IACS Common Structural Rules for Double Hull Oil Tankers, January 2006

Background Document

SECTION 9/1 – DESIGN VERIFICATION
HULL GIRDER ULTIMATE STRENGTH

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1.1.1 Application

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1.2 Rule Criteria

1.2.1 Vertical hull girder ultimate bending capacity

For M_{SW} see *1.7.1*.

For M_{WV} see *1.7.2*.

For M_U see *Appendix A/1.1.1 of the Rules*. See *1.8.5* for comparison with non-linear FE calculations.

For partial safety factors see *1.9.3*.

1.3 Hull Girder Bending Moment Capacity

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For M_U see *Appendix A/1.1.1 of the Rules*. See *1.8.5* for comparison with non-linear FE calculations.

1.4 Partial Safety Factors

1.4.1 General

For partial safety factors see *1.9.3*.

1.5 Calibration Procedure

1.5.1 Introduction

1.5.1.a The Hull Girder Ultimate Capacity is an explicit control of one of the most critical failure modes of a double hull tanker. The criterion for the ultimate strength of the hull girder is given in a partial safety factor format and has been calibrated using structural reliability analysis techniques.

1.5.1.b The hull girder ultimate capacity check is categorised as an ultimate limit state. Failure in sagging is identified as the most critical failure mode for double hull tankers. Failure in hogging is not considered to be critical for conventional double hull tankers due to the way they are loaded and due to the conventional structural arrangement with a double bottom and single skin deck. Hence only sagging is included within the current Rules.

1.5.2 Scope

1.5.2.a The scope covers a design rule to validate the hull girder ultimate strength for:

(a) Double hull oil tankers equal to or greater than 150 m in length

(b) Sagging bending moment condition only.

1.5.2.b The load effect considered is vertical bending moment due to still water and wave loads. North Atlantic environmental conditions are used as basis. Abnormal waves are not explicitly considered. The net thickness approach is applied with the ultimate capacity checked with 50% t_{corr} applied to all structural members.

1.5.3 Test ships

1.5.3.a The five test ships used as reference during development of the Rules were used as the basis for the structural reliability analysis. A summary of ship particulars is given in *Table 9.1.a,* this set of ships is assumed to span the scope of the Rules.

1.5.3.b The test ship reference scantlings ("target scantlings") are defined by the project, and are generally slightly increased compared with the as built scantlings. Tabulated values of sectional data and deck panel data for the reference scantlings are given in *Table 9.1.i.*

Table 9.1.a
Test Ships

Case	Ship type	Lpp (m)	Breadth (m)	Depth (m)
1	Suezmax	263	48	22.4
2	Product/Chemical Carrier	174.5	27.4	17.6
3	VLCC 1	320	58	31
4	VLCC 2	316	60	29.7
5	Aframax	234	42	21

1.5.4 Methodology

1.5.4.a Structural reliability analysis has been used as the tool to calibrate a design rule for hull girder ultimate strength. The aim is to obtain a rule that ensures that a sufficient and appropriate safety level is obtained for the structures and structural components covered by the rule. A partial safety factor format has been employed.

1.5.4.b In the structural reliability analysis the randomness in environment, structural load effects and strength parameters is accounted for. Uncertainties in the prediction models are also considered. The aim of the structural reliability analysis is to represent the the problem as realistically as possible reflecting the uncertainty involved and hence avoiding undue conservatism due to generalisations. The main result is a prediction of the nominal annual probability of failure together with the sensitivity of this result with respect to the various parameters. Effects of gross error are not considered in a structural reliability analysis.

1.5.4.c The aim is to generate a deterministic rule requirement that is consistent and practical to use.

1.5.4.d The safety level obtained depends on how the characteristic values are defined and the magnitude of the corresponding partial safety factors. It is assumed that the same target safety level is applicable for all ships to be covered by the rule.

1.5.5 Single test case method

1.5.5.a *Figure 9.1.a* illustrates the structural reliability approach for deriving the partial safety factors based on a "single ship case" approach. Here the partial safety factors are calculated as the ratio between the design point values (that are the most likely values at failure) at the target probability of failure level and the characteristic values. This is straightforward when considering a single ship case only. However, when more cases and variations in the designs are considered it becomes more complex since such ratios will usually vary between cases.

1.5.5.b In the calibration process, the magnitudes of the partial safety factors need to be optimised to provide a consistent probability of failure level (or reliability level) for the test ship cases spanning the scope of the rule; i.e. avoiding significant under-design and excessive over-design. The definition of the characteristic values may in principle also be considered in this optimisation.

1.5.6 Calibration process

1.5.6.a *Figure 9.1.b* illustrates a more general procedure that has been adopted to calibrate the partial safety factors for the test ship cases. The steps involved are described as follows:

(a) Start out with the characteristic values for the still water bending moment and the wave moment together with initial trial partial safety factors. Results obtained from a "single ship case" calibration as illustrated in *Figure 9.1.a*, may be used as guidance to select the initial trial safety factors.

(b) Apply the rule criteria to compute the required characteristic capacity. In order to obtain this capaciy, the test ship reference scantlings need to be modified. The modification is defined in terms of a design modification factor (DMF) which is further defined in *1.4.4*. The DMF is a deck area scaling factor following a defined procedure on how to modify the deck (stiffener size and plate thickness) in order to increase (or decrease) the capacity relatively to that of the test ship reference scantlings. The loads are assumed to be unaffected by the design modification.

(c) Determine the probability of failure corresponding to the DMF, from step (b), and find its deviation from the specified annual target probability of failure.

(d) Evaluate whether the optimum set of partial safety factors are obtained; i.e. minimising the deviation from the target probability of failure considering all cases in the test set. Modify the safety factors and recalculate from (b) if necessary.

(e) Calibration complete.

Figure 9.1.a
Calibration "Single Test Case" Illustration

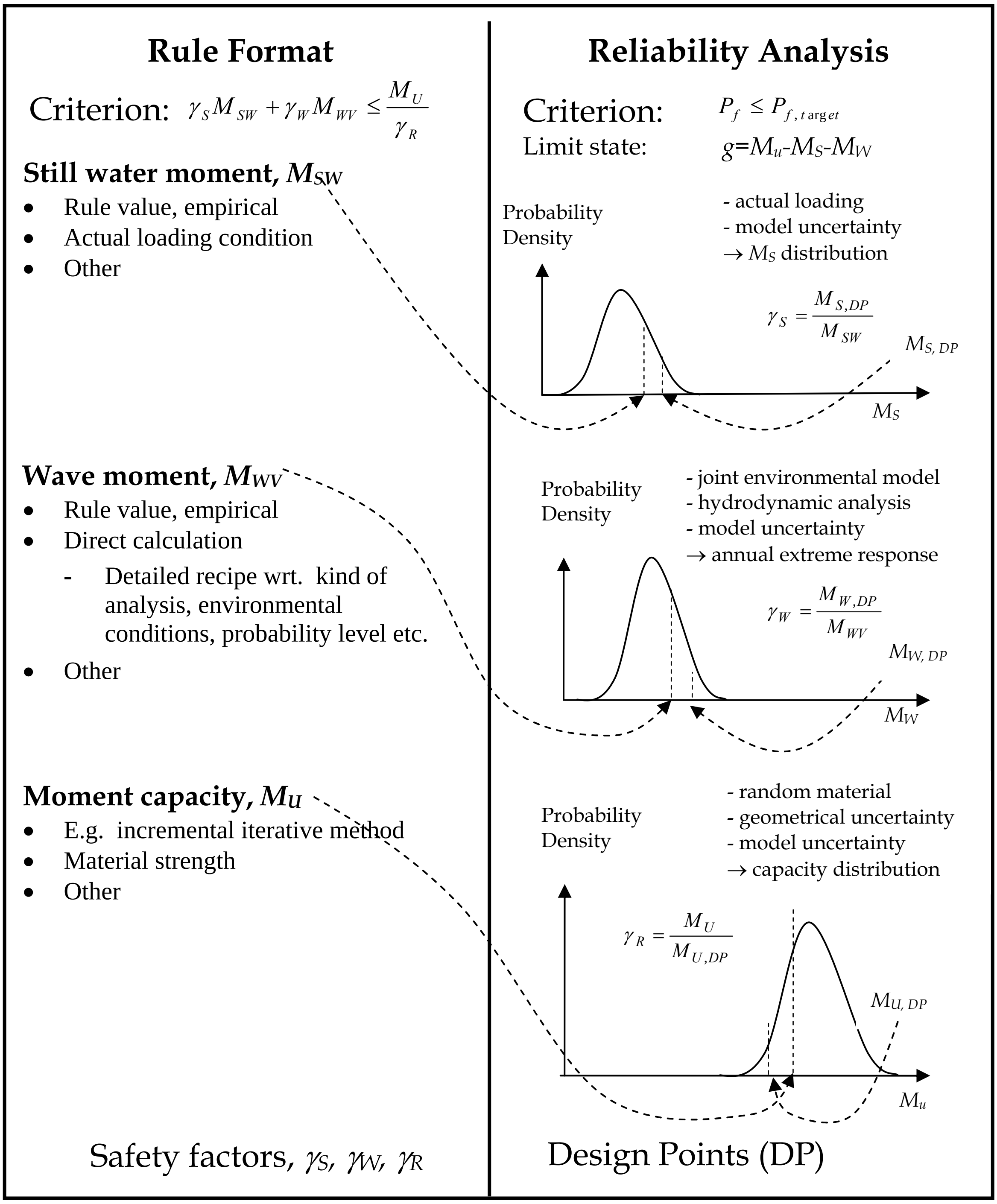
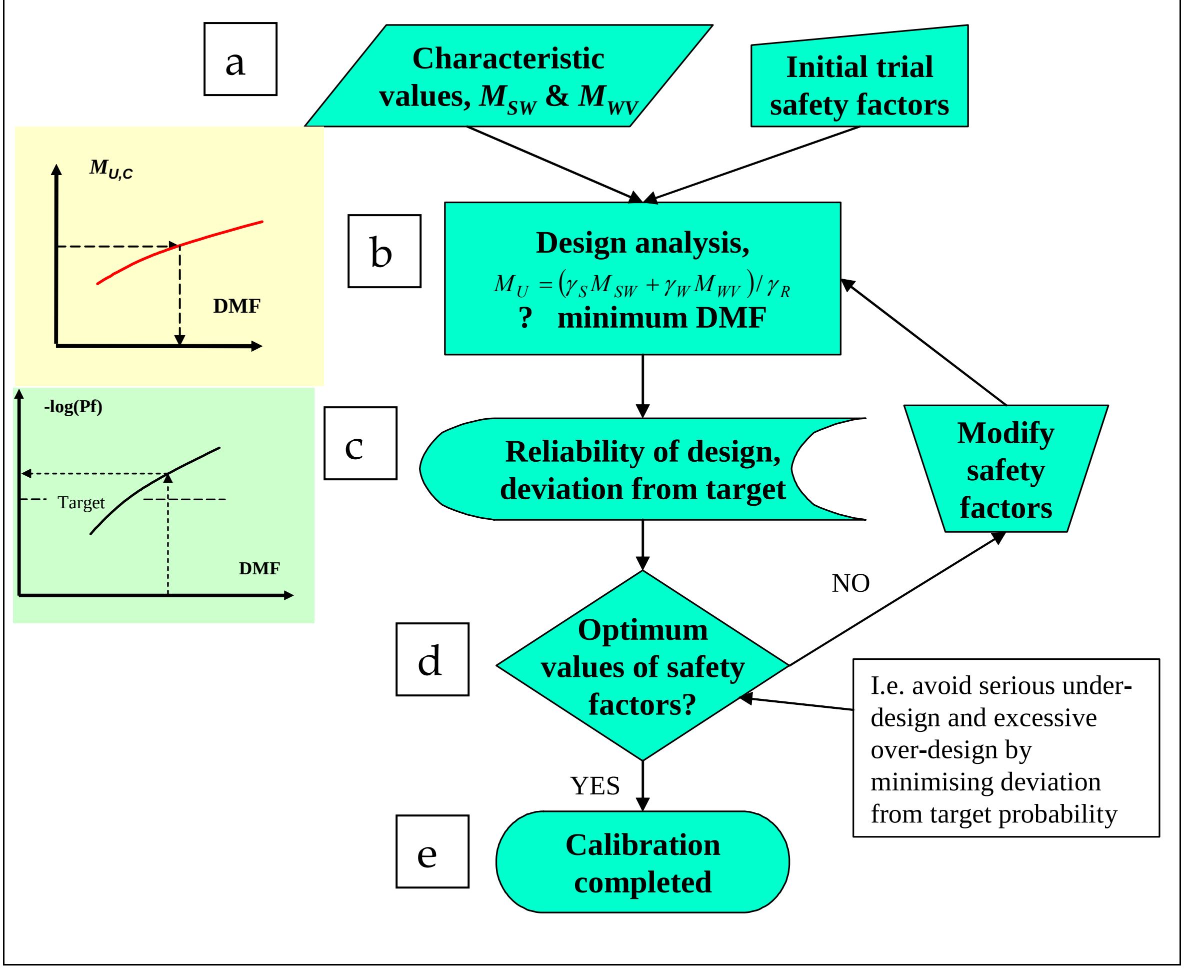


Figure 9.1.b
Calibration, Applied Procedure



1.6 Rule Criteria

1.6.1 Rule format

1.6.1.a The rule format for the hull girder ultimate strength is based on the design principles given in *Section 2/4 and 5 of the Rules*, with particular reference to the load scenarios given in *Section 2/Table 2.5.1.*. The rule requirement was assigned the following format:

$$\gamma_S M_{SW} + \gamma_W M_{WV} \le \frac{M_U}{\gamma_R}$$

Where:

M_{SW} is the characteristic still water sagging vertical bending moment

γ_S is the partial safety factor for the sagging still water bending moment

M_{WV} is the characteristic sagging vertical wave bending moment

γ_W is the partial safety factor for the sagging wave bending moment covering environmental, wave load and vertical wave bending moment prediction uncertainties

M_U is the characteristic vertical hull girder bending moment capacity

γ_R is the partial safety factor for the vertical hull girder bending moment capacity covering material, geometric and strength prediction uncertainties

1.7 Characteristic Values

1.7.1 Still water bending moment

1.7.1.a The Rules consider two conditions to cover the uncertainties with both still water and wave induced bending moments. These are referred to as Combination A or B:

1. Characteristic value for Combination A

   Permissible sagging still water bending moment, , see also *Section 7/2.1.1 of the Rules*

2. Characteristic value for Combination B

   The maximum sagging still water bending moment for homogenous full load condition

1.7.1.b The actual characteristic values for the 5 test ships are shown in *Table 9.1.b* The minimum Rule still water bending moment for all the 5 ships is higher than the maximum sagging still water bending moment for the homogenous full load condition, and well below the assigned permissible value used to design the ships using the then current Rule approach. Note, the assigned permissible value for most of the test ships was derived from the IACS UR S7 minimum requirement for sectional modulus in combination with the S11 requirement for bending strength amidships and hence is a conservative value as it does not actually reflect what is required for the operation of the ship.

1.7.2 Wave bending moment

1.7.2.a The characteristic sagging wave bending moment is calculated according to *Section 7/3.4.1.1 of the Rules* and are shown in *Table 9.1.b*.

Table 9.1.b
Characteristic Still Water Bending Moment and Wave Bending Moment Values (kNm)

Bending moment	SUEZMAX	PRODUCT	VLCC 1	VLCC 2	AFRAMAX
Combination A: Permissible still water BM, Rule minimum, *see note 2*	2 716 243	602 937	4 910 937	4 955 888	1 811 777
Combination B: Still water BM, maximum homogenous full load condition	2 119 568	436 056 *see note 1*	4 439 967	4 858 373	1 194 240 *see note 1*
Combination B to Combination A ratio	78%	72%	90%	98%	66%
Still water BM, permissible from drawing. (Not used)	3 403 000	756 351	6 160 680	6 213 550	2 503 512
Sagging Wave BM, Rule formula	5 762 522	1 279 133	10 418 575	10 513 937	3 843 692

Notes:

1 The maximum still water sagging bending moment in the loading manual usually corresponds to the homogenous full load condition. For the present 5 test ships, higher values are given for the Product and the Aframax tanker in partial load conditions; values are 564 960 kNm and 1 435 429 kNm respectively.

2 For the calibration it has been assumed that the Rule minimum still water BM is representative for the permissible value. Depending on special loading conditions or margins requested by the builder/owner, the permissible may be somewhat higher than the Rule minimum.

1.7.3 Characteristic ultimate bending capacity

1.7.3.a The characteristic ultimate bending capacity may, in principle, be calculated according to any selected computational method, if the uncertainty and any potential bias in the calculation are properly covered by its associated partial safety factor. The characteristic capacities used in the calibration has been calculated according to the single step method, see *Appendix A/2.1 of the Rules.* Comparison studies carried out during IACS harmonization work show that the single step method and the method based on the incremental-iterative approach, as defined in *Appendix A/2.2 of the Rules*, provide similar results, and are both applicable with the same partial safety factor.

1.7.3.b In the single step method the area of each stiffened panel in the deck from the A_{net50} scantlings is reduced to an effective area of the deck A_{eff} based on the ratio between its ultimate capacity σ_U calculated using the advanced buckling approach and the yield stress σ_{yd}; i.e.:

$$A_{eff} = \frac{\sigma_U}{\sigma_{yd}} A_{net50}$$

1.7.3.c The sectional properties of the hull girder are calculated using this effective area and the ultimate moment capacity corresponds to initial yield in the deck based on the effective elastic section modulus of the modified section.

1.7.4 Test ship reference scantlings and Design Modification Factor DMF

1.7.4.a The starting point for the analyses of the 5 test ships are based on the initial "reference scantlings", see *Table 9.1.i*. The net thickness approach is applied using t_{net50} for all members.

1.7.4.b In the calibration, as illustrated in *Figure 9.1.b*, a design modification factor DMF is applied as a means of adjusting the moment capacity. The chosen DMF model increases or decreases the deck area in order to adjust the actual ultimate BM capacity to the required value. The following assumptions are made:

(a) The hull girder moment capacity is adjusted by modifying the deck design only, keeping dimensions of sides, bulkheads and bottom structure constant.

(b) The change in the deck design is implemented by changing the size of the stiffeners and the plate thickness only, keeping the spacing and the number of stiffeners constant.

(c) The change in stiffener size follows a "smoothed curve" fitted to available profile sizes.

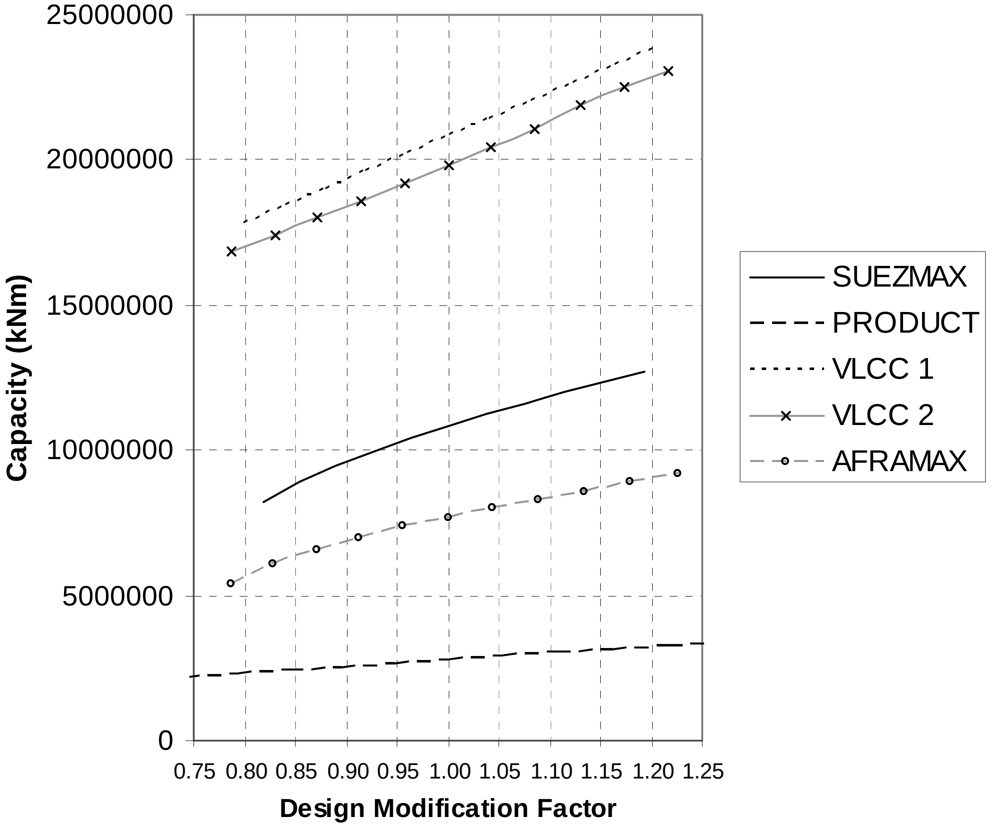
(d) The thickness of the deck plating is assumed to change in proportion to the change in thickness of the stiffener flange

(e) Loads are assumed remain unchanged by the design modification.

1.7.4.c The outlined procedure for deck modification is simple and does not necessarily lead to optimum designs. For small variations around the reference scantlings, it is considered a reasonable approach for the purpose of calibration.

1.7.4.d The implemented design modification factor represents relative changes in the area of the deck following the assumptions outlined in *1.4.4.b.* The sectional properties and typical deck panel dimensions for the deck structure are given in *1.7.1*. The capacity determined using the single step method is illustrated in *Figure 9.1.c* as a function of DMF.

Figure 9.1.c
Characteristic Ultimate Bending Moment Capacity as a Function of DMF

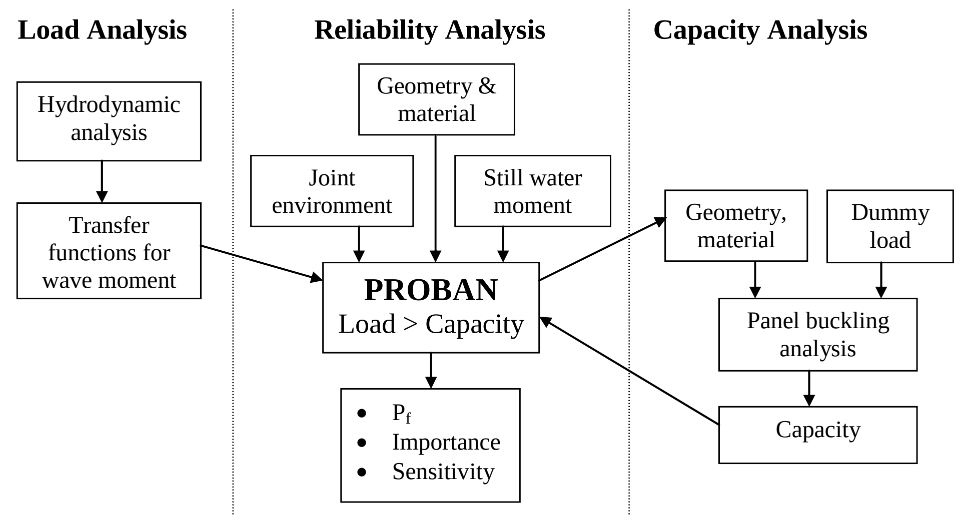


1.7.5 Reliability analysis

1.7.5.a In a structural reliability analysis the design criterion may be stated by requiring the probability of failure to be less than the target probability of failure. Failure is defined as the state when the load exceeds the capacity when the uncertainties in both load and capacity are accounted for.

1.7.5.b The setup of the analysis is illustrated in *Figure 9.1.d*, and described further in the following subsections. The probability of failure is calculated by the general probabilistic analysis program PROBAN, SESAM (1996), using the First Order Reliability Method (FORM). During the calibration process, the single-step method was used for calculating the sagging ultimate bending capacity, see *1.4.3*.

Figure 9.1.d
Hull Girder Collapse, Outline of the Reliability Analysis



1.8 Uncertainty Modelling

1.8.1 Environmental conditions

1.8.1.a A joint environmental model; i.e. a probabilistic model for the significant wave height and the zero-crossing period, for the North Atlantic environmental conditions is used. This model is developed from the scatter diagram used as basis for developing loads in the Rules (see *Section 2/4.2.6.2 of the Rules*), and implies some smoothing and extrapolation to unobserved conditions. The significant wave height H_s of a 3-hour sea state is modelled as a 3-parameter Weibull distribution:

$$f_{H_s}(h_s) = \frac{\beta}{\alpha}\left[\frac{h_s-\gamma}{\alpha}\right]^{\beta-1} \exp\left[-\left(\frac{h_s-\gamma}{\alpha}\right)^{\beta}\right]$$

with scale parameter α=2.721m, shape parameter β=1.401 and location parameter γ=0.866m.

1.8.1.b The zero-crossing wave period T_z is conditional on the significant wave height, and a lognormal distribution has been applied:

$$f_{T_z|H_s}(t_z \mid h_s) = \frac{1}{\sqrt{2\pi}\sigma t_z} \exp\left[\frac{(\ln t_z - \mu)^2}{2\sigma^2}\right]$$

Where:

$$\mu = E(\ln T_z) = 0.623 + 1.356 \cdot h_s^{\ 0.123}$$

$$\sigma = \sqrt{Var(\ln T_z)} = 0.146 + 0.044 \cdot e^{-1.712 \cdot h_s}$$

1.8.2 Wave moment

1.8.2.a The structural response due to waves is based on linear hydrodynamic analysis for the five test ships. Results in terms of transfer functions for the selected midship bending moment are used. The long-term response is computed inside PROBAN.

The basic assumption is a narrow banded Gaussian response in each sea state. This assumption implies Rayleigh distributed maxima for a given sea state, for which a Gumbel type extreme value distribution can be derived. Finally, the annual extreme value distribution is obtained assuming independence between sea states. This approach to use transfer functions with PROBAN is documented by Mathisen and Birknes (2003).

1.8.2.b The distribution using this approach has been verified versus a conventional Weibull distribution as obtained based on the standard long term response calculation procedure as used for deriving wave load values, see *Section 2/4.2.6.2 of the Rules*.

1.8.2.c The probability of sagging failure in ballast condition may be neglected since the still water moment in ballast generally gives hogging and hence leads to a significant reduction in the total sagging moment. See also *1.5.3*. The loaded conditions at sea are considered and wave loads corresponding to scantling draught are used. The annual probability of failure is calculated taking into account the relevant fraction of the year for which the ship is assumed to be in loaded condition at sea; i.e. 42.5% of the year as defined. The ship is in port or sailing in ballast the rest of the time.

1.8.2.d Here the focus is on hull girder collapse in heavy weather at sea, and in such severe conditions the ship is most likely to operate in head seas, or nearly head seas. In extreme sea states the waves tend to be more long-crested; e.g. a $\cos^4$ directional function or with an even higher exponent is appropriate.

1.8.2.e Some test runs for calculation of the wave moment distribution were carried out. A triangular distribution of the main heading between 150° and 210° (head seas is 180°) was assumed together with a $\cos^4$ spreading function. This was found to be almost equivalent to head sea and a spreading using $\cos^2$. For this reason, the structural reliability analyses are carried out for head sea with a short-crested representation corresponding to $\cos^2$.

1.8.2.f The Pierson Moskowitz (PM) spectrum has been applied in the analyses. Some sensitivity results using the Jonswap wave spectrum have been carried out. All results are for zero ship speed.

1.8.2.g A model uncertainty for the response calculation has been applied in terms of a normally distributed uncertainty factor with a mean value of 1.0 and a coefficient of variation of 0.1. This uncertainty is assumed to cover the uncertainty in the linear results itself, including the effect of uncertainty in the wave spectrum. Reference is made to DNV Classification Note 30.6.

1.8.2.h Furthermore, to use a linear analysis for the bending moment response in extreme weather is a simplification that is difficult to justify. ISSC 2000 Volume 2 Special Task Committee VI.1 “Extreme Hull Girder Loading” discusses direct calculation procedures for extreme wave loads on ship hull girders. It is stated that:

(a) No robust and exact non-linear hydrodynamic wave load procedure exists today, and almost all ship motion and wave load codes rely on potential theory.

(b) The validity of linear potential theory is well documented and it is widely used for both ships and offshore structures, and is accurate up to fairly large wave slopes.

(c) The difficulties arise in extreme seas.

1.8.2.i The problems are inherently non-linear dealing with large-amplitude non-linear wave fields and the variable geometry of the ship's hull as it comes in and out of the water as well as with slamming, wave breaking and green water on deck. Results concerning comparative calculations using different simplified non-linear analyses methods are discussed for a test container ship (S175). For the present work, considering tankers over 150m and zero speed, there appears not to be any directly applicable results in terms of nonlinear correction factors.

1.8.2.j Other sources have been investigated in order to find a measure for non-linear correction on the linear results. Results show a large scatter. In ISSC 1991 a bias factor of 1.15 is suggested for sagging (0.85 for hogging) and with a rather low standard deviation of 0.03. Hovem and Aasbø (1999) show a comparison of results using a non-linear strip theory program (NV 1418) and a linear 3D sink-source theory program (WADAM). Results are calculated for a 125dwt tanker, 290 000dwt VLCC and a 165 000dwt Bulk Carrier. Nonlinear correction factors near unity are obtained for the tankers; i.e. between 0.97 and 1.05, and between 0.91 and 0.96 for the Bulk carrier. The design wave amplitude has been varied (9.8m-11.8m), and the lowest corrections factors are obtained for the higher wave amplitudes.

1.8.2.k Also the DNV Classification Note 30.6 has been reviewed, where a general bias of 0.92 is given.

1.8.2.l The paper Pastoor, W., et. al. "Direct Nonlinear Hydrodynamic Analyses For High Speed Craft", HIPER '02, Bergen, Norway, pp. 469-484 provides some results showing that the non-linear effect first increases with increasing severity of the weather, but then decreases again when the severity further increases beyond some limit. Numerical results applicable for the tankers studied in the present project are not available, but the tendency of first increasing then decreasing is interesting.

1.8.2.m From the available data it is difficult to conclude on a "correct" model uncertainty to account for non-linear effects. A wide scatter in the results appears. An uncertainty factor with a mean value of 1.0 and a coefficient of variation of 0.1 has been applied in the present analyses to the total wave bending moment. Some sensitivity analyses have been performed to show the effect of different assumptions; i.e. analyses with bias factors of 1.1 or 0.9 and one analysis using a coefficient of variation of 0.2.

1.8.3 Still water moment

1.8.3.a In general for tankers, ballast conditions represent hogging and loaded conditions represent sagging. Also, the wave induced moment has been found to be greater in loaded than in ballast condition. For this reason the chance of sagging failure in ballast condition has been ignored.

1.8.3.b The calibration has been performed using the assumptions as outlined below.

(a) Identify all seagoing loaded conditions in the loading manual

(b) Emergency ballast and segregated/transitory/group load conditions (that often gives hogging) are omitted

(c) Calculate the mean value and the standard deviation based on numbers for the identified conditions, assuming equal weight for each condition

1.8.3.c This has been done for the five test ships together with three additional ships, and the results are included in *Table 9.1.c*.

Table 9.1.c
Still Water Bending Moment Statistics for the 5 Test Ships and Additional 3 Ships, in kNm

	Mean	Std.dev.	Max	Mean/max	Std.dev/Max.	(Max-mean)/ Std.dev
Suezmax	1805000	192000	2120000	85 %	9 %	1.64
Product	337000	140000	565000	60 %	25 %	1.63
VLCC 1	3059000	780000	4440000	69 %	18 %	1.77
VLCC 2	2856000	969000	4858000	59 %	20 %	2.07
Aframax	831000	365000	1435000	58 %	25 %	1.66
Aframax (2)	1030000	321000	1448000	71 %	22 %	1.30
Product (2)	157000	90000	288000	55 %	31 %	1.45
Product (3)	86000	61000	175000	49 %	35 %	1.46
Average				63 %	23 %	1.62

1.8.3.d It is seen that the mean value is between 49% and 85% of the maximum value of the conditions identified. When the mean value is relatively high, the standard deviation is relatively small. There is a tendency for the shorter ships to have a relatively lower mean and a higher standard deviation than the longer ships.

1.8.3.e On average, the maximum value is 1.6 times the standard deviations above the mean value. A conventional definition of a characteristic value is to use a consistent fractile of its associated distribution. For example the characteristic yield stress is usually defined as the 5% fractile of its distribution which, in fact, corresponds to 1.64 times the standard deviation below the mean value, if a normal distribution is used.

1.8.3.f The model that is used in the present work assumes that the still water moment is normally distributed with a mean value of 0.7 times the maximum value in the loading manual, and with a standard deviation of 0.2 times the maximum value. This distribution has been applied in the analyses of all 5 test ships. There is no upper threshold applied to the distribution. In other words, there is a chance that the still water moment may attain a value that exceeds the maximum value in the loading manual, although the probability of this is small; i.e. 7%.

1.8.3.g A model uncertainty factor on the still water moment has also been applied in terms of a normally distributed variable with a mean value of 1.0 and a coefficient of variation of 0.1.

1.8.4 Combination of wave and still water moment

1.8.4.a The still-water bending moment will be added to the wave moment by linear superposition. Two different combinations, following Turkstra's combination rule, Tursktra (1970), are evaluated:

(a) An annual extreme value of the wave induced moment with a random value of the still water moment.

(b) An annual extreme value of the still water moment together with an extreme value of the wave moment during one voyage.

1.8.4.b Depending on the magnitude, the variability and the duration of a voyage, either of these combinations may be governing. However, for the present tanker study, it appears that the extreme wave load is dominating and combination A is governing for the probability of failure. This has also been found in the present study and in other studies; e.g. Bach-Gansmo and Lotsberg (1989) and Kaminski (1997).

1.8.5 Ultimate bending capacity

1.8.5.a The physical model applied in the capacity calculation is similar to the model used for the computation of the characteristic capacity, see *1.4.3*. The uncertainties accounted for are the yield strength, which is modelled by a lognormal distribution, and a model uncertainty to reflect uncertainty in the calculation model. Geometrical dimensions are modelled as deterministic values.

1.8.5.b The results are conditional on the applied net thicknesses, hence, time variant corrosion is not considered. Initial imperfections are not modelled as such, but accounted for in the applied model uncertainty. The stiffness is modelled as a deterministic value since the associated uncertainty is rather small and has negligible influence on the results.

1.8.5.c The distribution of the yield strength is derived from its characteristic value which represents the lower 5% fractile. A coefficient of variation of 0.08 is used for normal grade steel (used for the Product tanker), and 0.06 has been applied for high strength steel used in the remaining cases. These values are taken from the DNV Classification Note 30.6 and by Skjong et. al (1995), and are commonly applied.

1.8.5.d In ISSC 2000 Volume 2 Special Task Committee VI.2 "Ultimate Hull Girder Strength" gives comparable yield strength coefficients of variation of 0.09 and 0.07 respectively. The distribution parameters are included in *Table 9.1.4*. The spatial variation of the material strength has not been considered. There is likely to be some averaging effects since one would expect some degree of independency in the steel properties for different plates and stiffeners around the hull section. For this reason, the applied distribution model is likely to be somewhat pessimistic.

1.8.5.e The magnitude of the model uncertainty is chosen with some basis in the obtained nonlinear finite element analysis results for the Suezmax, ref. Törnqvist (2004). The single step model provides comparable results to the non-linear analysis when rather pessimistic imperfections are applied. Somewhat higher capacity is obtained when a more realistic imperfection model is applied ("hungry horse"). These results are summarised in *Table 9.1.d*.

1.8.5.f The numbers indicated a model uncertainty factor with a bias higher than 1.0. A value of 1.05 with a standard deviation of 0.1 has been applied, assumed to reflect the difference between the single step model and the non-linear result as well as the difference between the non-linear result and real life.

1.8.5.g Additional non-linear analyses results for other ships are demanded in order to gain further confidence in the simplified approach.

Table 9.1.d
Comparison of Non-Linear ABAQUS Analyses Results and the Single Step Method, in kNm, from Törnqvist (2004)

	" as built" scantlings	50% t_{corr} relative to "as built"	Reference scantlings, gross	Change - 1 yield stress 235	Change - 2 yield stress 355	Change - 3 small stiffener
			Note the total deck area is kept constant , i.e. based on the reference gross scantlings			
Single step method	11240000	9923000	12179000	9169000	13571000	11251000
ABAQUS results:						
Imp. model 1	11300000	9810000	12560000			
Imp. model 2	11500000	9990000	12640000	9980000	13890000	12370000
Imp. model 3	12200000	10400000	13550000	10620000	14930000	13060000
Imp. model 4	13200000					
Imp. model 5	13300000	11600000	14410000			
Imp. model 6			13820000			
Imp. model 7			12900000			
Ratio of Abaqus results to the single step method						
Imp. model 1	1.01	0.99	1.03			
Imp. model 2	1.02	1.01	1.04	1.09	1.02	1.10
Imp. model 3	1.09	**1.05**	1.11	1.16	1.10	1.16
Imp. model 4	1.17					
Imp. model 5	1.18	1.17	1.18			
Imp. model 6			1.13			
Imp. model 7			1.06			

<u>Note</u>

ABAQUS imperfection model.

1. deck and ship side - harmonic and regular up-down (eigenmode close), - tolerance level
2. deck only - harmonic and regular up-down (eigenmode close)- tolerance level
3. deck - 0.80 plate hungry horse + 0.2 plate short waved harmonic- tolerance level
4. deck and ship side - Global single span, tolerance level
5. perfect
6. Hungry Horse - 50% of tolerance level
7. Hungry Horse - 200% of tolerance level

1.8.6 Summary of the uncertainties

1.8.6.a Summary of the applied uncertainties are included in *Table 9.1.e*.

Table 9.1.e
Summary of Applied Uncertainties

Variable name	Distribution	Parameters
Response variables:		
Significant wave height	Weibull	see *1.8.1*
Zero-crossing wave period	Lognormal	Function of H_s, see *1.8.1*
Short term extreme wave moment	Gumbel	Function of sea state
Annual extreme wave moment	Numerically computed	see *1.5.2*
Still water moment	Normal	Mean=0.7 times max of manual Std.dev=0.2 times max of manual (+ sensitivity)
Capacity variables:		
Yield strength (normal grade)	Lognormal	Mean=269 N/mm^2, CoV=0.08, Lower limit=0
Yield strength (High strength)	Lognormal	Mean=348 N/mm^2, CoV=0.06, Lower limit=0
Model uncertainties:		
Wave moment, uncertainties in linear result	Normal	Mean=1.0, Std.dev.=0.1
Wave moment, nonlinear effects	Normal	Mean=1.0, Std.dev.=0.1 (+ sensitivity)
Still water moment	Normal	Mean=1.0, Std.dev.=0.1
Capacity calculation	Normal	Mean=1.05, Std.dev.=0.1

1.9 Calibration Results

1.9.1 Annual probability of failure

1.9.1.a For each ship, the annual probability of failure was calculated using the single test case method, see *1.2.5*.

1.9.1.b The following analyses were performed:

- gross, t_{grs}, scantlings, based on the test ship reference scantlings
- 50% t_{corr} net scantlings with $t=t_{grs}-0.5t_{corr}$ applied to all structural members
- 100% t_{corr} net scantlings with $t=t_{grs}-1.0t_{corr}$ applied to all structural members

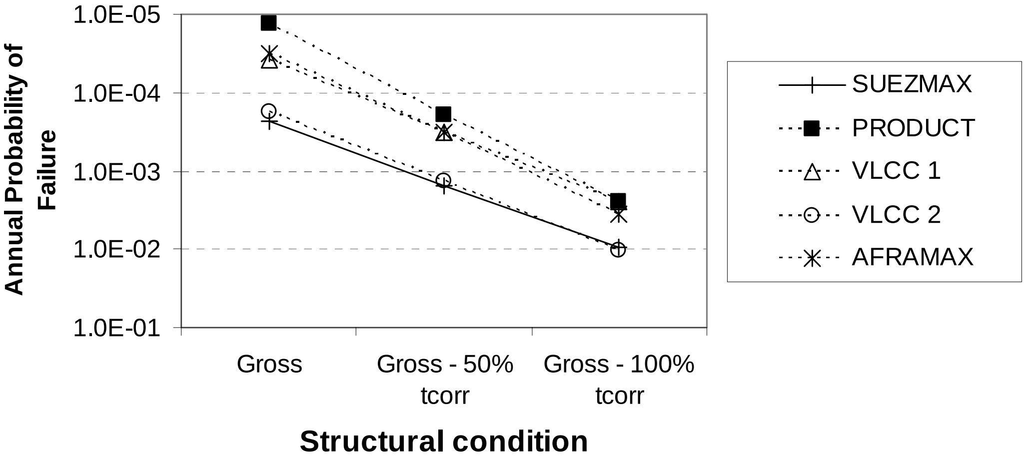
1.9.1.c The results are illustrated in *Figure 9.1.e*. The following notes are made:

(a) The probability of failure increases by a factor near 10 going from gross to 50% t_{corr} net scantlings ($t=t_{grs}-0.5t_{corr}$), and nearly by 100 for gross to 100% t_{corr} net scantlings ($t=t_{grs}-1.0t_{corr}$). The highest consequence of corrosion on the probability of failure is seen for the Product tanker. This is expected since it has the lowest deck plate thickness, and consequently the highest relative reduction in steel area due to t_{corr} deduction.

(b) Considering the net scantling ($t=t_{grs}$-$0.5t_{corr}$) for which the rule applies, the lowest probability of failure obtained ($2x10^{-4}$) is for the Product tanker and the highest ($1.5x10^{-3}$) is for the Suezmax.

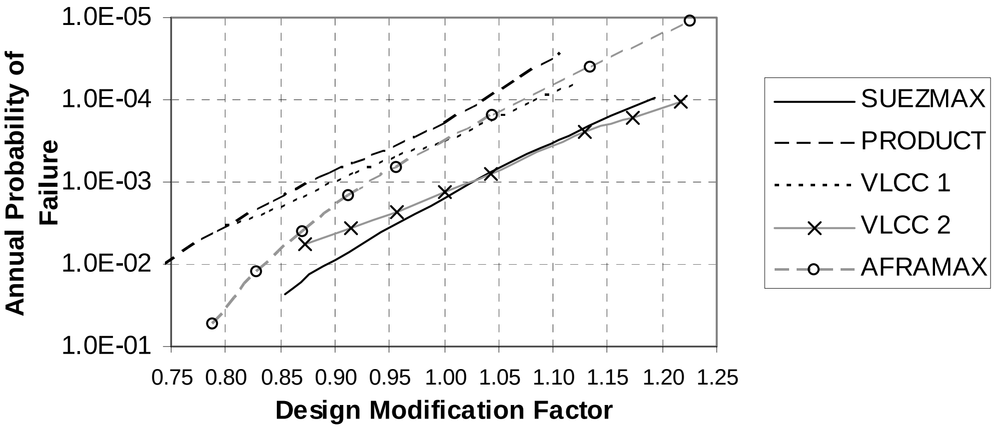
1.9.1.d It should be noted that for overall hull girder ultimate strength, degradation of scantlings to 100% t_{corr} is not permitted; repair is required when the elastic overall hull girder strength properties degrade below those associated with 50% t_{corr} scantlings everywhere in a section.

Figure 9.1.e
Effect of Corrosion on the Annual Probability of Failure, P_f



1.9.1.e The main calibration process was calculated using 50% t_{corr} net scantlings ($t=t_{grs}$-$0.5t_{corr}$) with varying design modification factors. These results are illustrated in *Figure 9.1.f.*

Figure 9.1.f
Probability of Failure as a Function of Design Modification Factor



Note The design modification factor represents the ratio between the modified cross-sectional area of the deck and the cross-sectional area corresponding to the test ship reference scantlings using gross values. The procedure for deck modification is described in *1.7.4*.

1.9.2 Design point values and partial safety factors

1.9.2.a The design point values come from the structural reliability analysis when a First Order or Second Order Reliability Method is used (FORM or SORM), and represent the most likely outcome of variables at failure. The partial safety factor is then the ratio of the design point value to the characteristic value. Partial safety factors are computed for each individual case in the test set corresponding to the design point values for the still water, wave moment and the moment capacity according to the single test case method given in *1.2.5*.

1.9.2.b This has been done for different values of the design modification factor and the results are illustrated in *Figure 9.1.g* and *Figure 9.1.h* as function of the annual probability of failure. The partial safety factors have been derived for the two design combinations to cover the two definitions of the characteristic still water bending moment used. *Figure 9.1.g* represents combination A (permissible SWBM), whereas *Figure 9.1.h* represents combination B (SWBM defined by the homogenous full load condition) , see *1.4.1*.

1.9.2.c Comments to the *Figures 9.1.g*:

(a) The partial safety factors for combination A, characteristic still water bending moment in *Figure 9.1.g* are less than unity and also show reasonable scatter between the various cases. The physical interpretation of this is that the permissible SWBM is higher than the still water bending moment that is most likely to occur at failure. The partial safety factors increase slightly with decreasing probability of failure level. The Suezmax and the Aframax cases have the lowest partial safety factors, which can be explained by the relatively high value of the permissible still water bending moment compared to the homogeneous full load SWBM, see *Table 9.1.b*. To conform with normal practice and an intuitive understanding of partial safety factors, it was decided to set the partial safety factor for still water bending moment to unity, although the results indicate a lower value may be appropriate.

(b) The partial safety factors for combination B characteristic still water bending moment in *Figure 9.1.h* show higher values of the partial safety factor than *Figure 9.1.g*. The difference is equal to the ratio between the two definitions of the characteristic values; i.e. the permissible divided by the homogenous full load value. There is also a scatter for this case and a partial safety factor of unity appears reasonable.

(c) The partial safety factors for the ultimate bending capacity are near 1.1 at target probability levels between 10^{-3} and 10^{-4} and the scatter between the cases is small. This result indicates that the randomness in the capacity is less than in the wave moment; i.e. the lower tail of the capacity distribution has a smaller area than the upper tail of the wave load distribution.

(d) The partial safety factors for the wave bending moment show some scatter between the cases, and the partial safety factors increase more than the other partial safety factors with decreasing probability of failure level.

Figure 9.1.g
Combination A Partial Safety Factors as a Function of Probability of Failure, based on "Single Test Case" Procedure, see *1.2.5*.
The Partial Safety Factors are Applicable for the Permissible Still water Bending Moment Characteristic Value.

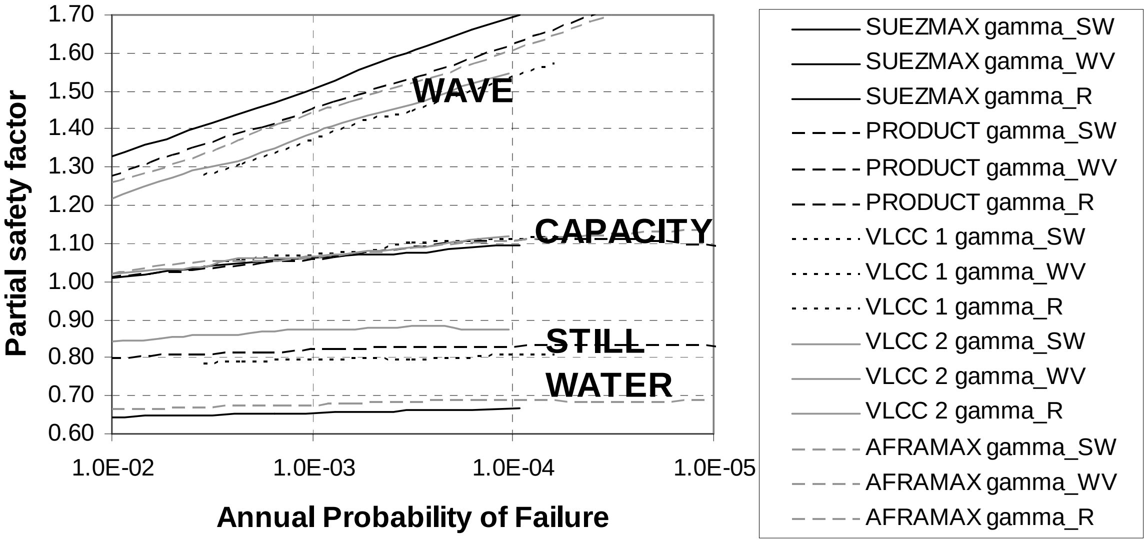
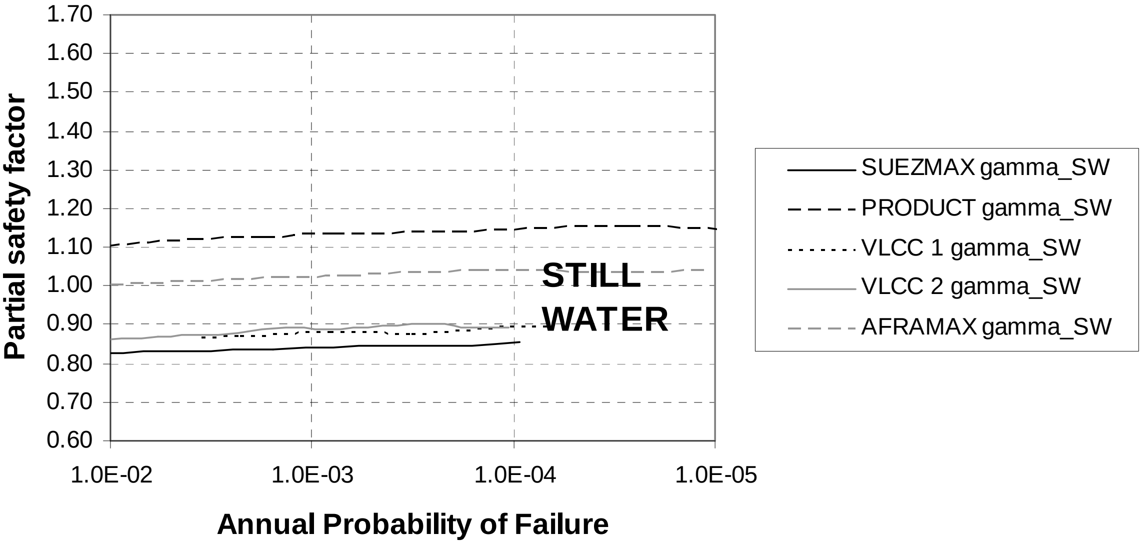


Figure 9.1.h
Combination B Partial Safety Factors as a Function of Probability of Failure, based on "Single Test Case Procedure, see *1.2.5*".
The Partial Safety Factors are Applicable for the Characteristic Value Defined by the Maximum Still Water Bending Moment for the Homogenous Full Load Condition.



Note

The partial safety factors for wave bending moment and ultimate bending moment capacity are the same as for combination A, see *Figure 9.1.g*

1.9.3 Calibration of partial safety factors

1.9.3.a The partial safety factors were calibrated using the procedure outlined in *1.2.6*. In this optimisation the deviation in annual failure probability from target failure probability is calculated for each ship and the optimised partial safety factors are obtained by minimising the objective function in *1.6.3.b.*

1.9.3.b This type of objective function implies a very high penalty on under-design. The N value may also serve as a weighting factor if one wishes to assign different weights to the various cases in the test set. Here the same weight is assumed for each of the 5 ships in the test set. The calibration is performed using an EXCEL spreadsheet.

$$\Delta(P_T, \vec{\gamma}) = \sum_{i=1}^{N} \left(P_T - P_i(\vec{\gamma})\right)^2$$

Where:

P_T	is the target annual probability of failure
$\vec{\gamma}$	is the vector of partial safety factors subjected to calibration
P_i	is the annual probability of failure for case *i* associated with the calibrated partial safety factors
N	the number of cases included in the calibration analysis

1.9.3.c The partial safety factors following the "single test case" procedure in *Figure 9.1.a* are included in *Figure 9.1.g* and *Figure 9.1.h* for several target probability of failure levels. The partial safety factor for the still water bending moment is set to 1.0, to conform with normal practice. A partial safety factor value of 1.1 has then been set for the ultimate bending moment capacity based on the results provided in *Figure 9.1.g*. Finally, the partial safety factor for the wave moment is derived using the above procedure.

1.9.3.d Considerations have also been given to extensive consequence studies and professional judgements during the rule development. An important argument for the two different Rule combinations is that 1) a realistic and likely still water moment corresponding to the homogenous full load condition (Condition B) is combined with an extreme wave load condition defined by a high value of partial safety factor γ_W, as this is a common loading condition for the ship to be in and 2) the permissible value (Condition A) normally exceeds the maximum still water bending moment in loading manual and hence the corresponding lower partial safety factor γ_W accounts for the less likelihood of the ship being in this loading condition.

1.9.3.e Note that the consequences of hull girder failure in full load condition are serious with respect to life, property and the environment. The environmental impact is more serious in loaded condition than in ballast conditions. A risk evaluation of sagging vs. hogging (ballast) would for this reason call for a lower probability of failure in sagging than in hogging. The calibration results are included in *Table 9.1.f.*

Table 9.1.f
Calibrated Partial Safety Factors based on 50% t_{corr}

Target probability of failure P_f	Design load combination	Still water bending moment γ_{SW}	Wave bending moment γ_{WV}	Ultimate bending moment capacity γ_R
10^{-3} *se note 2*	A) Permissible still water bending moment	1.00	1.20	1.10
	B) Maximum bending moment for homogenous full load condition	1.00	1.30	1.10

Notes

1 The target probability of failure P_f is a nominal value and does not correspond to the "real" probability of a tanker failing in sagging. It should not be regarded as an absolute value.. The target probability of failure is not based on statistics of actual failures in service.

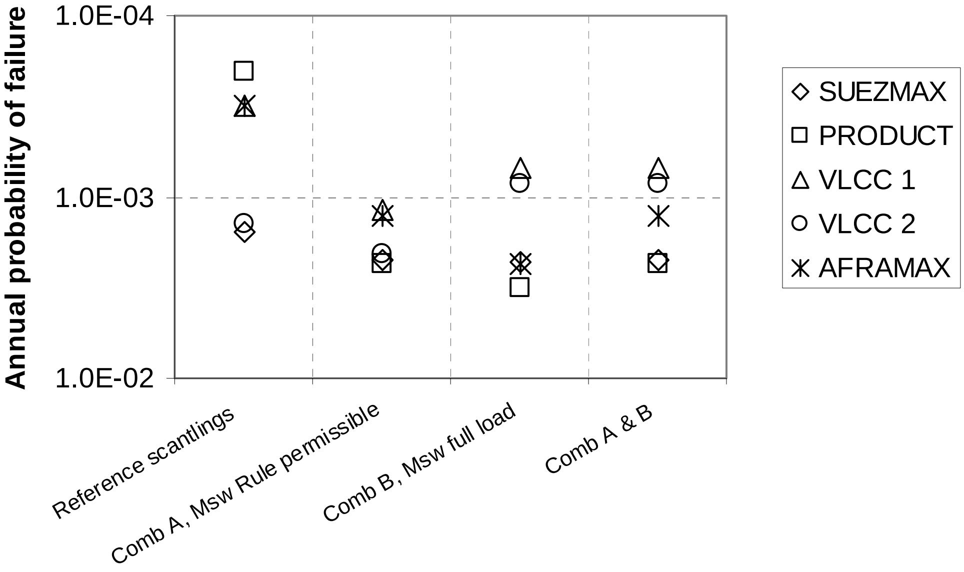
2 Initially a target annual P_f of 10^{-3} was used. As a consequence of IACS harmonization and professional judgements, the resulting partial safety factors and definitions of characteristic values were adjusted and slightly relaxed. The final Rule approximately corresponds to a target annual P_f of $1.5 \cdot 10^{-3}$, based on the relatively strict penalty function in *1.6.3.b*.

1.9.3.f *Figure 9.1.i* shows the resulting probability of failure for the various cases in the test set when the Rule criterion is applied using the partial safety factors as reported in *Table 9.1.f*. The probabilities of failure for reference scantlings of the test ships, taken from *Figure 9.1.e*, are included for reference.

1.9.3.g The Rules require that both Combinations A and B are to be satisfied. Hence the scantlings are to be sufficient to satisfy the combination with the lower probability of failure, which will then automatically satisfy the combination with the higher probability of failure. For the test case ships, the governing combination giving the lower annual probability of failure is Combination A for the Suezmax, Product and Aframax tankers and Combination B for the VLCCs. The "Comb A & B" data in *Figure 9.1.i* shows the probability of failure when both Combinations are satisfied, i.e. based on the lower probability of failure from combination A or B.

1.9.3.h The application of the Rule hull girder ultimate strength requirements to the test ships shows that the reference scantlings are acceptable for all test ships apart from VLCC 2. For VLCC 2 (circle marker), the probability of failure of the reference scantlings is lower than for either of the Combination. The reference scantlings verses "Comb A & B" comparison indicates that sufficient hull girder ultimate strength is usually achieved by satisfying the other requirements in the Rules.

Figure 9.1.i
Probability of Failure Obtained After Calibration.



1.9.4 Consequence evaluations

1.9.4.a The consequences of applying the hull girder ultimate strength Rule requirement have been evaluated in terms of the effect of changing:

(a) the required characteristic ultimate moment capacity M_U given by the hull girder ultimate strength criterion relative to the actual characteristic ultimate strength corresponding to the test ship reference scantlings, see *Figure 9.1.j*.

(b) the deck cross-sectional area to achieve the required characteristic ultimate moment capacity in (a), see *Figure 9.1.k*.

1.9.4.b The left hand bar of *Figure 9.1.j* shows the required M_U taken from the structural reliability analysis results at the target annual probability of failure of 10^{-3}. This result is obtained from the DMF at $P_f=10^{-3}$ in *Figure 9.1.f* and the corresponding M_U in *Figure 9.1.c*. The result is given as a percentage of the actual M_U for the test ship reference scantlings; i.e. M_U for DMF=1.0 in *Figure 9.1.c*. It is seen that increased capacity by 2-3 % is required for the Suezmax and the VLCC 2, explained by the annual probabilities of failure which are higher than 10^{-3} for the reference scantlings of these two ships, see *Figure 9.1.i*.

1.9.4.c The right hand bar of *Figure 9.1.j* shows the Rule required M_U based on application of the calibrated Rule, using the partial safety factors as reported in *Table 9.1.f*. It is seen that the calibrated Rule requires increased capacity compared to that of the reference scantlings for the VLCC 2 case only, by about 3%. The Rule required M_U is lower than that of the reference scantlings for the remaining ships; e.g. the M_U may be reduced by 10% for the Product tanker.

1.9.4.d The difference between the left hand and the right hand bars in *Figure 9.1.j* is because the Rule does not provide exactly the target annual probability of failure, but leaves some scatter around the target, see *Figure 9.1.i*. When the rule (right hand bar) is greater than the structural reliability analysis at result (left hand bar), then the rule gives a conservative design; i.e. with an annual probability of failure lower than 10^{-3}. This is the case for the two VLCCs, see *Figure 9.1.i*.

1.9.4.e *Figure 9.1.k* shows comparable results to those in *Figures 9.1.j*. Here the left hand bar for each case is the DMF corresponding to the target annual probability of failure of 10^{-3}, taken from *Figure 9.1.f*. The right hand bar shows the DMF as a result of the Rule check, using the calibrated partial safety factors as reported in *Table 9.1.f*. Cases where the DMF is less or equal to unity indicate that the hull girder ULS check is not governing; i.e. the M_U corresponding to the reference scantlings already satisfy the Rule requirement. *Figure 9.1.c* provides the one to one link between the DMF and M_U, and hence defines the relationship between *Figure 9.1.j* and *Figure 9.1.k*.

1.9.4.f In the cases where DMF is greater than unity, a reinforcement of the deck relative to the reference scantlings is required to meet the criteria. This is the case for the VLCC 2 only.

1.9.4.g By comparing *Figure 9.1.j* and *9.1.k* it may be seen that the required change in percentage of M_U can be obtained by changing the deck cross-sectional area with almost the same percentage.

Figure 9.1.j

Required M_U by: 1) Structural Reliability Analysis at Target P_f=10^{-3} and 2) Rule (Partial Safety Factors from *Table 9.1.f*). Normalised to the Actual M_U for Test Ship Reference Scantlings.

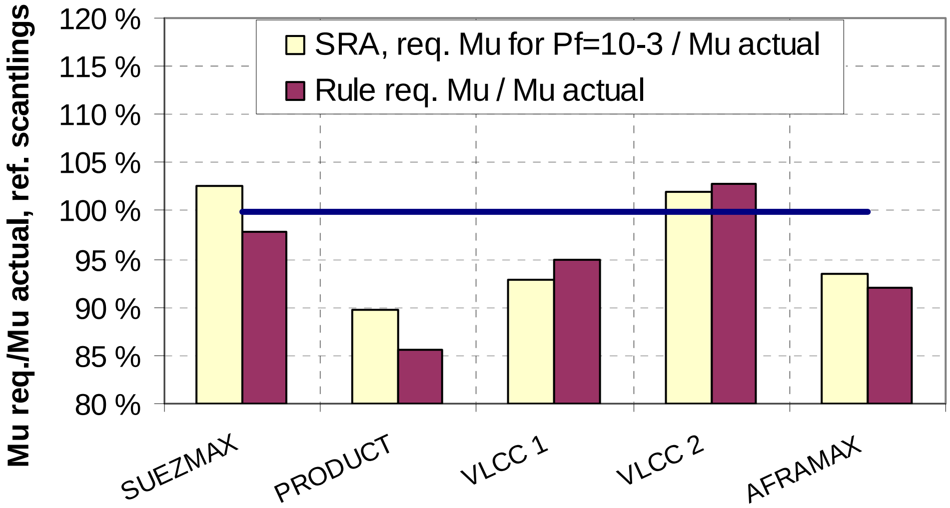
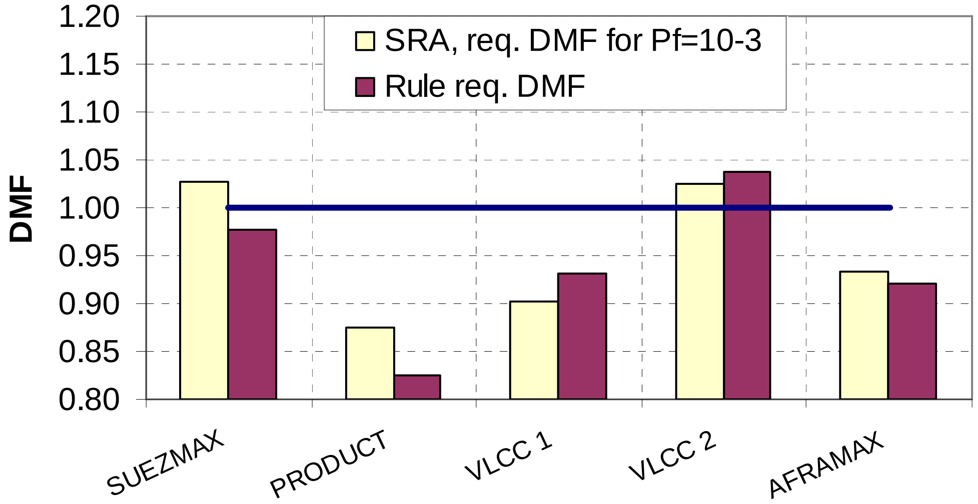


Figure 9.1.k
Required change in deck area (DMF) to achieve: 1) The required M_U by Structural Reliability Analysis at Target P_f =10^{-3} and 2) by The Rule required M_U (Partial Safety Factors from *Table 9.1.f*). .



1.9.5 Target reliability level

1.9.5.a In the previous section, partial safety factors are calibrated for different target probability levels. A target level based on existing structures should be somewhere between 10^{-3} and 10^{-4}.

1.9.5.b A target level based on tabulated values, such as those used in DNV Classification Note 30.6 as included in *Table 9.1.g* indicates a stricter target level. One should, however, keep in mind that the calculated probability of failure is a nominal value which is sensitive to the reliability model and uncertainties applied. It should also be kept in mind that the probability of failure using "net thickness" is near 10 times higher than the gross result.

1.9.5.c North Atlantic environmental conditions are more severe than most other environmental conditions and any benefit of weather routing has not been considered.

1.9.5.d A review of historical data may add some value to the discussion around the target probability of failure, but this has not yet been performed.

1.9.5.e Cost-benefit or cost-effectiveness analysis can be a rational approach to set the target probability of failure, according to the FSA methodology given in the IMO guideline. Such an analysis has not been performed.

Table 9.1.g
Acceptable Annual Probability of Failure

Class of failure	Consequence of failure	
	Less serious	Serious
I - Redundant structure	10^{-3}	10^{-4}
II – Significant warning before the occurrence of failure in a non-redundant structure	10^{-4}	10^{-5}
III – No warning before the occurrence of failure in a non-redundant structure	10^{-5}	10^{-6}

1.9.6 Some sensitivity results

1.9.6.a Sensitivity results in terms of annual probability of failure under different assumptions than those reported above have been carried out for the PRODUCT tanker. The results are included in *Table 9.1.h*.

(a) Jonswap spectrum results in more than twice the probability of failure than when using the Pierson Moskovitz spectrum.

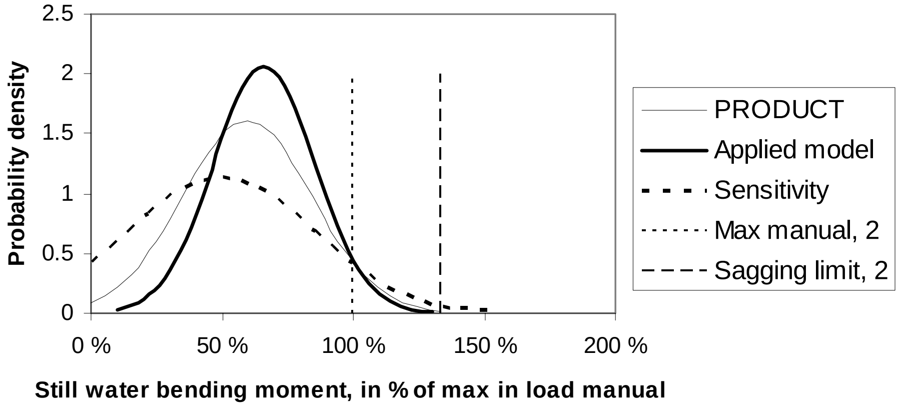
(b) Using a World Wide environmental model instead of the North Atlantic leads to a significant reduction in the probability of failure; i.e. by a factor of 15.

Table 9.1.h
Sensitivity Results, Annual Probability of Failure, Product Tanker

Case description	***Pf***	***Pf/Pf-B.C.***
Base case (B.C.)	2.1×10^{-4}	1.0
Jonswap spectrum	4.7×10^{-4}	2.3
World wide environment	1.5×10^{-5}	0.07
Fixed M_{SW}=564960kNm (max. sagging value in manual)	4.0×10^{-4}	1.9
Fixed M_{SW}=756351kNm (permissible limit value)	1.8×10^{-3}	8.5
M_{SW} distribution, mean=50% of max, std.dev=35% of max.	1.7×10^{-4}	0.83
Model uncertainty, non-linear effects: Normal(μ=1.1, σ=0.1)	5.9×10^{-4}	2.8
Model uncertainty, non-linear effects: Normal(μ=0.9, σ=0.1)	5.4×10^{-5}	0.26
Model uncertainty, non-linear effects: Normal(μ=1.0, σ=0.2)	9.3×10^{-4}	4.4

By modelling the still water moment as a deterministic value equal to the maximum value in the loading manual and without any model uncertainty, the probability of failure doubles. If the specified permissible limit value (for this particular ship) is applied as deterministic, the probability of failure increases by a factor of 8.5. A minor reduction in the probability of failure was obtained when a wider distribution (standard deviation 35% of max) with a lower mean value (50% of max) was used for the still water bending moment. The still water distribution applied for the base case is illustrated together with the maximum sagging value from the loading manual and the specified permissible limit in *Figure 9.1.l*. The distribution as obtained based on the loading manual for the Product tanker is also included, and so is the distribution used for the sensitivity calculation. (The distributions are not truncated at zero, but extend into the hogging range which is not included in the figure.)

Figure 9.1.l
Illustration of the Distribution Versus the Fixed Values and Alternative Distribution as Used for M_{SW} in the Sensitivity Study Results given in *Table 9.1.h*.



1.10 Geometrical Input

1.10.1 General

1.10.1.a The cross-sectional data and panel input for reference scantlings used as basis for the analyses are summarised in *Table 9.1.i*.

Table 9.1.i
Sectional Data and Panel Input for Test Ship Reference Scantlings

	SUEZMAX		PRODUCT		VLCC 1		VLCC 2		ARFAMAX	
	Reference scantlings gross	Reference scantlings 50% t_corr	Reference scantlings gross	Reference scantlings 50% t_corr	Reference scantlings gross	Reference scantlings 50% t_corr	Reference scantlings gross	Reference scantlings 50% t_corr	Reference scantlings gross	Reference scantlings 50% t_corr
Sectional data										
Moment of inertia, elastic (mm4)	5.55E+14	5.02E+14	1.55E+14	1.37E+14	1.45E+15	1.32E+15	1.38E+15	1.25E+15	3.80E+14	3.40E+14
Total hull girder crossectional area (mm2)	6830400	6177000	3199200	2830800	10419800	9475000	10565600	9610200	5414500	4853400
Height, base line to deck (mm)	22400	22400	17600	17600	31000	31000	29700	29700	21000	21000
Neutral axis (from base line), elastic (mm)	10061	10090	7590	7612	13577	13583	12605	12549	9270	9284
Total deck area, plates + stiffeners (mm2)	1380800	1249250	581880	508068	1675500	1510136	1637820	1466122	1028944	919794
Height difference, deck centerline to side	1150	1150	600	600	1300	1300	1400	1400	1050	1050
Typical deck panel data (for PULS)										
Panel length (mm)	5450	5450	5360	5360	5120	5120	5600	5600	3700	3700
Plate thickness (mm)	22.5	20.5	15	13	21	19	19.5	17.5	19.5	17.5
Stiffener spacing (mm)	900	900	800	800	911	911	853	853	891	891
Stiffener height (mm)	400	400	350	350	418	418	418	418	300	300
Web thickness (mm)	11.5	10	12	10.5	12	10.5	12	10.5	11	9.5
Flange width (mm)	100	100	100	100	150	150	110	110	90	90
Flange thickness (mm)	16	14.5	17	15.5	18	16.5	18	16.5	16	14.5
Flange eccenticity (mm)	44.25	44.25	44	44	0	0	0	0	39.5	39.5
Modulus of elasticity (MPa)	208000	208000	208000	208000	208000	208000	208000	208000	208000	208000
Poissons ratio	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Yield strength plate (MPa)	315	315	235	235	315	315	315	315	315	315
Yield strength stiffener (MPa)	315	315	235	235	315	315	315	315	315	315
Breadth moulded, B	48000	48000	27400	27400	58000	58000	60000	60000	42000	42000
Total number of stiffeners	50	50	30	30	61	61	69	69	46	46

Note
The number of stiffeners defined in the buckling check was set to 6.

1.11 References

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