Common Structural Rules for Bulk Carriers, January 2006

Background Document

CHAPTER 8 – FATIGUE CHECK OF STRUCTURAL DETAILS

NOTE:

- This TB is published to improve the transparency of CSRs and increase the understanding of CSRs in the industry.
- The content of the TB is not to be considered as requirements.
- This TB cannot be used to avoid any requirements in CSRs, and in cases where this TB deviates from the Rules, the Rules have precedence.
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SECTION 1 – GENERAL CONSIDERATION

1 GENERAL

1.1 Application

1.1.1

1.1.1.a The design life considering fatigue is taken as 25 years, same as in other strength requirements. The assessment is not applicable to bulk carriers under 150 m, considering that design loads from actual service routes are not appropriate and considering the damage results.

1.1.2

1.1.2.a Load factors other than design loads are taken as out of the scope of applicability since design loads are based on assessment of external loads due to normal wave pressures.

1.1.3

1.1.3.a Applicable to structural steel with yield point below 400 N/mm^2 based on the design curves used in the assessment. For steel with yield point higher than 400 N/mm^2, data obtained from approved test plans is to be used. Submission of fatigue design parameters summarized in the data above becomes the condition for approval.

1.2 Net scantlings

1.2.1

1.2.1.a In CSR for Bulk Carriers, all strength regulations including those for fatigue strength assessment are based on the net scantling approach. Please refer to 3.2 of Section 3, Chapter 3.

1.3 Subject members

1.3.1

1.3.1.a The required locations for fatigue strength assessment have been selected based on fatigue damage statistics and strength assessment results of bulk carriers with standard structure.

1.3.1.b The fatigue damage statistics shows that the almost fatigue damages were experienced in a ballast hold.

1.3.1.c Following a well developed structural detail design is one of the effective fatigue design methods.

2 DEFINITIONS

2.1 Hot spot

2.1.1

2.1.1.a Fatigue strength should be assessed based on the assessed results of local stress states at locations where fatigue cracks are likely to occur (hot spots).

2.2 Nominal stress

2.2.1

2.2.1.a Multiplying SCF (Stress Concentration Factor) by nominal stress is a simplified method to obtain hot spot stress.

2.3 Hot spot stress

2.3.1

2.3.1.a Structural discontinuities or hot spot stresses including stress concentration due to attachments indicate the local stress state. However, crack occurrences are affected by the existence of weld toe or stress concentration due to the existence of notch, etc.

2.4 Notch stress

2.4.1

2.4.1.a By using notch stress considering the stress concentration due to the existence of weld toe, fatigue strength can be assessed consistently without discriminating parent material and weld joints.

3 LOADING

3.1 Loading condition

3.1.1

3.1.1.a Fatigue phenomena depend on cumulative fatigue damage due to cyclic loads over a long period. Thus, typical loading conditions were selected considering the loading frequency in standard bulk carriers.

3.2 Load case

3.2.1 Load cases

3.2.1.a For definition of load cases, refer to the explanations in Section 4, Chapter 4.

3.2.2

3.2.2.a To assess fatigue at hatch corners, the oblique sea state that generates dominant stresses at hatch corner is considered.

3.2.3 Predominant load case

3.2.3.a The long-term distribution of stress range is characterized by the stress range (maximum value) corresponding to a certain exceedance probability and the shape parameter. The load case which gives the maximum stress range is selected as the predominant load case.

SECTION 2 – FATIGUE STRENGTH ASSESSMENT

1 GENERAL

1.1 Application

1.1.1

1.1.1.a Fatigue strength assessment is performed by the linear cumulative damage rule based on fatigue design curves (S-N curves).

1.1.1.b From our experience with fatigue damage in hull structures until now, it has been observed that the trend of occurrence of fatigue damage differs from the fatigue damage in land-based welded structures such as bridges, or in offshore structures, and that its primary cause is the effect of mean stress. In these rules, the assessment method based on equivalent hot-spot stress range considering the effect of mean stress is used.

1.1.2

1.1.2.a The fatigue strength of welded joints is affected by the stress concentration due to the existence of welds. Taking account of this effect enables to assess unified fatigue strength.

1.1.3

1.1.3.a Since the stress assessment procedure for the fatigue strength assessment is different according to primary members, longitudinal stiffeners connections and hatch corners, the stress assessment procedure is described respectively.

1.1.4 Primary members and longitudinal stiffeners connections

1.1.4.a The methods to assess hot spot stress of primary members and longitudinal stiffeners are specified in Section 3 and Section 4 respectively.

1.1.5 Hatch corners

1.1.5.a The method to assess hot spot stress of hatch corner is specified in Section 5.

2 EQUIVALENT NOTCH STRESS RANGE

2.1 Predominant load case

2.1.1

2.1.1.a The fatigue strength assessment is performed by calculating the cumulative fatigue damage based on long-term distribution of stress range. This long-term distribution has a shape that approximates to the exponential distribution when the long-term service of the ship is considered. Thus, shape of the long-term distribution can be decided by using the stress range of load cases assigned to maximum stress ranges in the design load case.

2.1.1.b Multiple load factors are associated with the stress response of hull structural members. Note that even for the same member, if the loading condition differs, the predominant load case differs.

2.2 Loading "Condition 1"

2.2.1

2.2.1.a The mean stress effect must be considered when assessing the fatigue strength of hull structural members. The local mean stress state can be expressed as the sum of structural mean stress and residual stress. However, if the maximum stress after considering the cyclic stress range exceeds the yield stress, the residual stress changes due to shakedown.

2.2.2

2.2.2.a If the local mean stress state can be determined from the loading condition at which the stress on the tensile side becomes maximum, then the assessment can be performed taking this state as the standard state.

2.3 Equivalent notch stress range

2.3.1 Equivalent notch stress range

2.3.1.a The hot spot stress is multiplied with the notch factor to estimate the notch stress. The fatigue strength of welded and non-welded parts can be assessed by a consistent reference stress.

2.3.1.b Originally, the notch stress is assessed as a peak stress at the bottom of notch, but if the crack is found to have propagated to such an extent that fatigue life can be identified by crack as in the hull structure, stress concentration may be considered as having eased from the state at the bottom of notch with the propagation of the crack. This effect is included in the design S-N curves. Thus, the fatigue notch factor was proposed after considering the stress concentration factors due to structural discontinuities considered during design and the local stress concentration factors due to the presence of welding beads, which are generally included in the proposed S-N curves.

2.3.2 Equivalent hot spot stress range

2.3.2.a The method used in the MIL-HDBK is followed to determine the effect of local mean stress state of the hot-spot part and it is assigned as a factor for the sake of convenience.

2.3.2.b The local mean stress state can be expressed by structural mean stress and residual stress, but when the maximum stress exceeds the yield stress when stress fluctuations are loaded, the residual stress varies due to shakedown. Therefore, the local mean stress state was assigned a formula considering the variation. In this case, the shakedown was estimated from the relationship between occurrence time of maximum stress anticipated during the continuous period of navigation in the same loading condition and its magnitude.

3 CALCULATION OF FATIGUE DAMAGE

3.1 Correction of the equivalent notch stress range

3.1.1

3.1.1.a Factors other than mean stress that influence the fatigue strength must be considered when design S-N curves are used in the assessed stress range. In this rule, the effects of corrosive environment, material strength, and plating thickness are considered.

3.1.1.b The design S-N curves give the fatigue strength in air in a non-corrosive environment or in a state protected from the corrosive environment. The Guidelines for Offshore Structures of the UK HSE specifies 1/2 the service life in a corrosive environment. In this rule, the factor was set considering that paint is effective in protecting from a corrosive environment for 20 years out of the design life of 25 years. The effective period of paint was set as 22 years for compartments that are difficult to identify as having an easily-corrosive environment.

3.1.1.c The fatigue life of parent material is enhanced according to the enhancement in material strength. On the other hand, the fatigue strength of welded joints does not change regardless of the differences in material strength when weld residual stress close to the yield stress exists in the welds. However, if the weld residual stress can be inhibited, the fatigue strength can be enhanced according to the material strength. In this rule, the magnitude of the residual stress due to shakedown according to the yield stress of the material is estimated, and the effect of the mean stress is considered. Accordingly, the effect of enhancing the fatigue strength according to yield stress is given by a factor that is based on the experimental results of fatigue strength. If weld residual stress close to the yield stress is assumed in the welded condition, the same fatigue strength can be assigned regardless of the type of material used.

3.1.1.d The description of degradation in fatigue strength when plating thickness increases, given in the Guidelines for Offshore Structures of the UK HSE has been incorporated.

3.2 Long-term distribution of stress range

3.2.1

3.2.1.a The long-term distribution of stress range can be approximated by a Weibull distribution close to an exponential distribution. The value of shape parameter expressing the shape of the Weibull distribution cannot be fixed at a uniform level because of the differences in external load conditions and stress response characteristics, such as wave environment, loading conditions during assessment, size of ship, and type and position of member to be assessed. For the sake of convenience, it was decided to use an exponential distribution.

3.3 Elementary fatigue damage

3.3.1

3.3.1.a The cumulative fatigue damage is calculated according to the Palmgren-Miner linear cumulative damage rule. However, elementary damage in the large frequency, small stress range is calculated according to the Haibach's rule. The design S-N curves used in calculating elementary damage are the B curves for the parent material proposed in the Guidelines for Offshore Structures in the UK HSE, and are the lower limiting lines of double the standard deviation, which include the safety margin.

3.3.1.b Damage calculation is performed for the cycles of wave fluctuations in 25 years, which is the design life. However, 85% of the full life was taken as effective considering that the ship may be at anchor because of reasons such as cargo loading/unloading, inspection and maintenance, and considering voyage in calm areas in the vicinity of cargo loading/unloading areas.

3.3.1.c The frequency of typical loading condition of standard bulk carriers is set based on questionnaires given to the shipping companies and on the comments received.

4 FATIGUE STRENGTH CRITERIA

4.1 Cumulative fatigue damage

4.1.1

4.1.1.a The criterion for assessed fatigue damage for all cases is taken as 1.0, but since the curve used includes the safety margin, the assessed results also includes the safety margin implicitly.

SECTION 3 – STRESS ASSESSMENT OF PRIMARY MEMBERS

1 GENERAL

1.1 Application

1.1.1

1.1.1.a The assessment procedure for hot-spot stresses is described here for performing fatigue strength assessment of primary members.

2 HOT-SPOT STRESS RANGE

2.1 Stress range according to the direct method

2.1.1

2.1.1.a Design loads must be applied in the hold model using fine mesh to assess the stresses in the hot-spot parts of primary members. In the direct model, the hull girder moment and loads due to design waves are simultaneously applied on the model and stress assessment is performed. The stress range is determined from the difference in the stress values at two conditions - at the crest and the trough.

2.1.1.b For details of stress analysis of hold model using fine mesh, refer to Section 4, Chapter 7 of the Rules.

2.2 Stress range according to the superimposition method

2.2.1 Hot spot stress range

2.2.1.a In the superimposition method, stress due to hull girder moment determined separately is superimposed on the stress assessed by applying the load due to design waves on the model, and the combined stress is assessed.

2.2.2 Stress due to hull girder moments

2.2.2.a The stress due to hull girder moment is determined by considering the bending moment on the hull girder. The nominal stress determined from beam theory and the stress concentration factors are considered when determining the hot-spot stress. However, for primary members the stress concentration factor corresponding to the stress due to hull girder moment is almost equal to 1.0, and therefore, the stress concentration factor corresponding to stress due to hull girder moment is considered as 1.0 in these Rules.

3 HOT-SPOT MEAN STRESS

3.1 Mean Stress range according to the direct method

3.1.1

3.1.1.a To assess the mean stress in the hot-spot part of primary members, the mean value of stress from design loads and hull girder moment in two conditions - wave crest and wave trough - applied in the hold model using fine mesh, is determined.

3.2 Mean stress according to the superimposition method

3.2.1 Hot spot mean stress

3.2.1.a In the superimposition method, the mean stress is found by adding the mean value of stresses assessed by loading the model with loads due to the design waves in the two conditions of wave crest and wave trough, to the stress due to still water vertical bending moment determined separately.

3.2.2 Stress due to still water hull girder moment

3.2.2.a For details of the still water vertical bending moment, refer to Section 3, Chapter 4 of the Rules.

3.2.2.b The assessment method in each loading condition using the permissible still water vertical bending moment is shown for the case when the still water vertical bending moment has not been set at the initial design stage.

SECTION 4 – STRESS ASSESSMENT OF STIFFENERS

1 GENERAL

1.1 Application

1.1.1

1.1.1.a The assessment procedure for hot-spot stresses is described here, for performing the fatigue strength assessment of end connections of longitudinal stiffeners.

2 HOT-SPOT STRESS RANGE

2.1 Stress range obtained by the direct method

2.1.1

2.1.1.a Refer to 2.1 of Section 3, Chapter 8.

2.2 Stress range according to the superimposition method

2.2.1

2.2.1.a Refer to 2.2 of Section 3, Chapter 8.

2.3 Stress range according to the simplified procedure

2.3.1 Hot spot stress ranges

2.3.1.a This is a procedure in which the nominal stress is assessed by beam theory, and multiplied by the stress concentration factor to assess the hot-spot stress. The stress assessment is performed by determining the stress by beam theory for each load component and superimposing the stresses. In this case, it should be noted that the sign of the stress varies with the direction in which the lateral pressure is applied.

2.3.1.b For details of each component of load, refer to the relevant section of Chapter 4 of the Rules.

2.3.1.c At positions where longitudinal stiffeners pass through transverse bulkheads, the deformation of the entire cargo hold or tank is constrained. Thus, secondary bending stress due to relative deformation occurs at the penetrating position of the bulkhead, and the penetrating positions of the forward and aft transverse bulkheads.

2.3.2 Stress due to hull girder moments

2.3.2.a Refer to 2.2 of Section 3, Chapter 8.

2.3.3 Stress due to wave pressure

2.3.3.a When longitudinal stiffeners are connected by flat bars or brackets at the position where they pass through transverse bulkheads or transverse webs, the stress concentration due to structural discontinuity at the connections is to be considered. In the simplified procedure, assessment is performed by multiplying the nominal stress with the stress concentration factor. Since there have been many instances of design and construction of structural details of joints of longitudinal stiffener at these locations, stress concentration factors for these typical detailed joints are given for design assistance. The values of these factors are the results of FE analysis according to the detailed models. From the assessment points shown in the table, for points that are evidently not severe considering stress, the difference in the factor due to the difference in whether the penetration is blocked by collar plate or not can be ignored, and is thus omitted.

2.3.3.b In the assessment of stress due to waves, the effect of increase in stress accompanying the tripping of stiffeners of asymmetric cross section is considered separate from the stress concentration factor due to the shape of the detailed joint, and the stress concentration factor determined from elastic beam theory is considered.

2.3.3.c For definitions of effective span and center distance, refer to Section 6, Chapter 3 of the Rule.

2.3.3.d During assessment of stress range according to fluctuating wave pressure, sometimes pressure may not be received (negative pressure may not be generated) because of positional relationships such as position of member to be assessed and position of wave surface fluctuation near the water line. Assessment must be performed considering the effect of this positional relationship of fluctuating surface of wave and the position of member to be assessed, and also considering the effect of height of the fluctuating surface, or the magnitude of acceleration and its occurrence frequency. These effects are considered in the Rules, and a correction coefficient was assigned to treat the non-linear stress range for fluctuations of waves as probabilistically equivalent linear stress range.

2.3.4 Stress due to liquid pressure

2.3.4.a Stress due to liquid pressure is assessed according to the same procedure as one assessing stress due to wave pressure.

2.3.5 Stress due to dry bulk cargo pressure

2.3.5.a Stress due to dry bulk cargo pressure is assessed according to the same procedure as one assessing stress due to wave pressure.

2.3.6 Stress due to relative displacement of transverse bulkhead

2.3.6.a In these Rules, the equivalent formula for stress was developed from relative deformation by correcting the coefficients from the results of FE analysis in the formulation of rules by elastic continuous beam theory. The relative displacement must be determined from FE hold analysis for applying the equivalent formula.

3 HOT-SPOT MEAN STRESS

3.1 Mean stress according to the direct method

3.1.1

3.1.1.a Refer to 3.1 of Section 3, Chapter 8.

3.2 Mean stress according to the superimposition method

3.2.1

3.2.1.a Refer to 3.1 of Section 3, Chapter 8.

3.3 Mean stress according to the simplified procedure

3.3.1 Hot spot mean stresses

3.3.1.a The structural mean stress is assessed by evaluating stress in the still water condition in the simplified procedure.

3.3.1.b For assessment procedures of stress for various load factors, refer to 2.3, Section 4, Chapter 8.

3.3.2 Stress due to still water hull girder moment

3.3.2.a Refer to 3.2 of Section 3, Chapter 8.

3.3.3 Stress due to hydrostatic pressure

3.3.3.a Refer to 2.3 of Section 4, Chapter 8.

3.3.4 Stress due to liquid pressure in still water

3.3.4.a Refer to 2.3 of Section 4, Chapter 8.

3.3.5 Stress due to dry bulk cargo pressure in still water

3.3.5.a Refer to 2.3 of Section 4, Chapter 8.

3.3.6 Stress due to relative displacement of transverse bulkhead in still water

3.3.6.a Refer to 2.3 of Section 4, Chapter 8.

SECTION 5 – STRESS ASSESSMENT OF HATCH CORNERS

1 GENERAL

1.1 Application

1.1.1

1.1.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.

2 NOMINAL STRESS RANGE

2.1 Nominal stress range due to wave torsional moment

2.1.1

2.1.1.a The calculation is based on the evaluation of the stresses induced in the hatch corner by cross deck bending following torsional deflection of the ship hull. The calculation of the displacement of the hatch corner in longitudinal direction (warping deflection) u is done by using an empirical formulae derived by parametric FE-studies of cargo-hold models under constant torsional moment which was scaled to the maximum moment acc. to Ch 04 Sec 03 of CSR. The displacement u is dependent of the relation between the hatch opening and the ship size. Therefore an Deck Opening Coefficient was introduced in the calculation of u. The relationship of the calculated displacements and the Deck Opening Coefficient is shown in figure 1.

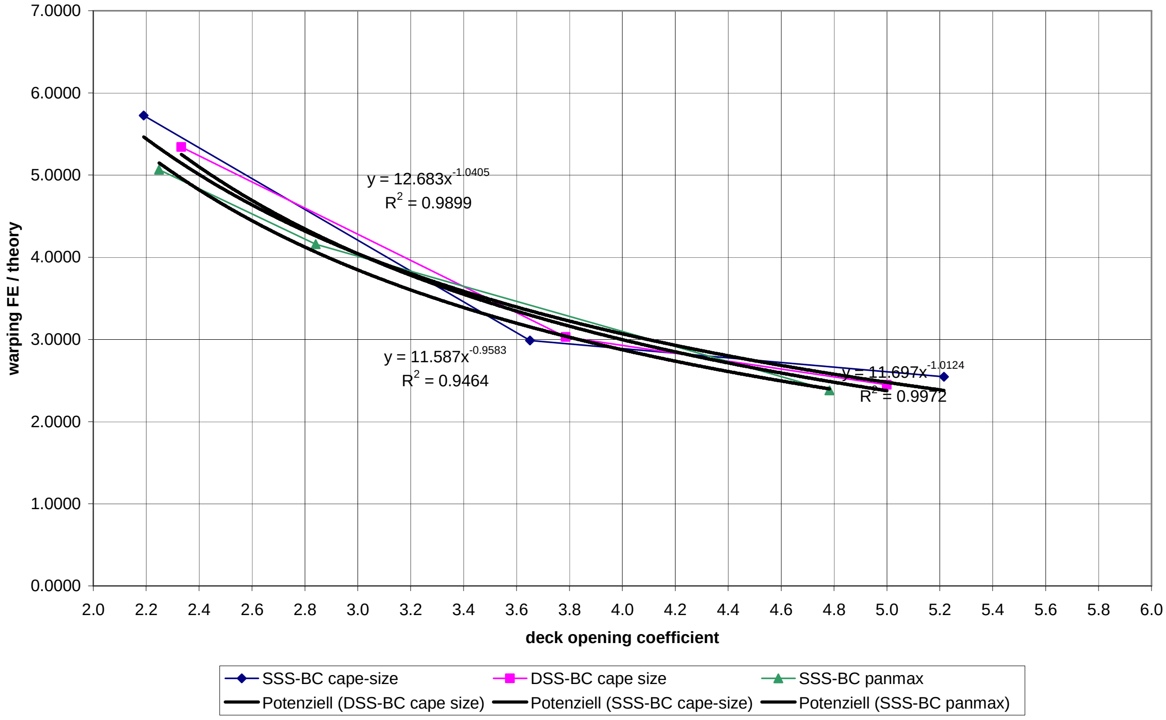

Figure 1: **Relationship between normalized displacement u and deck opening coefficient**

The displacements of the FE-analyses shown in figure 1 are normalized by using a theoretical value, based on St.-Venant Torsion-Theory (equation (1)).

$$u = -\phi' \cdot \omega \qquad (1)$$

where:

Φ´	torque of the cross section = MT / (IT G)
Ω	sector coordinate
MT	torsion moment
IT	torsion moment of inertia of the cross section
G	shear modulus of the material

The analysis of the results in figure 1 yields to the following formulation for the calculation of the hatch corner displacement due to torsion.

$$u = \frac{31.2}{1000} \cdot \frac{M_{WT} \cdot \omega}{I_T \cdot E \cdot DOC} \qquad (2)$$

where:

MWT	maximum torsion moment acc. to JBP rules Ch.04 sec 3.4 [kNm]
IT	torsional moment of inertia of the cross section at the hatch corner calculated within cross deck area (closed cross section) by neglecting upper and lower stool of the bulkhead [m^4]
E	elastic modulus of the material [N/mm^2]
DOC	deck opening coefficient = $\frac{L_C \cdot B}{\sum_{i=1}^{n} L_{H,i} \cdot B_{H,i}}$
ω	sector coordinate calculated at the same cross section as IT and at the Y and Z location of the hatch corner [m^2]

The deck opening coefficient is the quotient of the deck area (Length between engine room bulkhead and collision bulkhead (LC) times ships breadth B) and the summation of the area of the cargo hatch openings (n = number of hatches, LH,i length of Hatch i, BH,i breadth of hatch i).

The shear force within the cross deck can calculated by the following formulae:

$$Q = u \Big/ \left(\frac{(B_H + b_s)^3}{12EI_Q} + \frac{2.6B_H}{EA_Q} \right) \qquad (3)$$

where:

u	displacement of hatch corner as derived in equation (2)
B_H	breadth of hatch opening [m]
b_s	breadth of remaining deck-strip [m]
I_Q	moment of inertia of cross deck, including upper stool and hatch coaming near the hatch corner (see figure 13 for components they should be considered) [m^4]
A_Q	shear area of cross deck section, including upper stool near the hatch corner [m^2]

With the shear force now the stress at the hatch corner can be calculated based on cross deck bending acc. to the following formulae:

$$\sigma_{WT} = F_S \cdot \frac{Q \cdot B_H}{W_Q} \qquad (4)$$

with:

F_S	stress concentration factor FS=5 - this factor is caused by neglecting the torsion of the cross deck and simplifying/neglecting the transition zone between the cross deck and the wing tank, which gives a large discontinuity in stiffness at the location of hatch corner
Q	shear force calculated acc. eq. (3)
W_Q	bending resistance of cross deck section (bending around vertical axis of the ship, hatch coamings will act as flanges of the considered cross section) [m^3]

For the consideration of the stress distribution related to the position of the hatch cover in ships longitudinal direction, the stress obtained by equation (4) has to be multiplied by Factor FL which is given as follows:

FL = 1.75 x/L	for 0.57 < x/L < 0.85
FL = 1.0	for x/L < 0.57 and x/L > 0.85

The factor FL (shown at figure 2) was determined by comparison of stress results of the 2 hold cargo-hold-model used for the parametric investigation with stresses determined by calculations for the whole ship as shown in figure 5 for example.

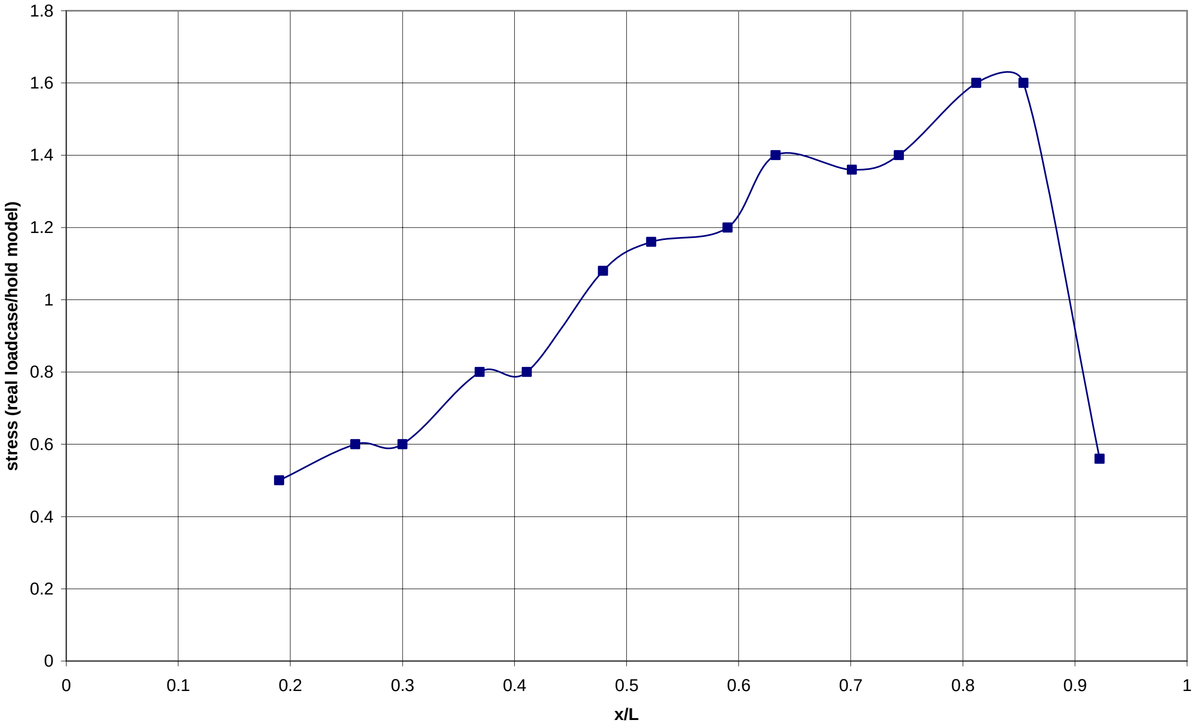

Figure 2: **distribution of hatch edge stresses along the ship length (PANMAX Single-Side BC – Maximum Torsion Moment acting at the fore part of the ship)**

2.2 Nominal mean stress

2.2.1

2.2.1.a The mean stress due to still water vertical bending moment within the cross deck is set to 0.

The correction factor for mean stress fmean is set to 0.77 which was determined by verification of the calculated results with results calculated acc. to the GL-rules. The mean stress factor is relatively large caused by the expectation of compressive residual stresses induced by thermal cutting of the hatch corner. It is expected, that these compressive stresses will remain during the ship life and no reloading effects are expected.

3 HOT SPOT STRESS

3.1 Hot spot stress range

3.1.1

3.1.1.a The determination of the stress concentration factor Kgh is based on an adaptation of the formulation for the stress concentration factor for a stepped flat tension bar with fillet shoulder as given by Heywood [Heywood, R. B., “Photo-elasticity for Designers”, Pergamon, New York, 1969] to the hatch corner geometry by NK.

APPENDIX 1 – CROSS SECTIONAL PROPERTIES FOR TORSION

4 CALCULATION FORMULAE

4.1 Torsion Function Φ

4.1.1

4.1.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.

4.2 Co-ordinate system, running coordinate s

4.2.1

4.2.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.

4.3 Computation of several properties for each part of the cross section

4.3.1

4.3.1.a It should be considered that the symbols used under this topic are only valid for the calculation of the properties of the parts of one cross section. They should not be confounded with the symbols and expressions used in 1.4.1

4.4 Computation of cross sectional properties for the entire cross section

4.4.1

4.4.1.a It should be considered that the symbols and expressions used under this topic are only valid for the calculation of the properties of the whole cross section. Expressions at the right hand side of the formulas (under the sum signs) are related to the results of 1.3.1. The results of this table should not be confounded with the symbols and expressions used in 1.3.1

5 EXAMPLE CALCULATION FOR A SINGLE SIDE HULL CROSS SECTION

5.1 Cross section data

5.1.1

5.1.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.

5.2 Determination of the torsion function Φ

5.2.1

5.2.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.

5.3 Determination of the line-segment properties

5.3.1

5.3.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.

5.4 Determination of cross-section properties

5.4.1

5.4.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.

5.5 Notes

5.5.1

5.5.1.a It is considered that for this topic, no information in addition to that shown in the Rules is necessary to explain the background.