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Marine Structures 19 (2006) 83–96

MARINE STRUCTURES

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Assessment of fatigue capacity in the new bulk carrier and tanker rules

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Received 18 August 2005; accepted 18 March 2006

Abstract

During 2004 and 2005 new design rules for bulk carriers and tankers were proposed. The rule proposals were developed in two different projects: The Joint Bulker Project denoted JBP and the Joint Tanker Project denoted JTP. The result from this is that two very different procedures for fatigue assessment of ship structures have been developed. In this paper, the two procedures are reviewed with respect to fatigue capacity. The proposed JBP and JTP analysis procedures have been compared with 200 fatigue test data where the test specimens were subjected to 5 different loading conditions. The procedures are also compared for a typical welded connection subjected to different mean stress levels.

Keywords: Fatigue design rules; Bulk carriers; Tankers; Comparison with fatigue test data; Comparison of rules

1. Introduction

During 2004 and 2005 new design rules for bulk carriers and tankers were proposed. The rule proposals were developed in two different projects:

- The rules for bulk carriers were developed in the Joint Bulker Project (JBP) with participation of the following Classification societies: BV, CCS, GL, NK, RINA, KR and RS.

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0951-8339/$ - see front matter
doi:10.1016/j.marstruc.2006.03.001

- The rules for tankers were developed in the Joint Tanker Project (JTP) with participation of the following Classification societies: ABS, DNV and LR.

The result from this is that two very different procedures for fatigue assessment have been developed. In this paper, the two procedures are reviewed with respect to fatigue capacity. This assessment is based on draft 2 of the JBP procedure from April 2005 [1] and the JTP procedure as presented in 2004 [2]. Both procedures are based on linear elastic structural analysis.

2. Description of analysis procedures

2.1. Description of proposed JBP fatigue analysis procedure

2.1.1. Definition of predominant load case

The JBP procedure implies analysis for the following defined loading conditions:

"homogenous load condition", "alternate load condition" , "normal ballast condition" and "heavy ballast condition". For each loading condition the following load cases are considered: Head sea, following sea and beam sea. Then the JBP procedure implies definition of a predominant load case. The predominant load case "*I*" in fatigue assessment for each loading condition is the load case for which the combined stress range for the considered member is the maximum among the load cases specified in JBP procedure [1]

$$\Delta\sigma_{W,I(k)} = \max_i\{\Delta\sigma_{W,i(k)}\} \tag{1}$$

where $\Delta\sigma_{W,\ i(k)}$ is the hot spot stress range in load case "*i*" of loading condition "*k*", *I* the suffix which denotes different load cases, (*k*) the suffix which denotes loading condition "homogenous load condition", "alternate load condition", "normal ballast condition" or "heavy ballast condition", Ref. [1], *I* the suffix which denote the selected predominant load case for loading condition "(*k*)".

2.1.2. Definition of loading condition "1"

A "condition 1" is defined as the condition in which the maximum stress calculated by equation below for the considered member is the largest on the tension side among the loading conditions "homogenous", "alternate", "normal ballast" or "heavy ballast"

$$\sigma_{\max,1} = \max_k\left\{\sigma_{\text{mean},\,I(k)} + \frac{\Delta\sigma_{W,\,I(k)}}{2}\right\} \tag{2}$$

where $\sigma_{\text{mean},\ I(k)}$ is the structural hot spot mean stress in predominant load case of loading condition "(*k*)", and $\sigma_{W,\ I(k)}$ the hot spot stress range in predominant load case of loading condition "(*k*)".

2.1.3. Equivalent notch stress range

The equivalent notch stress range for each condition is calculated as

$$\Delta\sigma_{\text{eq},j} = K_f\Delta\sigma_{\text{equiv},j} \tag{3}$$

Table 1
Fatigue notch factors

Subject	Fatigue notch factors
Butt welded joint	1.35
Fillet welded joint	1.42
Non welded part	1.00

where j is the suffix which denotes the loading condition after the determination of "condition 1", $\Delta\sigma_{\text{equiv},\,j}$ the equivalent hot spot stress range in loading condition "j", and K_f the Fatigue notch factor defined in Table 1.

2.1.4. Equivalent hot spot stress range

The equivalent hot spot stress range for each condition is calculated as

$$\Delta\sigma_{\text{equiv},j} = f_{\text{mean},j}\Delta\sigma_{W,j} \tag{4}$$

where $f_{\text{mean},\,j}$ is the correction factor for mean stress corresponding to the condition "j":

$$f_{\text{mean},j} = \max\left[0.4, \left\{\max\left(0, \frac{1}{2} + \frac{-\ln(10^{-4})}{4}\,\frac{\sigma_{m,j}}{\Delta\sigma_{W,j}}\right)\right\}^{0.25}\right] \tag{5}$$

$\sigma_{m,\,j}$ = local hot spot stress in condition "j" calculated as

$$\Delta\sigma_{m,\,1} = \begin{cases} R_{eH} - 0.6\Delta\sigma_{W,\,1} & \text{for } \sigma_{\text{res}} + \sigma_{\text{mean},\,1} + 0.6\Delta\sigma_{W,\,1} > R_{eH} \\ \sigma_{\text{mean},\,1} + \sigma_{\text{res}} & \text{for } \sigma_{\text{res}} + \sigma_{\text{mean},\,1} + 0.6\Delta\sigma_{W,\,1} \leqslant R_{eH} \\ -0.18\Delta\sigma_{W,\,1} & \text{for } 0.6\Delta\sigma_{W,\,1} \geqslant R_{eH} \end{cases} \tag{6}$$

$$\Delta\sigma_{m,\,j(j\neq 1)} = \begin{cases} \sigma_{m,\,1} - \sigma_{\text{mean},\,1} + \sigma_{\text{mean},j} & \text{for } \sigma_{m,\,1} - \sigma_{\text{mean},\,1} + \sigma_{\text{mean},j} - 0.24\Delta\sigma_{W,j} > -R_{eH} \\ -R_{eH} + 0.24\Delta\sigma_{W,j} & \text{for } \sigma_{m,\,1} - \sigma_{\text{mean},\,1} + \sigma_{\text{mean},j} - 0.24\Delta\sigma_{W,j} \leqslant -R_{eH} \\ -0.18\Delta\sigma_{W,j} & \text{for } 0.6\Delta\sigma_{W,j} \geqslant R_{eH} \end{cases} \tag{7}$$

where $\sigma_{\text{mean},\,j}$ is the structural hot spot mean stress in condition "j", R_{eH} the material yield strength.

The residual stress is obtained from

$$\Delta\sigma_{\text{res}} = \max\left\{\sigma_{\text{res},j} \quad j = 1, 2, 3, 4\right\} \tag{8}$$

where

$$\Delta\sigma_{\text{res},\,j} = \begin{cases} \max\lfloor -R_{eH}, \min\{R_{eH}, \sigma_{\text{res}0} + \sigma_{\text{mean},j} + 0.6\Delta\sigma_{W,j}\} - \sigma_{\text{mean},j} - 0.6\Delta\sigma_{W,j} \quad \text{for } \sigma_{\text{mean},j} \geqslant 0 \rfloor \\ \min\lfloor R_{eH}, \max\{-R_{eH}, \sigma_{\text{res}0} + \sigma_{\text{mean},j} - 0.24\Delta\sigma_{W,j}\} - \sigma_{\text{mean},j} + 0.24\Delta\sigma_{W,j} \quad \text{for } \sigma_{\text{mean},j} < 0 \rfloor \end{cases} \tag{9}$$

The initial residual stress is calculated as

$$\Delta\sigma_{\text{res}0} = \begin{cases} 0.25R_{eH} & \text{for welded joint,} \\ 0 & \text{for non welded part.} \end{cases} \tag{10}$$

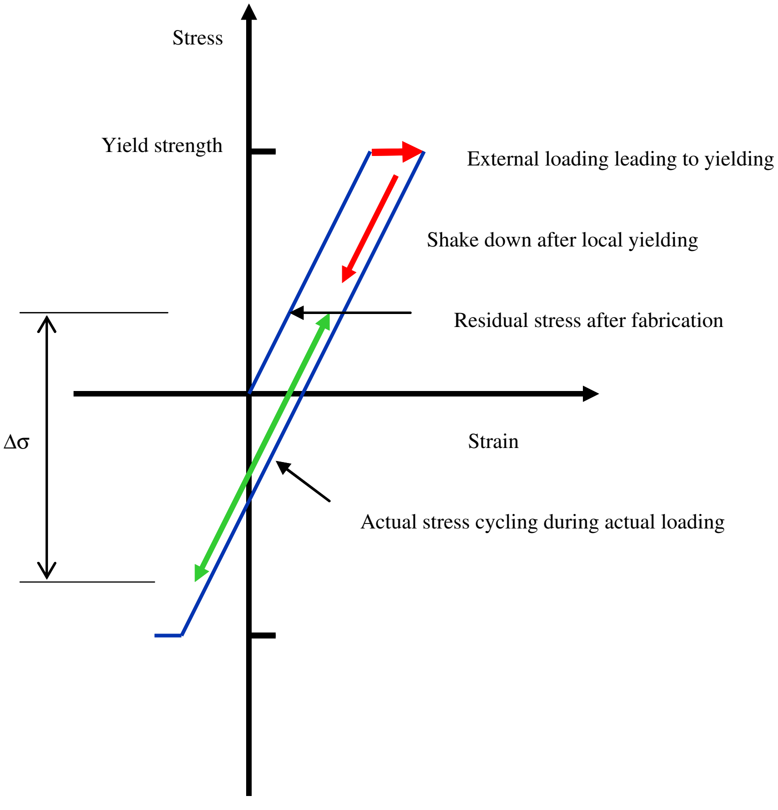

Fig. 1. Illustration of stress cycling after shake down of stresses at hot spot.

The procedure may be illustrated schematically as shown in Fig. 1. If the loading in a predominant loading condition is such that yielding at a considered hot spot will occur then shake down will be established for the following load cycles as indicated in the figure.

2.1.5. *S–N curve*

The calculated equivalent notch stress range for each loading condition is to be entered an S–N curve with $m = 4.0$ and $K = 1.014 \times 10^{15}$ for $N \leqslant 10^7$ cycles and $m = 7.0$ for $N > 10^7$ cycles where the format of the S–N curve is $\log N = \log \mathrm{K} - m \log S$.

This is the same S–N curve as used for the base material in BS 7608:1993 [3].

2.1.6. *Fatigue strength criteria*

The cumulative fatigue damage D calculated for the combined equivalent stress is to comply with the following criterion:

$$D = \sum_j D_j \leqslant 1.0, \tag{11}$$

where D_j is the elementary fatigue damage for each loading condition "*j*"

The long-term distribution of stress ranges is expressed in terms of a two-parameter Weibull distribution for each loading condition. The fatigue damage can be calculated using closed-form equations or alternatively by a direct integration of the fatigue damage linked to the bilinear *S–N* curve. The methodology for this is similar in JBP and JTP.

The design life is 25 years based on operation in North Atlantic environment.

2.2. Description of JTP fatigue analysis procedure

2.2.1. Assessment of the fatigue strength

Assessment of the fatigue strength of welded connections in JTP procedure includes the following three phases:

(a) calculation of stress ranges,
(b) selection of design *S–N* curve,
(c) calculation of cumulative damage.

2.2.2. Equivalent hot spot stress range

The actual mean stress level can be taken into account by an equivalent nominal stress

$$\Delta\sigma_{eq} = \sigma_{tension} + 0.6\sigma_{compression}, \quad (12)$$

where $\sigma_{tension}$ is the tension part of stress cycle, $\sigma_{compression}$ the compression part of stress cycle.

Then this equivalent stress is entered into a relevant nominal stress *S–N* curve where the stress concentration for the considered detail is accounted for.

It is observed that the calculation of equivalent stress with reduction factor on compressive stress cycle in Eq. (12) is similar to that used in BS 7608:1993 [3] for fatigue analysis of the base material.

2.2.3. S–N curves

Nominal stress *S–N* curves are used where the stress concentration for the considered detail is accounted for. The *S–N* curves are the same as defined in BS 7608:1993 [3]. Alternatively, a hot spot stress can be calculated and the corresponding stress range can be entered a hot spot stress *S–N* curve *D* which also is the same as defined in BS 7608:1993 [3].

2.2.4. Fatigue strength criteria

The cumulative damage is to be less than 1 for the design life of the vessel. The design life is not to be less than 25 years based on operation in North Atlantic environment. The resultant fatigue damage is calculated as the sum of the damages for the full load and ballast conditions. In each of these conditions a two-parameter Weibull distribution may be fitted to the long-term stress range distribution of stress ranges. Then integration of fatigue damage can be calculated similar to that described by JBP.

3. Comparison of fatigue assessment procedures against fatigue test data

3.1. Small-scale fatigue test data used for comparison

In the following the procedures are assessed against fatigue test data from the FPSO Fatigue capacity JIP [4]. The test specimens are shown in Fig. 2. The material was specified

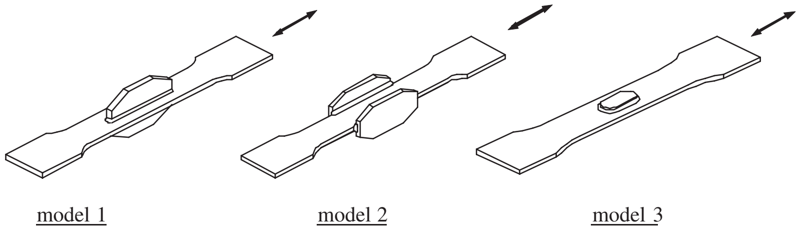

Fig. 2. Fatigue tested specimens in the FPSO fatigue capacity JIP.

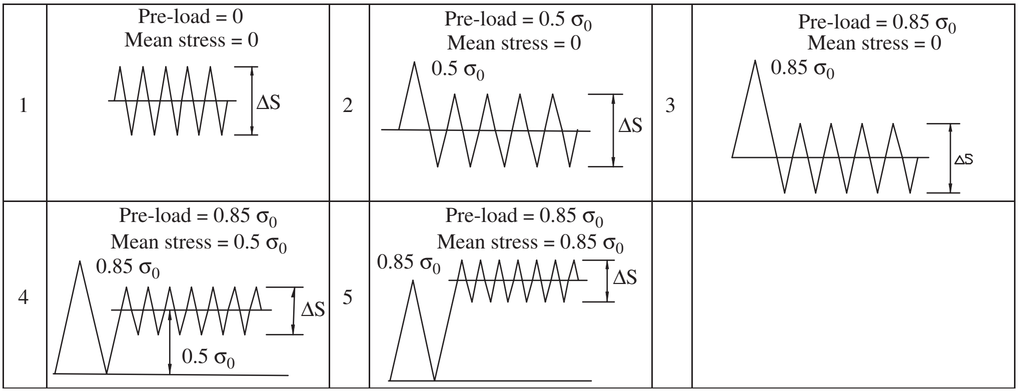

Fig. 3. Fatigue test conditions for models 1–3.

Table 2
Stress concentration factors for the tested specimens

Model no.	K_g-factor resulting from fatigue S–N data
1	1.32
2	1.96
3	1.33

as normal yield strength. For this material a nominal stress of 235 MPa is used for design. Note that this is the nominal stress (σ_o) that the test loading in Fig. 3 is related to.

The yield strength for this material from mill sheets was given as 299–336 MPa. Tensile tests of actual material showed yield strengths 290–299 MPa. Thus, here the actual yield strength is in the order of 25% larger than the nominal yield strength used in design. When comparing the procedure with test data the nominal yield strength is used as that also will be used for design.

Loading conditions 1–5 (Fig. 3) for models 1–3 (Fig. 2) are considered to be relevant with respect to fatigue of side longitudinals and these are used for comparison in the following.

Geometric stress concentration factor for the specimens are derived from Lotsberg and Sigurdsson [6]. The geometric K_g-factors are also listed in Table 2.

3.2. Full-scale fatigue test data used for comparison

Reference is made to Lotsberg and Landet [5] for description of full-scale fatigue testing of side longitudinals that is used for comparison of analysis procedures. The testing was performed under constant amplitude. The material used for the side longitudinals was NVD 36. When comparing the procedure with test data the nominal yield strength is used as that also will be used for design.

3.3. JBP procedure compared with fatigue test data

The proposed JBP procedure is assessed in the following for details 1–3.

Using the procedure it is now assumed that the initial residual stress at the weld toe after fabrication is equal to 25% of the yield stress.

The fatigue test data for model 1 have been plotted for 5 different loading conditions in terms of equivalent stress using the proposed JBP procedure. The results are shown in Fig. 4 for models 1–3. It is observed that load case 3 plots low in the S–N diagrams. This is a load case to be representative for details in tanks subjected to tank testing. Due to some uncertainty about the relevance of this load case for bulk carriers it is excluded when performing regression analysis and for comparison of test data from models 1–3 when they are compared with the design S–N curve B in Fig. 4.

However, the test data for load case 3 shows that the procedure does not reflect the physical behaviour for this test condition. The reduction factor on stress range after shake down is simply too low such that the reduction on fatigue damage becomes too large. By

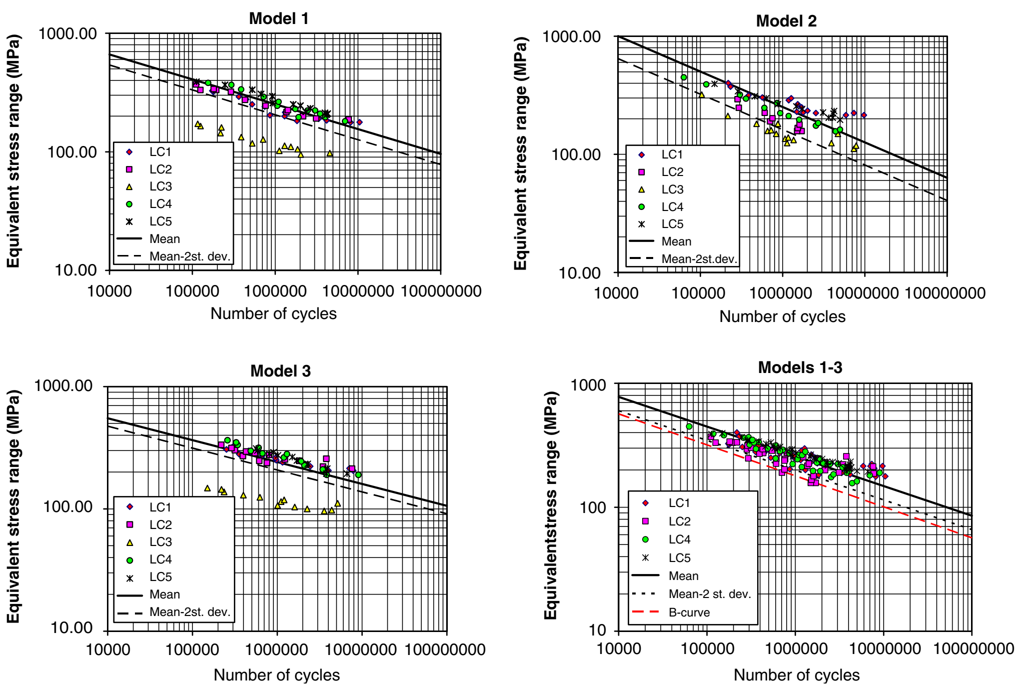

Fig. 4. Fatigue test data for load cases 1–5 in terms of equivalent stress range using the JBP procedure.

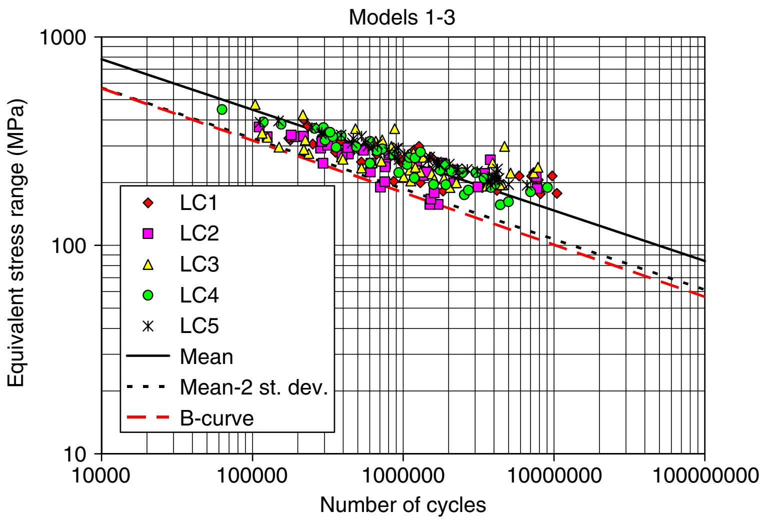

Fig. 5. Fatigue test data using the JBP procedure with modified minimum reduction factor 0.8.

Table 3
Regression analyses using the JBP procedure with m in S–N curve as free variable

Model no.	Loading condition	$\log K$	m	Standard deviation in $\log N$
1	1, 2, 4 and 5	17.448	4.767	0.214
2	1, 2, 4 and 5	14.001	3.332	0.319
3	1, 2, 4 and 5	19.311	5.587	0.181
1–3	1, 2, 4 and 5	16.060	4.173	0.233

changing the minimum reduction factor from 0.4 to 0.8 in Eq. (5) it is observed that the data points also for this load case is lifted above the design S–N curve (Fig. 5).

A regression analysis of the data was performed to derive a mean S–N curve in Fig. 4. The mean curve and the design S–N curve (mean minus 2 standard deviations) are also shown in Fig. 4. The numerical values from the regression analysis are shown in Table 3. The numerical values from the regression analysis with a fixed negative inverse slope of the S–N curve $m = 3.0$ are shown in Table 4. A regression analysis including all together 159 data points has been performed. From Table 3 it is observed that the slope parameter in the S–N curve is dependant on type of model. Also, the test data are compared with the S–N curve B that is proposed used for design analysis. A regression analysis has also been performed for a fixed slope $m = 4.0$ as this is the slope of the design S–N curve. This slope is not far from that calculated from the test data with the slope of the S–N curve as free variable in Table 3. A design value for $\log K$ for $m = 4.0$ can be calculated as $15.639 - 2 \times 0.234 = 15.171$ which is slightly larger than that of the design S–N curve B.

The standard deviation in Fig. 5 with a proposed modified reduction factor on compressive stress cycles is 0.286 when also including loading case 3. This figure includes 200 fatigue test data (Table 4).

Table 4
Regression analyses using the JBP procedure with fixed negative slope

Model no.	Loading condition	log K	m	Standard deviation in log N
1	1, 2, 4 and 5	13.212	3.0	0.281
2	1, 2, 4 and 5	13.209	3.0	0.321
3	1, 2, 4 and 5	13.291	3.0	0.260
1–3	1, 2, 4 and 5	13.209	3.0	0.264
1–3	1, 2, 4 and 5	15.639	4.0	0.234

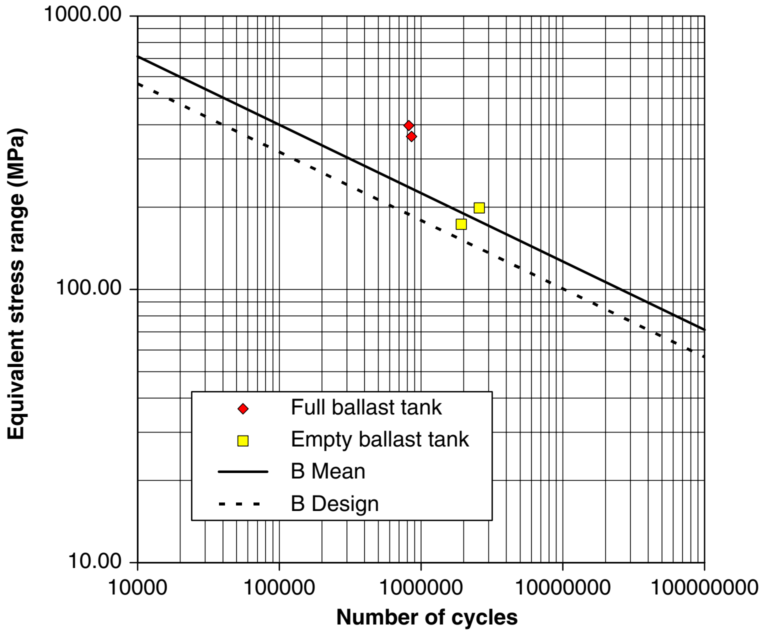

Fig. 6. Full-scale fatigue test data compared with the *B*-curve using the JBP procedure.

The full-scale fatigue test data for loading conditions corresponding to full ballast tanks and empty ballast tanks using the JBP procedure is shown in Fig. 6. The results using this procedure are above the design S–N curve B for stress ranges giving tension at the hot spot while it falls approximately on the mean B curve for stress cycles giving compression at the hot spot. It should be kept in mind that these test data were derived for constant amplitude loading. For derivation of this diagram stresses into compression were defined as a predominant load case. In a real structure this will likely not be the situation except for empty tanks.

3.4. JTP procedure compared with fatigue test data

The fatigue test data for models 1–3 have been plotted for 5 different loading conditions in terms of equivalent hot spot stress using the JTP procedure (Eq. (12)) in Fig. 7. The mean curve and the design S–N curve (mean minus 2 standard deviations) are also shown. The numerical values from the regression analysis are shown in Table 5. The numerical values from the regression analysis with a fixed negative inverse slope of $m = 3.0$ are shown in Table 6. A regression analysis including all the 200 fatigue test data points has been performed for comparison with the design S–N curve. It is observed that the scatter in the plotted data using JTP procedure is not significantly larger than that using JBP keeping in

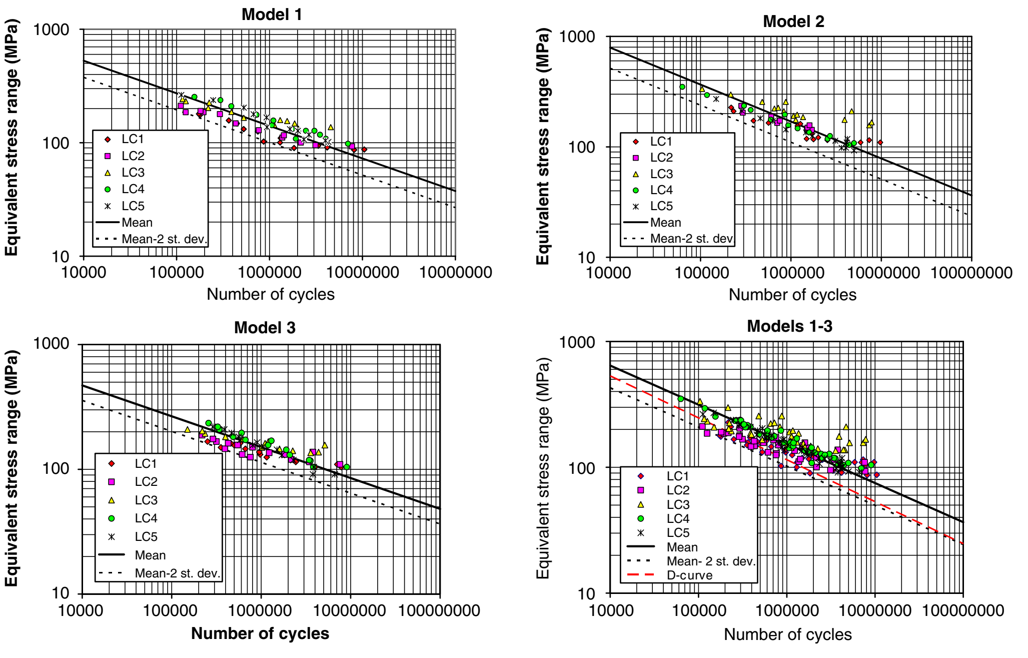

Fig. 7. Fatigue test data for models 1–3 in terms of alternative equivalent hot spot stress range using the JTP procedure.

Table 5
Regression analysis using JTP procedure with m in S–N curve as free variable

Model no.	Loading condition	$\log K$	m	Standard deviation in $\log N$
1	1–5	13.492	3.487	0.256
2	1–5	12.660	2.982	0.280
3	1–5	14.793	4.039	0.244
1–3	1–5	13.024	3.213	0.286

Table 6
Regression analysis using JTP procedure with fixed negative slope $m = 3.0$

Model no.	Loading condition	$\log K$	m	Standard deviation in $\log N$
1	1–5	12.443	3.0	0.264
2	1–5	12.699	3.0	0.280
3	1–5	12.536	3.0	0.264
1–3	1–5	12.559	3.0	0.288

mind that load case 3 is excluded in Tables 3 and 4 using JBP. Reference is made to standard deviations in Tables 6 and 4, respectively. From Fig. 7 it is seen that the JTP design procedure is slightly non-conservative for the test data from load cases 1 and 2. This situation is improved if the reduction factor on the compressive stress cycle in Eq. (12) is changed from 0.6 to 0.8 as shown in Fig. 8.

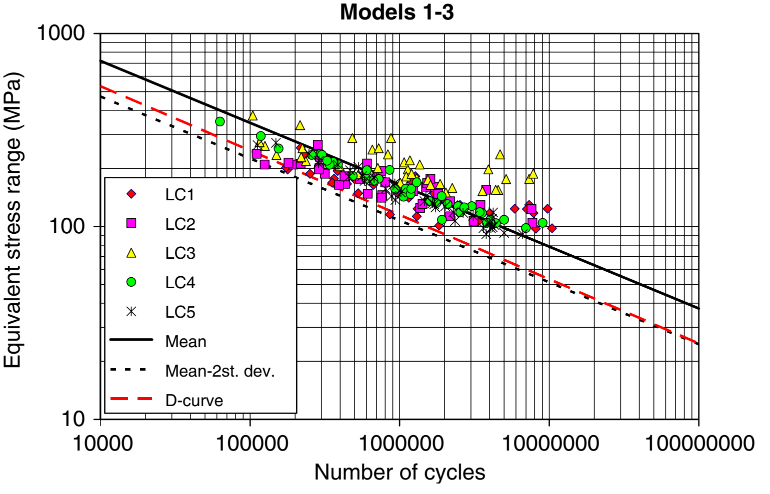

Fig. 8. Fatigue test data for models 1–3 in terms of alternative equivalent hot spot stress range using the JTP procedure with factor 0.8 on compressive part of the stress range.

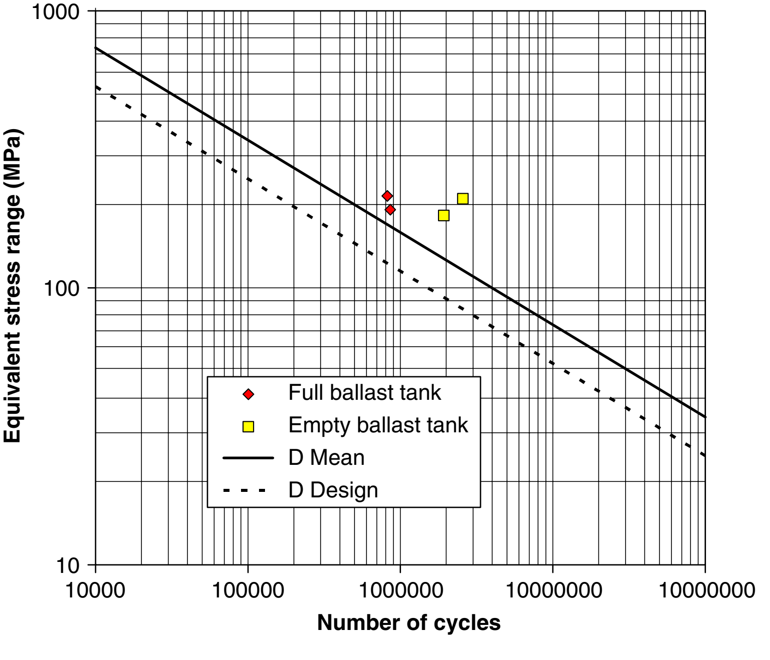

Fig. 9. Full-scale fatigue test data compared with the *D* curve using the JTP procedure.

The full-scale fatigue test data for loading conditions corresponding to full ballast tanks and empty ballast tanks using JTP procedure is shown in Fig. 9. The results using this procedure are above that of the design hot spot *S–N* curve *D*.

4. Comparisons of fatigue assessment procedures for a welded connection subjected to different load histories

A typical welded connection in a vessel is considered. This detail is assumed to be subjected to a number of different loading conditions. The same long-term nominal stress range distribution is assumed for all the different loading conditions in the different fatigue assessment procedures in order to visualize the differences more clearly. A Weibull long-term stress range distribution with shape parameter $h = 1.0$ is assumed. A Weibull scale parameter is determined that gives a calculated fatigue life equal 20 years following DNV CN 30.7 [7] for stress cycles in tension. The corresponding nominal long-term stress range distribution is then used for comparison of analyses. $\Delta\sigma_o$ = maximum stress range out of 10^8 cycles = 394.49 MPa following CN 30.7. The corresponding hot spot stress range is $394.49/1.5 = 262.99$ MPa and the notch stress following JBP is 373.45 MPa (The weld notch factor in CN 30.7 is 1.5). Material with a nominal yield strength equal 315 MPa is assumed.

For comparison of procedures the following conditions are considered:

1. mean tension 25% of yield stress as a nominal stress,
2. zero mean stress,
3. mean compression 25% of yield stress as a nominal stress.

The present comparison is based on similar calculated hot spot stresses as a starting point when using the two procedures. For a more complete assessment of the procedures also the loading and the stress concentration factors should be accounted for in the comparison.

It is seen that the loading case 1 is the predominant loading case when using the JBP procedure.

The results from analyses for the three different loading conditions are shown in Table 7. It is seen that the calculated fatigue damages are not very different following the different approaches for loading condition 1. The differences between the JTB and the JTP

Table 7
Calculated fatigue damage for different approaches

Approach	$\Delta\sigma_o$ (MPa)	Fatigue damage in different loading conditions			Sum of fatigue damages
		1	2	3	
Proposed JBP (notch stress in brackets)	262.99 (373.45)	1.428	0.410	0.001	1.84
Proposed JTP	179.13	0.976	0.420	0.168	1.56
CN 30.7	394.49	1.000	0.545	0.252	1.80
Recommended FPSO design procedure [8,9]	263.32	0.895	0.895	0.895	2.69

Table 8
Summary of the JBP and the JTP procedures with respect to fatigue capacity

Item	JBP procedure	JTP procedure
Stress to be used in fatigue assessment	Hot spot stress with a notch factor before entering the *S–N* curve	Nominal stress or hot spot stress
Residual stress and shake down	Included	Not included
Mean stress effect	Included	Included
S–N curve	*B*-curve	Nominal and hot spot stress *S–N* curves can be used

procedures are larger for loading conditions 2 and 3. The calculated fatigue damage in loading condition 3 for JBP is small. A change in minimum factor in Eq. (5) from 0.4 to 0.8 would increase the calculated fatigue damage to 0.082. However, the absolute values of the calculated damages for this loading condition is small and is considered to be of less importance as long as there are a predominant loading condition giving tensile stresses at the hot spot such as loading condition 1 keeping in mind that the total damage is the sum of the damages from each loading condition. The FPSO procedure is considered to be conservative for these loading conditions as this procedure does not account for positive effect of compressive stresses at the hot spot.

5. Conclusions

During 2004 and 2005 new design rules for bulk carriers and tankers were proposed. The rule proposals were developed in two different projects:

- The rules for bulk carriers were developed in the JBP with participation of the following Classification societies: BV, CCS, GL, NK, RINA, KR and RS.
- The rules for tankers were developed in the JTP with participation of the following Classification societies: ABS, DNV and LR.

The result from this is that two very different procedures for fatigue assessment have been developed. A summary of the procedures are listed in Table 8.

In this paper the two procedures are reviewed with respect to fatigue capacity. The JBP takes into account beneficial effects of shake down at hot spot regions after a loading that exceeds the yield strength combined with effective cyclic stresses into compression. It is based on an assumption that the initial residual stress at a hot spot such as a weld toe is 25% of yield stress.

The JTP is based on nominal *S–N* curves for plated structures. In the JTP procedure the mean stress is simply accounted for by a 60% reduction of the compressive stress at the hot spot.

The proposed JBP and the JTP analysis procedures have been compared with 200 fatigue test data where the test specimens were subjected to 5 different loading conditions. The scatter in the test data using JBP procedure is similar to that of using JTP for the same test data.

Both procedures are considered to be non-conservative for cyclic stresses into compression. It is found from comparison with fatigue test data that the JBP would behave acceptable for all load cases by increasing the minimum value of 0.4–0.8 in Eq. (5). Similarly, the reduction factor on compressive stress range in Eq. (12) of the JTP procedure should be considered increased from 0.6 to 0.8.

The procedures are compared for a typical welded connection in a vessel subjected to different long-term loading conditions. The calculated fatigue damage in one procedure relative to another depends on the loading condition. Having said this, it should be kept in mind that the present work does not include the loading and stress concentration factors which also are required for a more complete assessment of the procedures. The present comparison is based on similar calculated hot spot stresses using the two procedures.

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