreases.

Consequently, actual fatigue limit cannot be defined. To take into account this phenomenon, the mean S-N curve (See Fig. 2) is represented by two different formulae :

$$S^m N = C_{50} \quad \text{for } N \leq 10^7 \qquad (1)$$

$$S^{m+2} N = C'_{50} \quad \text{for } N > 10^7 \qquad (2)$$

where :

S is the nominal stress range as shown in Fig. 3,

N number of cycles to rupture,

C_{50}, C'_{50} and m are constants which depend on :

. material,
. weld type,
. mean and residual stresses,
. environmental conditions (air or sea water).

When the sample is subjected to N cycles of stress range S, the preceeding equations mean that the sample would fail with 50 % of probability.

For a probability of rupture p, the S-N curve is given by :

$$S^m N = C_p$$

$$\log C_p = \log C_{50} - K_p s_d \quad (3)$$

where s_d is the standard deviation of log C_{50} and K_p a coefficient depending on the probability level p and the number of samples considered to determine the mean S-N curve, see Fig. 4.

The level of probability p is to be selected according to the risk associated with the structural failure.

For the structural detail considered in the present analysis, the probability of rupture p is taken as 10 %.

From Fig. 5 which gives the relationship between K_p and p, for a probability of rupture equal to 10 %, $K_p = 1{,}3$.

2.2. As indicated in paragraph 2.1., the coefficient C_{50} depends on the static and residual stresses, which may be represented by the ratio :

$$R = \frac{S_{min}}{S_{max}}.$$

Experimental S-N curves are generally determined for R greater than 0,7, so that effects of static and residual stresses due to welding are taken into account

As a first approximation, the actual stress ratio R taking account simultaneously of static and residual stresses is assumed to be within the range of the experimental one.

Consequently, only the stress range S is considered in the present analysis

2.3. Selection of S-N Curve

Many experiments have been performed to determine S-N curves of basic local details in air.

Data considered in the present analysis are obtained from reports issued by the Welding Institute of Cambridge (UK) :

. "Fatigue design rules for welded steel joints", by T. R. GURNEY

. "Application of fatigue design rules for welded steel joints", by K. G. WYLDE.

From data provided by the Welding Institute and for the structural detail considered, Fig 6 gives the class of S-N curve to be used versus the direction of applied stresses.

Following table gives the values of m, C_{50} for the classes of S-N curves indicated in Fig. 5.

Class	Slope m	C_{50}	Standard deviation of log C
C	3,5	$1{,}082\ 10^{14}$	0,2041
D	3	$3{,}988\ 10^{12}$	0,2095
F	3	$1{,}726\ 10^{12}$	0,2183
F_2	3	$1{,}231\ 10^{12}$	0,2279

2.4. Determination of Stresses

Determination of the fatigue strength of the selected structural detail (see Fig. 1) makes necessary to calculate the stresses in the face plate of the bottom longitudinal, in the vicinity of the bracket toe.

To take account of the geometry of the member and consequently of the stress concentration factor (SCF) in the area concerned, stresses are to be appraised thanks to a finite element model.

Due to the large number of loading cases necessary to determine the long term distribution of stresses (see paragraph 3.), it was decided after several unsuccessful attempts using 3D models of the web frame and longitudinal stiffeners, to use a simplified 2D finite element model, as shown in Fig. 7, to represent the connection of longitudinals to bottom transverses.

From Fig. 7, it may be seen that, in way of the connection of tripping bracket to the bottom longitudinal, a fine mesh model has been used. The size of membrane elements is approximately 50 x 50 mm so that stresses can be calculated accurately.

Stresses considered to assess the fatigue strength are calculated as follows :

$$\sigma = \sigma_2 + \frac{\sigma_2 - \sigma_1}{2} \quad (4)$$

where σ_1 and σ_2 are the stresses in the face bar of the bottom longitudinals (detail A), as shown in Fig. 8.

Similar calculation may be carried out for detail B.

Table I gives the main particulars of the two structural finite element models.

3. DETERMINATION OF THE SHIP LOADING HISTORY

3.1. As said in paragraph 1 above, the ship structure is subjected to several types of cyclic loads which are of concern in the fatigue strength of the structure :

wave induced loads (quasi static)
dynamic loads (impact loads, vibrations),
still water
thermal loads.

The present analysis deals with static and quasi-static loads only. It has been considered that dynamic loads or high frequency loads such as slamming and whipping may be avoided by reducing speed and/or changing ship course.

Table I

Particulars	Mild Steel Structure	Higher Tensile Steel Structure
Spacing of web frames	5,1 m	5,1 m
Spacing of longitudinals	0,85 m	0,85 m
Depth of bottom transverses	3,5 m	2,5 m
Bottom longitudinals		
web	650 x 13	525 x 11,5
face plate	150 x 32	180 x 25
Tripping brackets		
web thickness	11,5	11,5
face plate	200 x 15	200 x 15
width	1,15 m	1,05 m

3.2. Long Term Distribution of Stresses

The determination of the long term distribution of stresses necessitates, in principle, that direct analysis of the ship behaviour at sea be carried out with a view to calculating the wave-induced stresses.

Following calculations are necessary to determine ship motions and wave loads :

- determination of transfer functions,
- short term response,
- long term response.

Based on the results of these calculations, the wave induced stresses and long term distribution of stresses, including stresses due to local bending, may be calculated using a similar procedure.

Obviously, such complex and time consuming calculations cannot be used as a standard procedure to assess the fatigue strength of structural details.

A further objective of this research study was to define a procedure of calculation of the long term distribution of stresses, as simple as possible and based on the direct application of BV rules for loads determination.

The procedure applied to the structural detail selected for the present study, is summarized hereafter :

a) from the loading manual, selection of the basic loading conditions. The full load and ballast conditions may be generally considered as representative of the ship loading,

b) for each basic loading condition, external and internal loads applied on the structure are determined for the head seas and beam seas conditions as specified in BV rules. Figures 9 and 10 summarize the elementary loading cases to be considered to determine the long term distribution of stresses.

It may be noted that these loading cases are those considered when verifying the scantlings of the primary structure.

In order not to consider too severe and unrealistic loads when calculating the stress range, extreme internal and external loads are not considered simultaneously. When internal loads are extreme, i.e. take account of dynamic effects, external loads are assumed to be static and vice-versa (refer to Fig. 9 and 10).

c) calculations are carried out for two probability levels of wave induced loads equal to 10^{-5} and 10^{-8} respectively.

d) for each probability level, the stress range is determined as follows, refer to Fig. 9 and 10 :

. head seas $S_1 = \max. (S_{11}, S_{12})$

. beam seas $S_2 = \max. (S_{21}, S_{22})$

Taking account of the simplified 2D finite element model, each elementary loading case as shown in Fig. 9 and 10 may be considered as the combination of both following cases :

- hull girder bending, and

- lateral uniform pressure.

From these calculations, the long term distribution of stresses may be determined for each basic loading condition (full load and ballast conditions) and for head seas and beam seas conditions, as shown in Fig. 11.

4. ASSESSMENT OF THE FATIGUE STRENGTH

4.1. Assessment of the fatigue strength is based on the direct application of the Miner cumulative damage rule.

The Miner sum may be expressed as follows, without corrosion :

- the damage contributed by one cycle of stress range S_i is equal to $\frac{1}{n(S_i)}$,

  where $n(S_i)$ is the number of cycles to rupture under a constant amplitude stress range S_i,

- by superposition, the total damage D caused by stress ranges $S_1, S_2 \dots S_i$ applied $n_1, n_2 \dots n_i$ cycles respectively, is given by :

$$D = \sum_{i=1}^{i=n} \frac{ni}{n(S_i)} = \frac{N_t}{C} \int_0^{\infty} S^m f(S)\, dS \qquad (5)$$

where

- ni is the number of cycles for stress range S_i,
- $n(S_i)$ the number of cycles to rupture for $S = S_i$,
- N_t number of wave cycles in the life of ship,
- $f(s)$ probability density function for the long term stress range,
- n, C coefficients of the S-N curve.

If the probability density function may be represented by a Weibull distribution, the cumulative fatigue damage ratio is given by :

$$D = \frac{Nt}{C} S_o^m Ln(Q)^{-m/K} \Gamma(1 + \frac{m}{K}) \qquad (6)$$

where

- S_o stress range corresponding to the probability level of exceedance Q,
- Γ Gamma function ($\Gamma(n) = (n-1)!$)
- K Weibull shape parameter.

If the Weibull shape parameter is taken as 1 (straight line in a decimal-log diagram), the damage cumulative ratio may be expressed by :

$$D = \frac{Nt}{C} (\frac{S}{Ln(Q)})^m \Gamma(1 + m) \qquad (7)$$

The fatigue cracking occurs when the cumulative damage ratio is equal to 1.

To calculate the damage ratio D, the basic loading conditions (full load and ballast conditions) and the sea states (head seas and beam seas) are assumed to be equi-probable.

Consequently, the cumulative fatigue damage ratio may be given by

$$D = \sum_{i=1}^{i=n_h} \sum_{j=1}^{j=nc} (\frac{nj}{n(Sj)})_i \qquad (8)$$

where

- n_h number of equi-probable long term distributions of stresses as shown in Fig. 11 ($n_h = 4$),
- n_c number of steps of equivalent length in log N.

If the probability density function of the long term stress range is represented by a Weibull distribution, with K = 1, the cumulative fatigue damage ratio is given by :

$$D = \sum_{i=1}^{i=n_h} \frac{Nt}{n_h C} (\frac{Si}{Ln(Q)})^m \Gamma(1 + m) \qquad (9)$$

5. APPLICATION TO THE SELECTED DETAIL

5.1. Presentation of the Main Results

It does not fall within the framework of this paper to give all the details of the calculations necessary to determine the long term distributions of stresses.

As said in paragraph 3.2., stresses at the connection of tripping brackets to bottom longitudinals are calculated from a 2D finite element model for the two following elementary loading cases :

- hull girder bending, and
- lateral uniform pressure.

Main results are summarized in Table II for details A and B shown in Fig. 1, where x and y represent longitudinal and vertical directions respectively.

The detail of calculations carried out for the structural detail A are summarized in Tables III and IV for a probability level of 10^{-5}.

Similar calculations may be performed for a probability level of 10^{-8} and for detail B.

5.2. Long Term Distributions of Stresses

The long term distributions of stresses as obtained from the results of calculations (refer to paragraph 5.1.) are given in Fig. 12 to 17 for details A and B :

5.3. Cumulative Fatigue Damage Ratio

5.31. As said in paragraph 2.4., the class of S-N curve to be considered for assessment of the fatigue strength depends on the direction of applied stresses.

Table V gives the characteristics of S-N curves for each of the structural details A and B.

5.32. Examination of Fig. 12 to 17 shows that the long term distribution of stresses is linear in a decimal-log diagram with a weibull shape parameter equal to 1.

Consequently, the damage ratio D may be calculated according to formula (9). Results of calculations are given in Table VI.

6. CONCLUSION

6.1. Application of the procedure described in the present paper and summarized in Fig. 18, enables to assess and compare the fatigue strength of a typical structural detail made either of mild steel or of higher tensile steel :

6.2. However, prior to any conclusion concerning the actual fatigue life of the structural detail examined, further investigation is necessary to calibrate the method by carrying out similar calculations on other critical structural details, all the more as several assumptions were made to perform the study.

Table II

Elementary Loading Case	Detail A		Detail B	
	Mild steel	HTS	Mild steel	HTS
Hull girder bending	$SCF_x = 1.1$	$SCF_x = 1.1$	$SCF_x = 1.1$ $SCF_y = 0.4$	$SCF_x = 1.1$ $SCF_y = 0.4$
Uniform pressure downwards (p = 100 KN/M)	$\sigma_x = -9$ MPa	$\sigma_x = -5$ MPa	$\sigma_x = 50$ MPa $\sigma_y = 56$ MPa	$\sigma_x = 64$ MPa $\sigma_y = 71$ MPa

Table V

S-N curve	- Detail A - Detail B (longitudinal direction)	- Detail B (transverse direction)
Class	F_2	F
m	3	3
C_{50}	$1{,}212\ 10^{12}$	$1{,}726\ 10^{12}$
sd	0,2279	0,2183
C	$6{,}126\ 10^{11}$	$8{,}979\ 10^{11}$

Table VI

Cumulative Damage Ratio	Detail B Detail A		Detail B Long direction		Vert direction	
	Mild Steel	HTS	Mild Steel	HTS	Mild Steel	HTS
D	0,87	2,4	1,5	3,85	0,16	0,4

In particular, additional calculations are to be performed using a 3D finite element model to validate the results of the 2D model.

6.3. Calculations were carried out for a total number of cycles equal to 10^8 which corresponds to a ship life of 25 years about.

Examination of Table VI shows that the cumulative damage ratio of the mild steel detail B is greater than 1 for that fatigue life of 25 years, which shows that the method used is possibly too conservative.

If one assumes that the mild steel structure does not fail during the ship life, the HTS structural detail considered in the analysis might be subject to fatigue cracking between the second and third special surveys, ie between 10 and 15 years.

However, based on experience in service, this structural detail seems to have a longer fatigue life.

6.4. As said in paragraph 2.2., only the stress range has been considered to calculate the fatigue damage ratio.

Influence of mean stresses on the fatigue life has to be examined, all the more as there is some relaxation of residual stresses with time. Experimental tests carried out for different R values show that C coefficients of S-N curves increase while the R ratio decreases (S-N curves used in the analysis are based on a R ratio greater than 0.7).

In particular, influence of mean compressive stresses which is not taken into account in the analysis is to be investigated more in detail.

6.5. The design of structural details influences significantly the fatigue life of ship structures.

For the detail examined in the present analysis, the reduction of the stress concentration factor from 1.1. down to 1 improves the fatigue life by 30 %.

6.6. Moreover, further investigation is necessary to appraise the influence of corrosion and workmanship (quality of welds, constructional tolerances, ...) on the fatigue life of usual structural details.

REFERENCES

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" Cyclic Fatigue of Welded Joints on Steel Ships "
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" Fatigue Characteristics of Fabricated Ship - Detail for Design "
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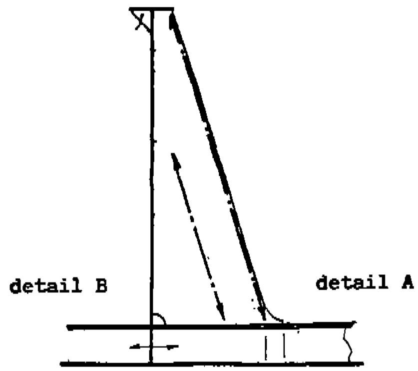


Fig. 1

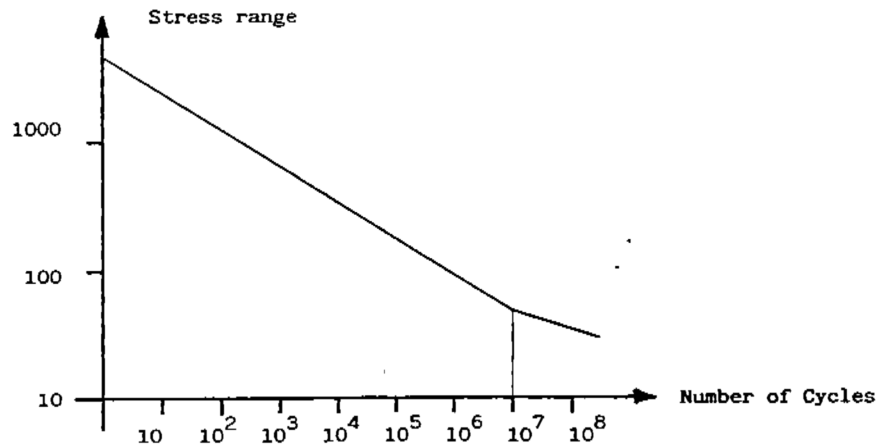


Fig. 2

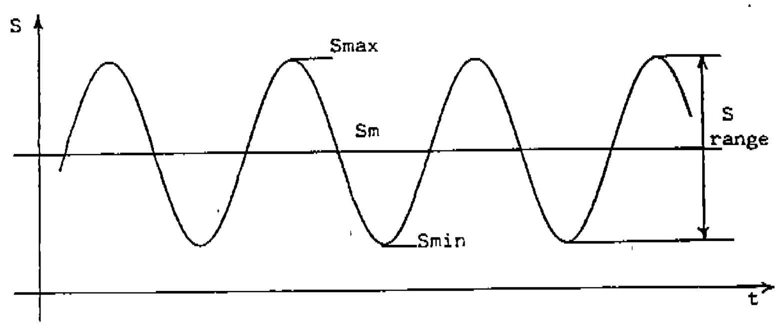


Fig. 3

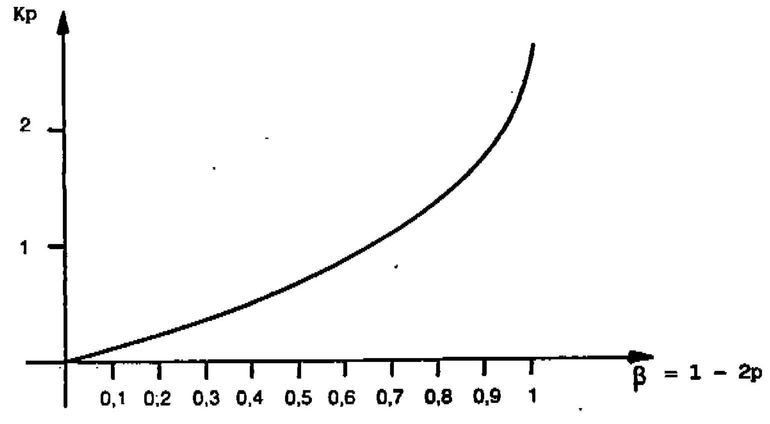


Fig. 5

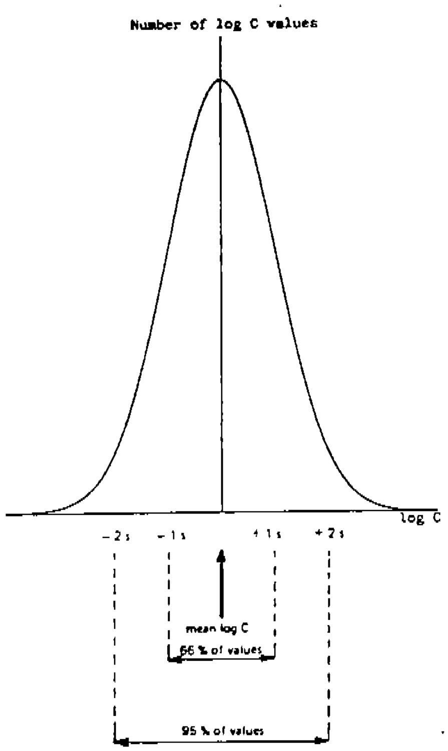


Fig. 4 - Typical log C distribution

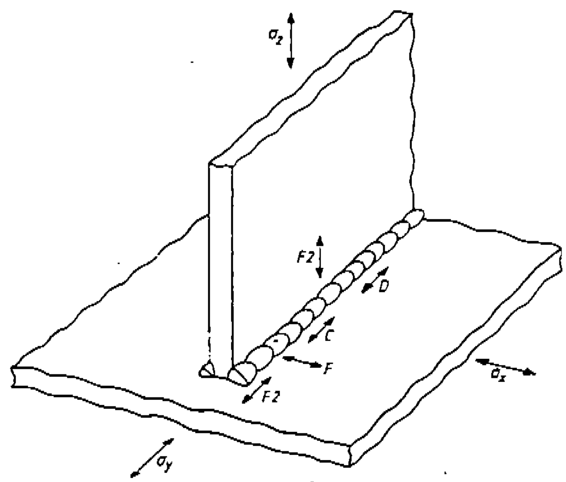


Fig. 6

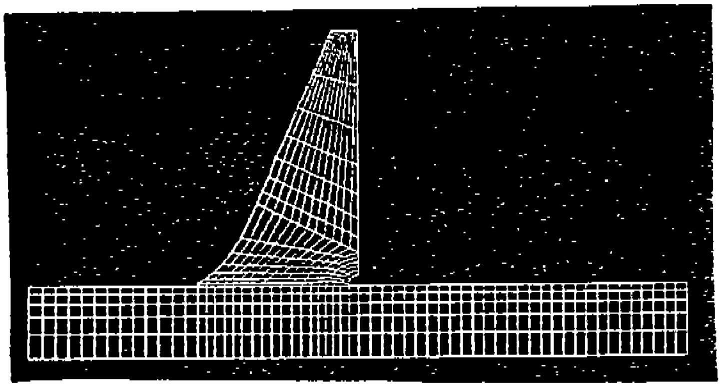


Fig. 7

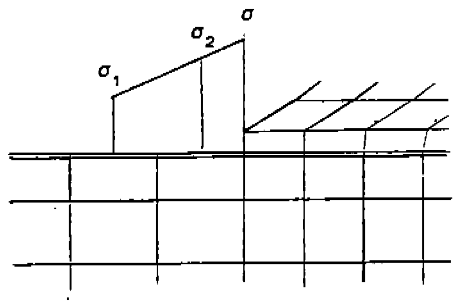


Fig. 8

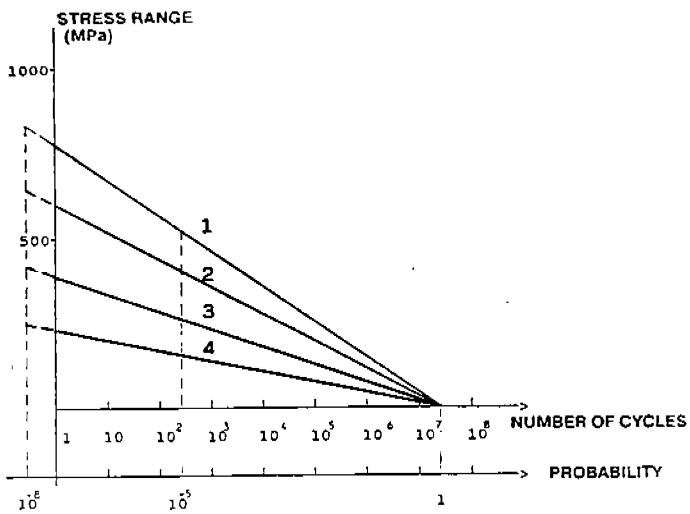


Fig. 11

(1) full load - head seas
(2) ballast - head seas
(3) full load - beam seas
(4) ballast - beam seas

Detail A

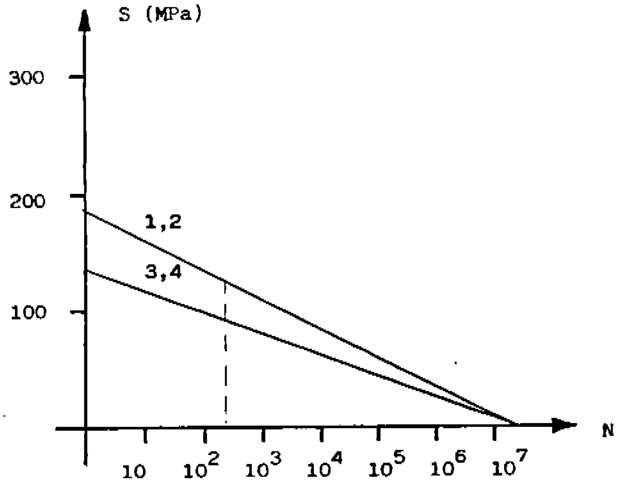


Fig. 12 - Mild Steel

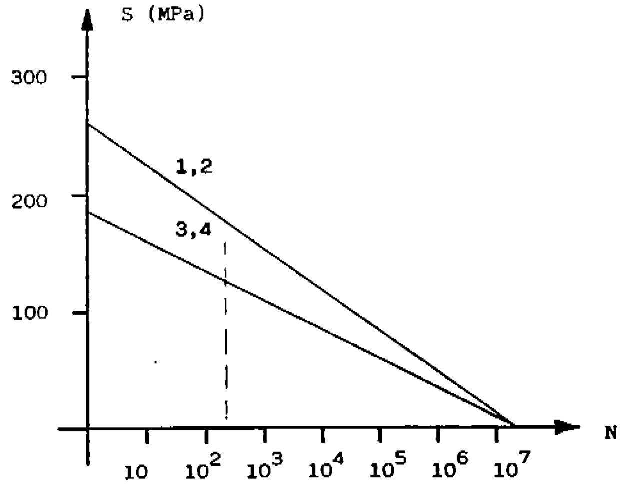


Fig. 13 - HTS

Detail B (Longitudinal direction)

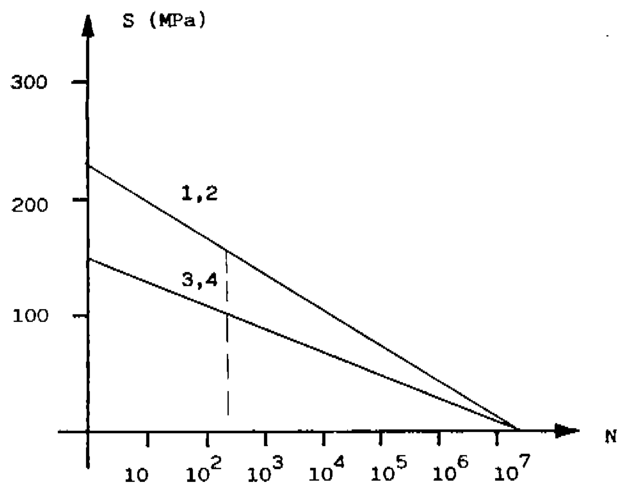


Fig. 14 - Mild Steel

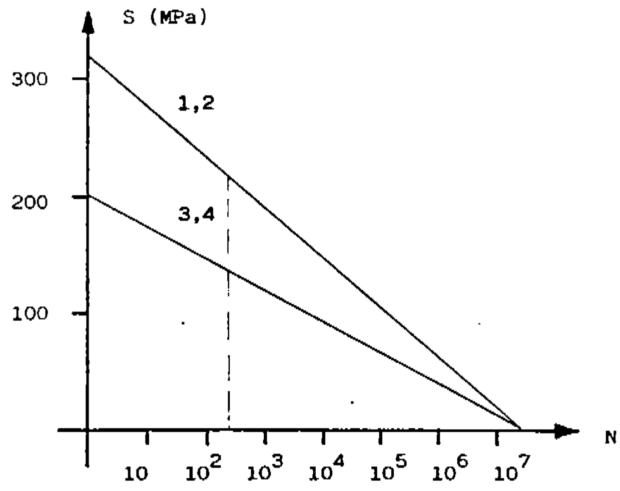


Fig. 15 - HTS

Detail B (Vertical direction)

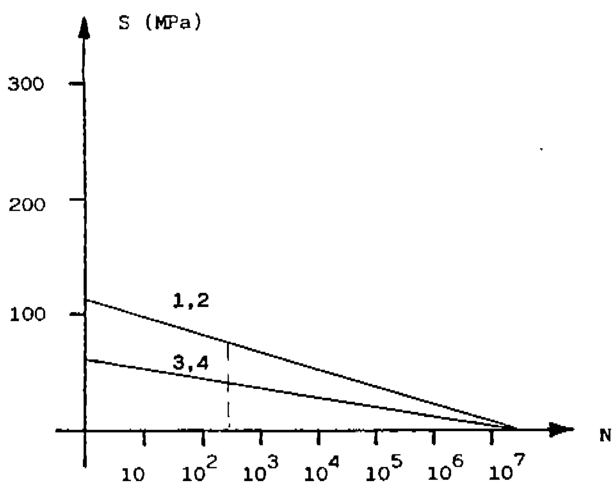


Fig. 16 - Mild Steel

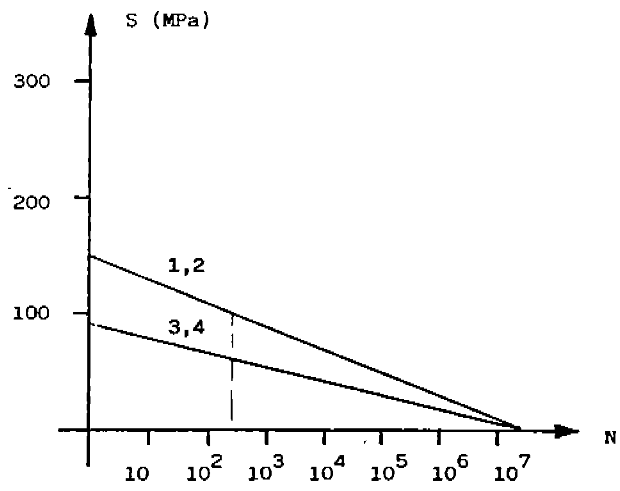
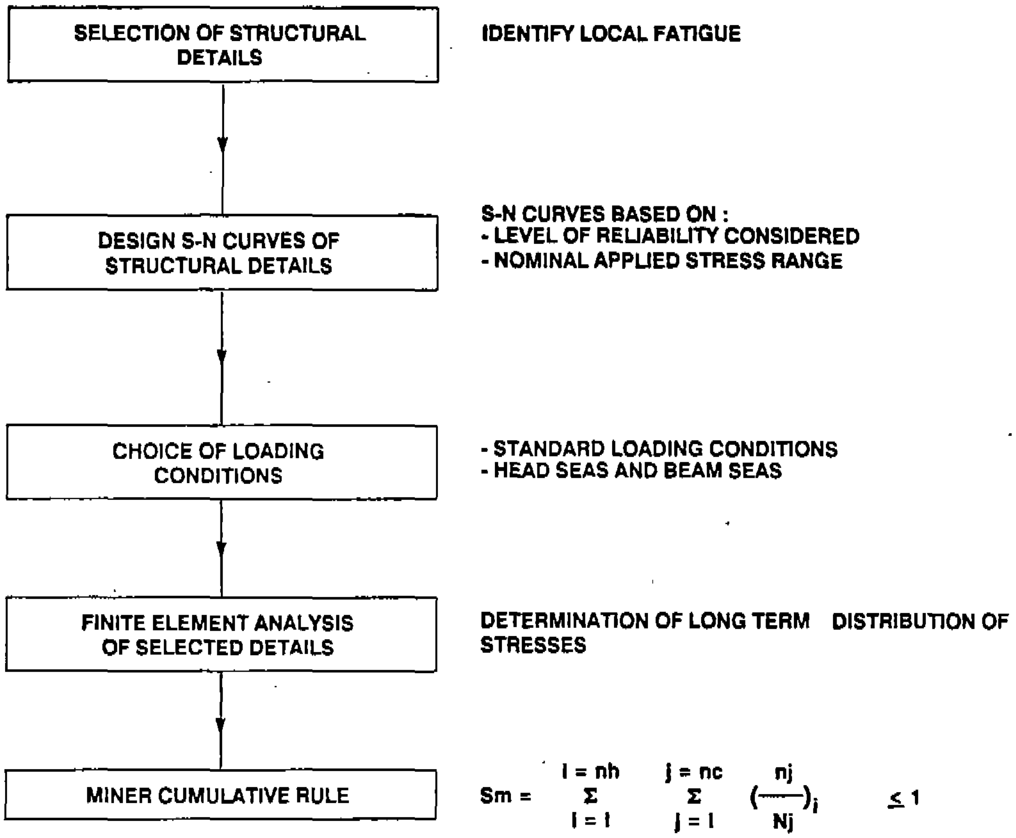


Fig. 17 - HTS

Fatigue Assessment Procedure



$$Sm = \sum_{i=1}^{i=nh} \sum_{j=1}^{j=nc} \left(\frac{nj}{Nj}\right)_i \leq 1$$

Fig. 18

Head Seas

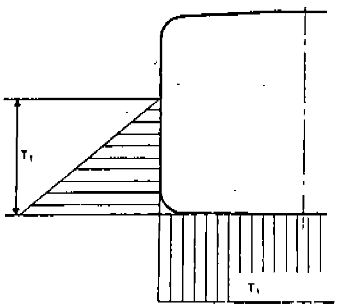
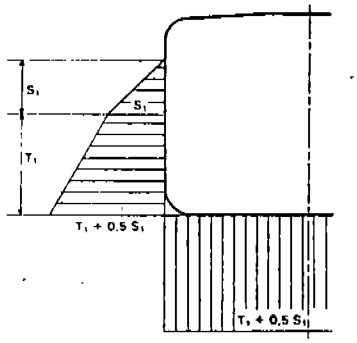
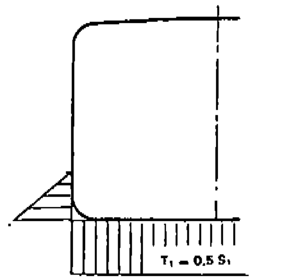
STATIC SEA PRESSURE DYNAMIC CARGO LOADS	SHIP ON CREST OF WAVE STATIC INTERNAL LOADS	SHIP ON TROUGH OF WAVE STATIC INTERNAL LOADS
HULL GIRDER BENDING : . STILL WATER	HULL GIRDER BENDING : . STILL WATER . HOGGING WBM	HULL GIRDER BENDING : . STILL WATER . SAGGING WBM
SEA LOADS $h = T - Z$ 	SEA LOADS $h = T + 0.5\,SM - Z$ 	SEA LOADS $h = T - 0.5\,SM - Z$ 
CARGO LOADS $h = h_{stat} \pm h_{dyn}$	CARGO LOADS $h = h_{stat}$	CARGO LOADS $h = h_{stat}$
STRESS RANGE $S_{11} = \sigma_{max} - \sigma_{min}$	STRESS RANGE $S_{12} = \sigma_{max} - \sigma_{min}$	

Fig. 9

Beam Seas

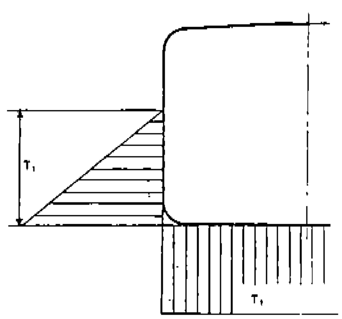
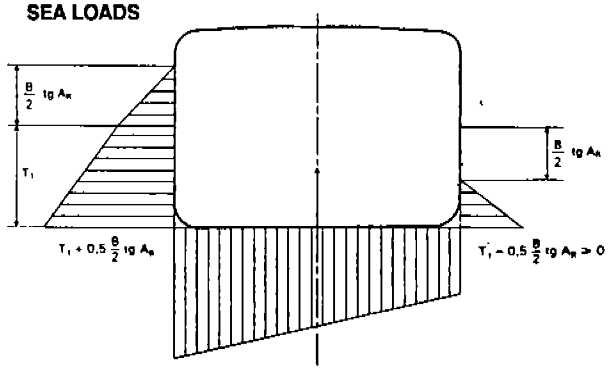
STATIC SEA PRESSURES DYNAMIC INTERNAL LOADS	DYNAMIC SEA PRESSURES STATIC INTERNAL LOADS
HULL GIRDER BENDING . STILL WATER	HULL GIRDER BENDING . STILL WATER . 60 % OF MAX. HOGGING OR SAGGING WBM
SEA LOADS 	SEA LOADS 
CARGO LOADS . STARBOARD $h = h_{stat} + h_{dyn}$. PORTSIDE $h = h_{stat} - h_{dyn}$	CARGO LOADS $h = h_{stat}$
STRESS RANGE $S_{21} = \sigma_{max} - \sigma_{min}$	STRESS RANGE $S_{22} = \sigma_{max} - \sigma_{min}$

Fig. 10

Table III - Detail A - Mild Steel Configuration

Probability level $p = 10^5$	Full load Condition				Ballast Condition			
	Head Seas		Beam Seas		Head Seas		Beam Seas	
	(11)	(12)	(21)	(22)	(11)	(12)	(21)	(22)
Hull Girder Bending Stress								
$(\sigma b)max$	61,3	121,7	61,3	103,6		-87		-69,8
$(\sigma b)min$	61,3	4,2	61,3	21,4		30,5		12,4
Max pressure (KN/m)	114,6	90	112,5	69,6		-83,8		-70
Min pressure (KN/m)	31,2	34,2	36,3	54,6		-38		-51,7
Max local stress $(\sigma_l)_{max}$	-10,3	-8,1	-10,1	-6,2		7,5		6,3
Min local stress $(\sigma_l)_{min}$	-2,8	-3,1	-3,2	-4,9		3,4		4,6
$\sigma_{max} = (\sigma_l)_{max} + SCF \times \sigma_b$	64,6	125,8	64,2	109		-88,2		-72,2
$\sigma_{min} = (\sigma_l)_{min} + SCF \times \sigma_b$	57,1	1,5	57,3	17,3		36,9		19,9
$S = \sigma_{max} - \sigma_{min}$	7,5	124,3	6,9	91,7		125,1		92,1

Table IV - Detail A - HTS Configuration

Probability level $p = 10^{-5}$	Full load Condition				Ballast Condition			
	Head Seas		Beam Seas		Head Seas		Beam Seas	
	(11)	(12)	(21)	(22)	(11)	(12)	(21)	(22)
Hull Girder Bending Stress								
$(\sigma b)max$	85,2	169	85,2	143,9		-120,8		-97
$(\sigma b)min$	85,2	5,9	85,2	29,7		42,4		17,2
Max pressure (KN/m)	114,6	90	112,5	69,6		-83,8		-70
Min pressure (KN/m)	31,2	34,2	36,3	54,6		-38		-51,7
Max local stress $(\sigma_l)_{max}$	-5,7	-4,5	-5,6	-3,5		4,2		3,5
Min local stress $(\sigma_l)_{min}$	-1,6	-1,7	-1,8	-2,7		1,9		2,6
$\sigma_{max} = (\sigma_l)_{max} + SCF \times \sigma_b$	92,1	181,4	91,9	155,6		-128,7		-104,1
$\sigma_{min} = (\sigma_l)_{min} + SCF \times \sigma_b$	88	4,8	88,1	29,2		48,5		22,4
$S = \sigma_{max} - \sigma_{min}$	4,1	176,6	3,8	126,4		177,2		126,5