



Guidelines for Fatigue Assessment of Steel Ships and Offshore Units

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**Guidance Note
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MARINE & OFFSHORE DIVISION

GENERAL CONDITIONS

ARTICLE 1

1.1. - BUREAU VERITAS is a Society the purpose of whose Marine & Offshore Division (the "Society") is the classification ("Classification") of any ship or vessel or offshore unit or structure of any type or part of it or system therein collectively hereinafter referred to as a "Unit" whether linked to shore, river bed or sea bed or not, whether operated or located at sea or in inland waters or partly on land, including submarines, hovercrafts, drilling rigs, offshore installations of any type and of any purpose, their related and ancillary equipment, subsea or not, such as well head and pipelines, mooring legs and mooring points or otherwise as decided by the Society.

The Society:

- "prepares and publishes Rules for classification, Guidance Notes and other documents ("Rules");
- "issues Certificates, Attestations and Reports following its interventions ("Certificates");
- "publishes Registers.

1.2. - The Society also participates in the application of National and International Regulations or Standards, in particular by delegation from different Governments. Those activities are hereafter collectively referred to as "Certification".

1.3. - The Society can also provide services related to Classification and Certification such as ship and company safety management certification; ship and port security certification, training activities; all activities and duties incidental thereto such as documentation on any supporting means, software, instrumentation, measurements, tests and trials on board.

1.4. - The interventions mentioned in 1.1., 1.2. and 1.3. are referred to as "Services". The party and/or its representative requesting the services is hereinafter referred to as the "Client". The Services are prepared and carried out on the assumption that the Clients are aware of the International Maritime and/or Offshore Industry (the "Industry") practices.

1.5. - The Society is neither and may not be considered as an Underwriter, Broker in ship's sale or chartering, Expert in Unit's valuation, Consulting Engineer, Controller, Naval Architect, Manufacturer, Ship-builder, Repair yard, Charterer or Shipowner who are not relieved of any of their expressed or implied obligations by the interventions of the Society.

ARTICLE 2

2.1. - Classification is the appraisalment given by the Society for its Client, at a certain date, following surveys by its Surveyors along the lines specified in Articles 3 and 4 hereafter on the level of compliance of a Unit to its Rules or part of them. This appraisalment is represented by a class entered on the Certificates and periodically transcribed in the Society's Register.

2.2. - Certification is carried out by the Society along the same lines as set out in Articles 3 and 4 hereafter and with reference to the applicable National and International Regulations or Standards.

2.3. - It is incumbent upon the Client to maintain the condition of the Unit after surveys, to present the Unit for surveys and to inform the Society without delay of circumstances which may affect the given appraisalment or cause to modify its scope.

2.4. - The Client is to give to the Society all access and information necessary for the safe and efficient performance of the requested Services. The Client is the sole responsible for the conditions of presentation of the Unit for tests, trials and surveys and the conditions under which tests and trials are carried out.

ARTICLE 3

3.1. - The Rules, procedures and instructions of the Society take into account at the date of their preparation the state of currently available and proven technical knowledge of the Industry. They are a collection of minimum requirements but not a standard or a code of construction neither a guide for maintenance, a safety handbook or a guide of professional practices, all of which are assumed to be known in detail and carefully followed at all times by the Client.

Committees consisting of personalities from the Industry contribute to the development of those documents.

3.2. - The Society only is qualified to apply its Rules and to interpret them. Any reference to them has no effect unless it involves the Society's intervention.

3.3. - The Services of the Society are carried out by professional Surveyors according to the applicable Rules and to the Code of Ethics of the Society. Surveyors have authority to decide locally on matters related to classification and certification of the Units, unless the Rules provide otherwise.

3.4. - The operations of the Society in providing its Services are exclusively conducted by way of random inspections and do not in any circumstances involve monitoring or exhaustive verification.

ARTICLE 4

4.1. - The Society, acting by reference to its Rules:

- "reviews the construction arrangements of the Units as shown on the documents presented by the Client;
- "conducts surveys at the place of their construction;
- "classes Units and enters their class in its Register;
- "surveys periodically the Units in service to note that the requirements for the maintenance of class are met.

The Client is to inform the Society without delay of circumstances which may cause the date or the extent of the surveys to be changed.

ARTICLE 5

5.1. - The Society acts as a provider of services. This cannot be construed as an obligation bearing on the Society to obtain a result or as a warranty.

5.2. - The certificates issued by the Society pursuant to 5.1. here above are a statement on the level of compliance of the Unit to its Rules or to the documents of reference for the Services provided for. In particular, the Society does not engage in any work relating to the design, building, production or repair checks, neither in the operation of the Units or in their trade, neither in any advisory services, and cannot be held liable on those accounts. Its certificates cannot be construed as an implied or express warranty of safety, fitness for the purpose, seaworthiness of the Unit or of its value for sale, insurance or chartering.

5.3. - The Society does not declare the acceptance or commissioning of a Unit, nor of its construction in conformity with its design, that being the exclusive responsibility of its owner or builder.

5.4. - The Services of the Society cannot create any obligation bearing on the Society or constitute any warranty of proper operation, beyond any representation set forth in the Rules, of any Unit, equipment or machinery, computer software of any sort or other comparable concepts that has been subject to any survey by the Society.

ARTICLE 6

6.1. - The Society accepts no responsibility for the use of information related to its Services which was not provided for the purpose by the Society or with its assistance.

6.2. - If the Services of the Society or their omission cause to the Client a damage which is proved to be the direct and reasonably foreseeable consequence of an error or omission of the Society, its liability towards the Client is limited to ten times the amount of fee paid for the Service having caused the damage, provided however that this limit shall be subject to a minimum of eight thousand (8,000) Euro, and to a maximum which is the greater of eight hundred thousand (800,000) Euro and one and a half times the above mentioned fee. These limits apply regardless of fault including breach of contract, breach of warranty, tort, strict liability, breach of statute, etc.

The Society bears no liability for indirect or consequential loss whether arising naturally or not as a consequence of the Services or their omission such as loss of revenue, loss of profit, loss of production, loss relative to other contracts and indemnities for termination of other agreements.

6.3. - All claims are to be presented to the Society in writing within three months of the date when the Services were supplied or (if later) the date when the events which are relied on were first known to the Client, and any claim which is not so presented shall be deemed waived and absolutely barred. Time is to be interrupted thereafter with the same periodicity.

ARTICLE 7

7.1. - Requests for Services are to be in writing.

7.2. - Either the Client or the Society can terminate as of right the requested Services after giving the other party thirty days' written notice, for convenience, and without prejudice to the provisions in Article 8 hereunder.

7.3. - The class granted to the concerned Units and the previously issued certificates remain valid until the date of effect of the notice issued according to 7.2. here above subject to compliance with 2.3. here above and Article 8 hereunder.

7.4. - The contract for classification and/or certification of a Unit cannot be transferred neither assigned.

ARTICLE 8

8.1. - The Services of the Society, whether completed or not, involve, for the part carried out, the payment of fee upon receipt of the invoice and the reimbursement of the expenses incurred.

8.2. - Overdue amounts are increased as of right by interest in accordance with the applicable legislation.

8.3. - The class of a Unit may be suspended in the event of non-payment of fee after a first unfruitful notification to pay.

ARTICLE 9

9.1. - The documents and data provided to or prepared by the Society for its Services, and the information available to the Society, are treated as confidential. However:

- "Clients have access to the data they have provided to the Society and, during the period of classification of the Unit for them, to the classification file consisting of survey reports and certificates which have been prepared at any time by the Society for the classification of the Unit ;
- "copy of the documents made available for the classification of the Unit and of available survey reports can be handed over to another Classification Society, where appropriate, in case of the Unit's transfer of class;
- "the data relative to the evolution of the Register, to the class suspension and to the survey status of the Units, as well as general technical information related to hull and equipment damages, may be passed on to IACS (International Association of Classification Societies) according to the association working rules;
- "the certificates, documents and information relative to the Units classed with the Society may be reviewed during certifying bodies audits and are disclosed upon order of the concerned governmental or inter-governmental authorities or of a Court having jurisdiction.

The documents and data are subject to a file management plan.

ARTICLE 10

10.1. - Any delay or shortcoming in the performance of its Services by the Society arising from an event not reasonably foreseeable by or beyond the control of the Society shall be deemed not to be a breach of contract.

ARTICLE 11

11.1. - In case of diverging opinions during surveys between the Client and the Society's surveyor, the Society may designate another of its surveyors at the request of the Client.

11.2. - Disagreements of a technical nature between the Client and the Society can be submitted by the Society to the advice of its Marine Advisory Committee.

ARTICLE 12

12.1. - Disputes over the Services carried out by delegation of Governments are assessed within the framework of the applicable agreements with the States, international Conventions and national rules.

12.2. - Disputes arising out of the payment of the Society's invoices by the Client are submitted to the Court of Nanterre, France, or to another Court as deemed fit by the Society.

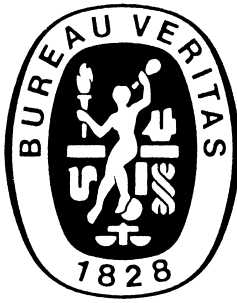
12.3. - Other disputes over the present General Conditions or over the Services of the Society are exclusively submitted to arbitration, by three arbitrators, in London according to the Arbitration Act 1996 or any statutory modification or re-enactment thereof. The contract between the Society and the Client shall be governed by English law.

ARTICLE 13

13.1. - These General Conditions constitute the sole contractual obligations binding together the Society and the Client, to the exclusion of all other representation, statements, terms, conditions whether express or implied. They may be varied in writing by mutual agreement. They are not varied by any purchase order or other document of the Client serving similar purpose.

13.2. - The invalidity of one or more stipulations of the present General Conditions does not affect the validity of the remaining provisions.

13.3. - The definitions herein take precedence over any definitions serving the same purpose which may appear in other documents issued by the Society.



GUIDANCE NOTE NI 611

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SECTION 1

GENERAL CONSIDERATIONS

Symbols

The following is a summary of the main symbols used throughout the Guidance Note:

E	: Young's Modulus, in N/mm ²
D	: Fatigue damage ratio
K_g	: Geometric stress concentration factor
L	: Floating unit rule length, in m
R_{eH}	: Specified minimum yield stress, in N/mm ²
R_m	: Specified minimum ultimate tensile strength, in N/mm ²
T_{DF}	: Design fatigue life, in years
T_{Prot}	: Time during which the fatigue detail is considered as protected against corrosion, in years
$\Delta\sigma$	: Stress range, in N/mm ² .

Other symbols are locally defined in Section where they are used.

1 Scope of application

1.1 Purpose

1.1.1 This Guidance Note provides guidelines for the assessment of fatigue capacity of marine and offshore structures throughout their entire life i.e. at design stage and during their service life.

Guidance for fatigue assessment is given for welded details and non-welded details (cut edge details, bolted connections) of marine and offshore structures as detailed in [1.2.1].

This Guidance Note presents recommendations in relation to fatigue analysis based on S-N curves approach or fracture mechanics approach including safety margin.

1.1.2 At design stage, the aim is to ensure that critical details are adequately designed to reach the required fatigue life. The associated fatigue assessment methodology is based on S-N curve/cumulative damage approach and several stress assessment methods are proposed according to the fatigue failure modes.

1.1.3 During service life, fatigue assessment may be necessary in the following cases:

- prior to a survey in view to optimize the inspection program
- for life extension study
- for repair when a fatigue failure is detected during an inspection.

Fatigue assessment may be performed either by means of S-N curve/cumulative damage approach for life extension for example or by means of fracture mechanics analysis for repair decision when cracks are detected.

1.2 Application

1.2.1 Types of structures

This Guidance Note is applicable for evaluation of fatigue strength of the following marine structures:

- sea-going steel ships
- floating steel offshore units
- fixed steel offshore structures such as jacket structures made of a frame of welded tubular steel members which is piled into the seabed (towers mentioned in API and ISO are not addressed).

1.2.2 Types of environment

Four types of fatigue detail conditions are considered:

- in air
- in corrosive environment without protection
- in corrosive environment with cathodic protection
- in corrosive environment with protective coating.

2 Definitions

2.1

2.1.1 Applicable rules

This means the rules or standards applicable for the design of the ship or offshore unit for which fatigue calculations are performed.

2.1.2 Constant amplitude loading

A type of loading causing a regular stress fluctuation with constant magnitudes of maximum and minimum stresses.

2.1.3 Crack propagation rate

Increase of crack size per stress cycle.

2.1.4 Crack propagation threshold

Limiting value of stress intensity factor range below which the crack propagation can be considered as negligible, i.e. stress cycles are not damaging.

2.1.5 Cycle counting method

A procedure for stress range counting from a stress time history. The “Rainflow” counting method is a standardized cycle counting method.

2.1.6 Eccentricity

Misalignment of plates at welded connections.

2.1.7 Equivalent stress range

For practical reasons, an equivalent stress range is defined in this Guidance Note to take into account the factors influencing the fatigue strength. It corresponds to the reference fatigue stress range affected by the correction that should have theoretically been applied to the S-N curve.

2.1.8 Fatigue

Process of deterioration of a structure subjected to fluctuating stresses, going through several stages from the initial “crack-free” state to a “failure” state.

2.1.9 Fatigue damage ratio

Ratio of the number of applied stress cycles and the corresponding number of stress cycles to failure at constant stress range (by use of S-N curve).

2.1.10 Fatigue life

Total time corresponding to the number of stress cycles required to cause fatigue failure of the component. The fatigue life is generally expressed in terms of number of years.

2.1.11 Fatigue limit

Stress range for which the fatigue strength under constant amplitude loading corresponds to a number of cycles large enough to be considered as infinite by a design code.

2.1.12 Fracture mechanics

A branch of mechanics dealing with the behavior and strength of components containing cracks. Fracture mechanics cover the domains of brittle fracture and crack propagation.

2.1.13 Geometric stress

The value of structural stress on the surface at the structural discontinuity.

2.1.14 Hot spot

A location in a structure where a fatigue crack may initiate, due to the combined effect of the structural stress fluctuation and of a stress concentration effect induced by a structural discontinuity such as a weld. It corresponds to the point where the geometric stress range is maximum.

2.1.15 Hot spot stress

The value of structural stress on the surface at the hot spot. Hot spot stress is defined as the maximum geometric stress relative to the structural discontinuity.

2.1.16 Local nominal stress

Nominal stress including macro-geometric effects, concentrated load effects and misalignments, but disregarding the stress raising effects due to structural discontinuities and due to the welded joint itself.

2.1.17 Loading condition

A loading condition is a distribution of weights carried in the ship or offshore unit spaces.

2.1.18 Load case

A load case is a state of the ship or offshore unit structure subjected to a combination of loads.

2.1.19 Local notch

A local notch is a localized geometric feature, such as the toe of a weld, which causes stress concentration. The local notch does not modify the structural stress but generates a non-linear stress peak.

2.1.20 Macro-geometric discontinuity

A global discontinuity such as a large opening, a curved part in a beam, a bend in a flange not supported by diaphragms or stiffeners, discontinuities in pressure containing shells, eccentricity in a lap joint.

2.1.21 Macro-geometric effect

A stress raising effect due to macro-geometric discontinuity in the vicinity of the welded joint, but not due to the welded joint itself.

2.1.22 Membrane stress

Average normal stress across the thickness of a plate or shell.

2.1.23 Miner sum

Summation of individual fatigue damage ratios caused by each stress cycle or stress range block according to the Palmgren-Miner rule.

2.1.24 Misalignment

Axial and angular misalignments caused either by detail design or by poor fabrication or welding distortion.

2.1.25 Nominal stress

A stress in a structural component, disregarding the stress raising effects due to structural discontinuities and due to the welded joint itself, calculated using general theories, e.g. beam theory.

2.1.26 Non-linear stress peak

The stress component of a notch stress which exceeds the linearly distributed structural stress at a local notch.

2.1.27 Paris's law

An experimentally determined relation between fatigue crack growth rate and stress intensity factor range (fracture mechanics).

2.1.28 Palmgren-Miner rule

Method for estimating fatigue life under variable amplitude loading from the constant amplitude S-N curve. Often referred to as Miner's rule.

2.1.29 Reference fatigue stress range

Stress range calculated for a dynamic load case at a given probability level and used as a reference to build a long-term stress range distribution when using rule based approach.

2.1.30 Shell bending stress

Bending stress in a shell or plate-like part of a component, linearly distributed across the thickness as assumed in the theory of shells.

2.1.31 S-N curve

Graphical presentation of the dependence of the number of stress cycles to failure (N) on the applied constant stress range ΔS , also known as Wöhler curve.

2.1.32 Stress cycle

A part of a stress history containing a stress maximum and a stress minimum.

2.1.33 Stress history

A time-based presentation of a fluctuating stress for either the total life or a certain period of time.

2.1.34 Stress intensity factor

Factor used in fracture mechanics to characterize the stress field at the vicinity of a crack tip.

2.1.35 Stress range

The difference between the maximum and minimum stresses in a stress cycle.

2.1.36 Stress range exceedance

A tabular or graphical presentation of the cumulative number of occurrences of stress range exceedance, i.e. the number of stress ranges exceeding a particular magnitude of stress range in stress history.

2.1.37 Stress ratio

Ratio of minimum to maximum stress values in a stress cycle.

2.1.38 Structural discontinuity

A geometric discontinuity due to the structural detail of the welded joint, but excluding the discontinuity due to the weld itself.

2.1.39 Structural stress

A stress in a component, calculated to take into account the effects of a structural discontinuity, and consisting of membrane and shell bending stress components.

2.1.40 Structural (or geometric) stress concentration factor

The ratio of the geometric stress to the local nominal stress.

2.1.41 Variable amplitude loading

A type of loading causing irregular stress fluctuation with stress ranges (and amplitudes) of variable magnitude.

2.1.42 Weld root structural stress

The stress corresponding to the maximum value of structural stress at the weld root.

3 Assumptions

3.1 Material

3.1.1 Yield stress

This Guidance Note is valid for ferritic/pearlitic or bainitic structural steel materials with specified minimum yield stress R_{eH} not greater than:

- 960 MPa for details in air
- 500 MPa for details in corrosive environment under free corrosion or with cathodic protection.

3.2 Temperature

3.2.1 Domain of application

For design temperatures up to 100°C, the steel material properties at room temperature may be considered.

For design temperatures greater than 100°C, the decrease of fatigue strength with the temperature increase is to be considered. IIW Fatigue Recommendations (IIW-XIII-1823-07, 2008) propose fatigue strength reduction factor for steel at temperatures greater than 100°C and less than 600°C.

Special attention should be paid to the validity of S-N curves and of fracture mechanics material characteristics for low temperature applications.

3.3 Corrosion

3.3.1 General

The effects of corrosive environment on fatigue life are taken into account by means of:

- Increase of stress in the considered detail due to thickness decrease induced by corrosion phenomenon
Net scantling concept is to be used as described in [3.3.2].

- Decrease of fatigue strength

The corrosive environment, such as sea water, decreases the fatigue resistance and modifies the S-N curves (see Sec 10, [6]).

3.3.2 Corrosion allowances

Appropriate corrosion allowances are to be considered (gross thickness reduction or net thickness increment) taking into account possible thickness reductions during the expected life of the structure, according to corrosion exposure for each type of structural components. Recommendations for minimum corrosion allowance recommendations are provided in the applicable rules.

Net scantlings are to be considered throughout the Guidance Note, as specified in the applicable rules.

3.3.3 Local stress and global stress corrosion allowances

The applicable rules may prescribe two different corrosion allowances, to be applied separately for the computation of global stress on one hand, and of local stress on the other hand. The corrosion allowances are typically higher for local stress calculation than for global stress calculation.

In such a case, two different approaches are proposed in this Guidance Note:

- A single structural model is used, for simplification reasons or in case where the global and local stress cannot be evaluated separately

In this case, some stress correction factors need to be applied in order to take into account, in a simplified way, the difference between the prescribed corrosion allowances and those in the structural model. These correction factors are introduced in Sec 3 and in Sec 11. The correction factors values to be used are given in the applicable rules.

- Two different structural models with the associated appropriate corrosion allowances are used for determining separately the local and global stress, using analytical models for example

In this case no stress correction is needed and correction factors are taken equal to 1,0.

4 Fatigue process in ship and offshore unit structures

4.1

4.1.1 Fatigue failure process

For steel structures, the fatigue process includes three main phases:

- initiation of crack at a hot spot location
- crack propagation or crack growth, and
- final failure by ductile tearing or brittle fracture, when the crack has reached a critical size.

4.1.2 Fatigue failure modes

For welded or cut edge details, fatigue crack growth to failure may occur according to several failure modes, as follows:

- weld toe failure: fatigue crack initiates from the weld toe and grows into the base material
- weld root failure: fatigue crack initiates from the weld root and grows through the weld throat or into the plate section under the weld
- cut edge failure: fatigue crack initiates from surface irregularity or notch at cut edge details and grows into the base material
- bolted connections failure.

The fatigue strength in each of these modes is substantially different, and every failure mode should be checked.

4.1.3 High-cycle / low-cycle fatigue

The fatigue phenomenon is normally divided in two different domains:

- high stress, low-cycle fatigue occurring for a low number of cycles, less than 10^4 , in the range of plastic deformations
- low stress, high-cycle fatigue occurring for a large number of cycles more than 10^4 , in the range of elastic deformations.

High-cycle fatigue is due to wave load cycles: it is the most common cause for fatigue cracking. During a service life of 20 to 25 years, sea-going ships will normally encounter between $6 \cdot 10^7$ to 10^8 wave load cycles.

Low cycles events may correspond to loading/unloading operations. Changing of loading condition from ballast to loaded condition generates fluctuating stress cycles, typically on primary supporting members connections. A typical example of low-cycle fatigue is units frequently subjected to loading and discharge operations like FPSO and FSO or ships with specific operational profile such as shuttle tankers.

5 Methodology

5.1 General

5.1.1 Fatigue assessment of structural details may be based on either one of the following approaches:

- S-N curves approach, which is appropriate for the initiation phase. It is used when no crack is considered. This approach is detailed in [5.2.1]
- Fracture mechanics approach, which is appropriate for the propagation phase. It is used when a crack is considered. This approach is detailed in [5.2.2].

5.2 Approaches for fatigue assessment

5.2.1 S-N curves approach

This approach is based on fatigue tests (S-N curves) combined with linear cumulative damage (Miner's law). Fatigue damage calculation procedure as detailed in Sec 11 is based on S-N curves approach. The calculated fatigue life is derived from the fatigue damage.

The achieved fatigue life is to be compared with the specified design fatigue life.

The following fatigue damage calculation procedures may be used:

a) Simplified approach based on equivalent design wave

Typically, it may be used for ship hull and offshore unit hull structures for which rule loads are defined. Stresses are based on analytical rule loads given at an appropriate probability level. They may be calculated by structural analysis (analytical analysis or finite element method). In this approach, a Weibull distribution is assumed for the long-term stress range distribution allowing a closed form approach fatigue damage.

b) Spectral calculation, where the environment is described by series of short-term spectra

This method may be used for ships, offshore floating or fixed units. It is a practical method allowing to represent the random nature of the wave environment. This approach assumes the linear load effect and linear stress response. Thus, suitable linearization of non-linear elements in the problem formulations is to be done.

c) Direct time-domain calculation, where the short-term spectra are used to generate time series of wave elevation

Time domain simulations are used for the non-linear response of the structure when dynamic effects are large. Full time domain simulation is the most accurate method to capture the combined high frequency (dynamic), wave frequency and low frequency responses but it is computer time consuming. In addition, resulting stress time series shall be post-processed using a cycle counting procedure to derive stress ranges to be considered for fatigue analysis. This method may be used for estimation of non-linear fatigue including whipping contribution to fatigue damage.

5.2.2 Fracture mechanics approach

This approach may be used to evaluate the residual life of in-service structure which involves existing cracks. It allows estimating the time of propagation of a crack with a specified initial size up to the final crack size corresponding to the failure criteria.

The failure criteria may correspond to a through thickness crack or a specific size of the crack leading to a brittle or ductile rupture.

Two levels of analysis may be used, depending on the complexity of the structure:

a) A simplified analytical method, which involves the following assumptions:

- stress determination in the intact structure
- calculation of the Stress Intensity Factors with an analytical solution
- no explicit stress redistribution while the crack is growing

b) An advanced approach, which involves the following assumptions:

- crack included in the FEM model
- calculation of the stress intensity factors by FEM
- explicit stress redistribution while the crack is growing.

5.3 Design stage fatigue assessment

5.3.1 Fatigue approach

The fatigue assessment of structural details at design stage is to be performed according to S-N curves approach.

Fatigue assessment is to be performed for structural details in order to prevent the following fatigue failure modes occurring:

- weld toe failure
- weld root Failure
- cut edge failure
- bolted connections failure.

The stress assessment methods for each of these fatigue failure modes are detailed in [5.3.2] to [5.3.5].

5.3.2 Weld toe failure assessment

Weld toe failure assessment requires to determine the stress at the weld toe according to the hot spot stress approach as detailed in Sec 3 to Sec 6 according to the type of structural analysis.

In this case, two stress assessment methods may be used, as required by the applicable rules:

- Hot spot stress calculation based on geometric stress concentration factor according to Sec 3 and Sec 4

The hot spot stress is based on analytical approach: it is obtained by multiplying the nominal stress by a geometric stress concentration factor (K_g).

- Hot spot stress calculation by FEM

Hot spot stress is calculated directly by a very fine mesh FE analysis according to Sec 5 for plated joints and Sec 6 for tubular joints.

5.3.3 Weld root failure assessment

Weld root failure assessment requires to determine the weld stress by FEM analysis or by an analytical approach according to Sec 7.

5.3.4 Cut edge failure assessment

Cut edge failure assessment requires to determine the local nominal stress at the hot spot according to Sec 5.

5.3.5 Bolted connections failure assessment

Bolted Connections failure assessment requires to determine the nominal stress, according to Sec 8.

5.4 In service life

5.4.1 Survey, inspection program

To help the definition of an inspection program, a fatigue assessment based on cumulative damage may be performed following the same procedure as for design, but using the estimated actual past load history.

The results allow to determine the most loaded areas and details with respect to cumulative fatigue.

5.4.2 Life extension

For life extension study, a fatigue assessment of the unit is to be performed following the same procedure as for design, including:

- a) calculation of the cumulative fatigue damage using the estimated actual past load history
- b) calculation of the cumulative damage for the expected following life time using the design load history limited to this time
- c) verification of the cumulative fatigue acceptance according to applicable rules.

5.4.3 In service failure

When a fatigue crack is detected during inspection, a fatigue analysis may be performed to evaluate possible repair solutions.

Fatigue crack propagation analysis (see Sec 12) may also be applied in order to plan repairs, taking into account the constraints due to operating conditions.

SECTION 2 LOADS TO BE CONSIDERED FOR FATIGUE ANALYSIS

1 Ships and floating offshore units

1.1

1.1.1 The common loads to be considered for fatigue analysis of hull details are as follows:

- hydrostatic internal liquid and external sea pressures
- inertial internal liquid pressure and wave sea pressures
- static loads resulting from fixed weights subjected to gravity
- inertial loads resulting from fixed weights subjected to accelerations induced by ship motions.

1.1.2 The hull girder loads to be considered for ships and ship-shaped offshore units are:

- hull girder still water loads such as bending moment and shear force resulting from internal weights (lightship, containers, bulks, liquids...) and external hydrostatic sea pressure
- hull girder wave induced loads such as wave bending moments, wave torque (only for ships with large deck openings such as bulk carriers and container ships) and shear forces resulting from inertial loads and external wave sea pressure.

1.1.3 When relevant, the following additional loads may be considered:

- loads due to cargo loading and unloading
- dynamic loads due to impact loads such as slamming, sloshing
- dynamic loads due to natural hull girder vibration (springing response)
- operational loads.

1.1.4 Additional loads for offshore units

Mooring loads are to be taken into account for hull foundations of permanent mooring equipment, and for turret/hull interface in case of turret moored offshore unit.

For units fitted with risers, the riser loads cycles are to be taken into account for fatigue assessment of riser supports and their foundations.

1.1.5 The following loads are not considered for fatigue analysis in this Guidance Note:

- dynamic loads resulting from main engine or propeller induced vibratory forces
- transient loads such as thermal stresses.

1.2 Loading conditions

1.2.1 The loading conditions, as well as the fraction of time for each loading condition over the life of the ship, to be considered for fatigue analysis are to be selected according to the applicable rules.

In this Guidance Note, quantities related to a particular loading condition are denoted with a (j) subscript.

1.2.2 Loading/unloading

For the analysis of fatigue due to loading/unloading process, a sequence of still water loads (loading conditions) representative of an entire loading and unloading sequence is to be used to derive the maximum stress ranges.

1.3 Rule calculations

1.3.1 Load cases

Load cases for fatigue assessment are to be selected according to the applicable rules. The load cases are associated to a reference level of probability p_R (meaning that the long-term probability for the wave loads to exceed the wave loads in the load case is equal to p_R) defined in the applicable rules. $p_R = 10^{-2}$ is the recommended value for fatigue load cases.

Load cases to be considered for fatigue assessment are to be selected according to the applicable rules.

For each loading condition defined above, all fatigue load cases are to be considered to determine the fatigue damage as per Sec 11.

1.4 Spectral and time domain calculations

1.4.1 Operational conditions

The operational conditions to be considered are as follows:

- Environmental conditions (scatter diagram, wave spectrum)

The wave scatter diagram is to be representative of the operational route or area. Wave spectrum (e.g. Pierson-Moskowitz, Jonswap) modelling the sea state energy is to be used:

- for sea-going ships, Pierson-Moskowitz spectrum is generally used as corresponding to navigation in open seas
- for offshore units, the wave Scatter diagram to be used is the one associated to the site under consideration, each sea-state being described by a wave spectrum of appropriate shape (e.g. Pierson-Moskowitz, Jonswap, Ochi-Hubble).

Selection of the applicable environmental conditions is to be performed according to the applicable rules.

- Loading conditions

Fatigue analysis is to be carried out for all the selected loading conditions, considering their corresponding occurrence probability.

The loading conditions, as well as the fraction of time for each loading condition over the life of the unit, to be considered for fatigue analysis are to be selected according to the applicable rules.

- Speed profile

Unless otherwise specified by the applicable rules, the ship speed is to be taken as 75% of the design speed. It is assumed that this above speed corresponds to the actual forward speed in moderate wave heights, which are responsible for most of the fatigue damage.

2 Fixed offshore structures

2.1 Loads types

2.1.1 For fixed offshore structures, the fluctuating loads resulting in fatigue damage are mainly due to wave induced loads during the in-service conditions.

The following sources of fatigue damage are also to be considered, when relevant:

- vortex induced vibrations (VIV) due to wave and/or wind
- wind cyclic loads
- transportation
- installation, in particular during pile driving.

2.2 Determination of loads

2.2.1 The determination of the fatigue loads depends on the calculation procedure. The ocean environment description considered for the local wave actions calculations can be addressed with the following methods:

- deterministic method: the ocean environment is described by series of individual periodic waves with a particular height, period and direction and an associated number of occurrences (see ISO 19902, 16.8)
- spectral calculation: the ocean environment is described by series of short-term sea spectra (see ISO 19902, 16.7)
- direct time domain: the short-term seastates are represented by time domain simulations on irregular waves (see Sec 11, [4]).

SECTION 3

HOT SPOT STRESS BASED ON ANALYTICAL APPROACH FOR LONGITUDINAL STIFFENERS

1 General

1.1 Application

1.1.1 Scope

This Section defines the procedure for the analytical calculation of the hot spot stress in longitudinal stiffener connections.

1.1.2 Fatigue modes

Two main types of fatigue cracks are encountered at longitudinal stiffeners connection with primary supporting members:

- axial and bending stress induced fatigue (see [1.2]), and
- shear stress induced fatigue (see [1.3]).

1.1.3 Net scantling

For the stress calculation, the net scantling approach as defined in Sec 1, [3.3] is to be applied, except otherwise prescribed by the applicable rules.

1.2 Axial and bending stress fatigue

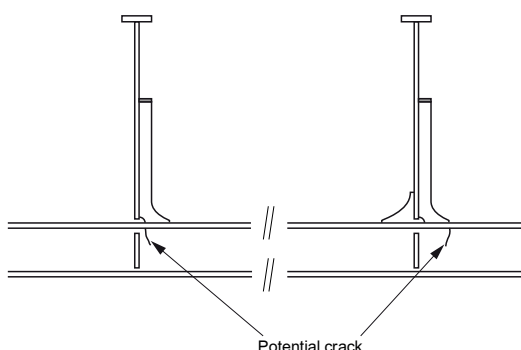
1.2.1 General

This sub-article deals with the assessment of fatigue induced by the axial and bending modes (see Fig 1) in way of longitudinal stiffener connections to primary members.

The analytical stress analysis aims at evaluating the hot spot stress at the flange of longitudinal stiffener connections with primary supporting members. The longitudinal stiffener is considered as a beam subjected to:

- axial loads induced by hull girder bending, and
- local bending induced by lateral pressure.

Figure 1 : Cracks in longitudinal stiffener web due to bending mode



1.2.2 Hot spots

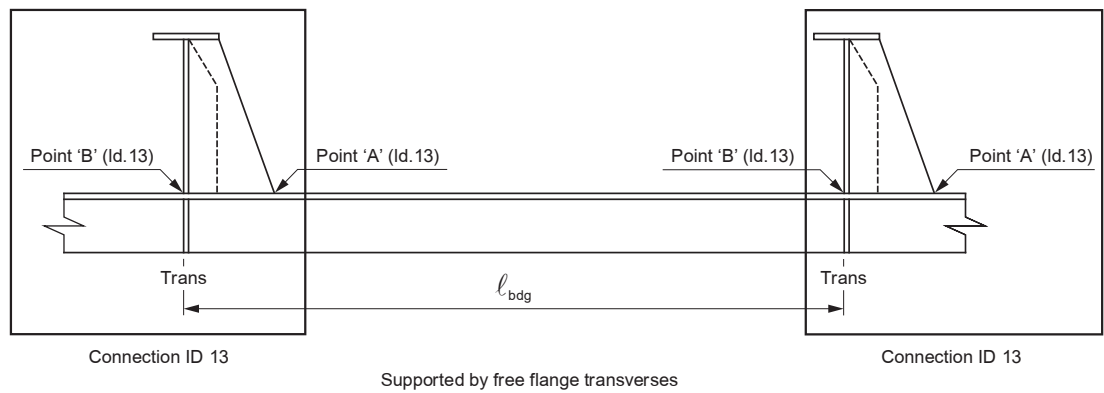
The hot spot stress ranges and hot spot mean stresses, in way of both end connections of longitudinal stiffeners, are to be evaluated at the flange of the longitudinal stiffener, at the hot spots located at point 'A' and point 'B' (see Fig 2).

1.2.3 Effect of primary structure distortion

For web frames or floors that are part of a transverse bulkhead or are in way of a transverse stool, the additional hot spot stress due to the relative displacement of the primary structure is to be considered.

For other web frames or floors, additional hot spot stress due to the relative displacement does not need to be considered.

Figure 2 : Hot spots at connection of longitudinal stiffeners with transverse members



1.2.4 Applicable S-N curve

The applicable S-N curve to be used for the assessment of longitudinal stiffener welded connections is the $P_{\perp}$ curve, since the calculated hot spot stress is taken perpendicular to the weld.

The basic $P_{\perp}$ S-N curve to be used is given in Sec 9, [2]. This basic S-N curve is to be corrected for factors affecting the fatigue strength as described in Sec 10.

If the weld toe angle is lower than or equal to 30° , the S-N curve to be used is $P_{//}$.

1.3 Shear stress fatigue

1.3.1 General

In addition to the fatigue cracks in the stiffener flange, some fatigue crack may occur in the web of the primary supporting members or in the collar plate, due to shear (see Fig 3).

The typical hot spots at the collar plate and in the slot are shown in Fig 4.

Figure 3 : Cracks in web of primary supporting members due to shear mode

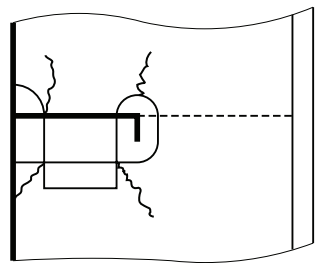
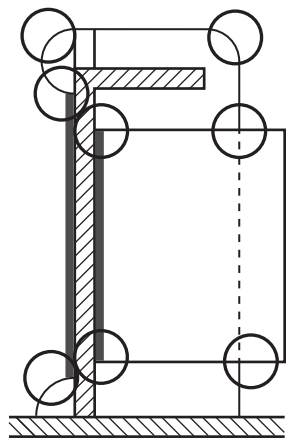


Figure 4 : Typical hot spots at collar plate and slot



1.3.2 Driving loads

Cracks under shear mode are mainly due to the combination of global and local phenomena (see Fig 5).

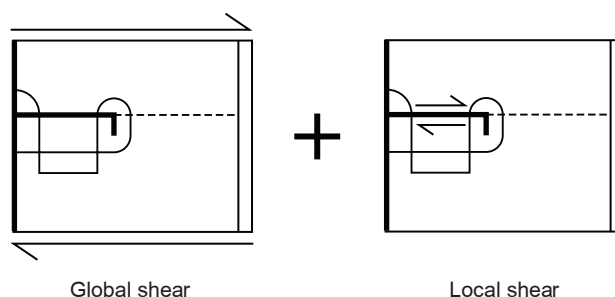
The global phenomenon corresponds to the bending of primary supporting members. The maximum shear stress induced by this bending occurs at the neutral fibre which is usually close to the cut out.

The local phenomenon corresponds to the shear stress induced in the longitudinal stiffener under lateral pressure.

1.3.3 Fatigue assessment

Prescriptions for the verification of the fatigue strength with regard to the shear mode fatigue can be found in the applicable rules.

Figure 5 : Fatigue phenomenon under shear mode



2 Axial and bending hot spot stress

2.1 General

2.1.1 Principle

The determination of the longitudinal stiffener end connections hot spot stress is based on nominal stresses and stress concentration factors.

The hot spot stress is to be calculated at both stiffener end connections (point 'A' and point 'B') of the stiffener flange (see Fig 2).

2.1.2 Nominal stress

The nominal stress includes:

- axial stress due to global hull girder bending moments
- local bending stress due to local pressures applied to the stiffener attached plate
- additional local bending stress due to the relative displacement of the primary structure for some locations (i.e. transverse webs or floors located at transverse bulkhead, including swash bulkhead, or in way of stool)
- warping stress when relevant.

Net thickness approach is used (see Sec 1, [3.3]).

2.1.3 Stress concentration factors

For each hot spot of each connection, two geometric stress concentration factors (K_{ga} and K_{gb}) are defined, for both the axial stress and the bending stress respectively.

Some geometric stress concentration factors are given in [3.1] for typical stiffener end connection geometries.

If a structural detail is different from those given in [3.1], the geometric stress concentration factors are to be calculated by a very fine mesh FE analysis according to the procedure given in [3.3].

2.1.4 Additional stress concentration factors

The following additional stress concentration factors are to be applied, as relevant:

- stress concentration for unsymmetrical stiffener on laterally loaded panels, as given in [3.2]
- stress concentration due to workmanship issues (axial and angular misalignments), as given in Sec 10, [5].

2.1.5 Hot spot stress range and mean stress for the rule based fatigue procedure

For the rule based fatigue procedure described in Sec 11, [2], the hot spot stress range calculation is described in [4.1.2]. The associated mean hot spot stress calculation is described in [4.1.3].

2.1.6 Hot spot stress for the direct calculation procedures

For the direct calculation fatigue procedures described in Sec 11, [3] and Sec 11, [4], the hot spot stress calculation is described in [4.2].

2.2 Global axial stress

2.2.1 Hull girder bending stress

The hull girder hot spot stress σ_G , in N/mm² is obtained from the following formula:

$$\sigma_G = f_{c-a} \cdot K_{ga} \cdot \left[\frac{M_V}{I_{yy}} \cdot (z - z_{NA}) - \left(\frac{M_H}{I_{zz}} \cdot y \right) \right] \cdot 10^{-3}$$

where:

- M_V : Vertical wave bending moment, in kN.m, taken positive when the upper part is in tension (hogging)
- M_H : Horizontal wave bending moment, in kN.m, taken positive when starboard side is in tension
- I_{yy} : Vertical hull girder moment of inertia at the longitudinal position being considered, in m⁴, in the net scantling as prescribed in [1.1.3]
- I_{zz} : Horizontal hull girder moment of inertia at the longitudinal position being considered, in m⁴, in the net scantling as prescribed in [1.1.3]
- y : Transverse coordinate of the stress calculation point under consideration, in m, taken positive toward portside
- z : Vertical coordinate of the stress calculation point under consideration, in m, taken positive upwards
- z_{NA} : Distance from the baseline to the horizontal neutral axis, in m
- K_{ga} : Geometric stress concentration factor due to axial load
- f_{c-a} : Correction factor for the effect of corrosion, applied on the axial stress:
 - in case the single structural model approach described in Sec 1, [3.3.3] has been selected: the value of f_{c-a} is given in the applicable rules
 - otherwise: $f_{c-a} = 1,0$

2.2.2 Hull girder warping stress

For ships with large deck openings, or if required by the applicable rules, the longitudinal stress induced by the restrained hull girder section warping is to be calculated in way of the fatigue details.

The hot spot warping stress σ_Ω , in N/mm², is obtained from the following formula:

$$\sigma_\Omega = f_{c-a} \cdot K_{ga} \cdot \sigma_{warp}$$

where:

- K_{ga} : Geometric stress concentration factor due to axial load
- σ_{warp} : Warping nominal stress due to the torsion, in N/mm²
- f_{c-a} : Correction factor for the effect of corrosion, applied on the axial stress, as defined in [2.2.1].

The nominal warping stress is determined according to the prescriptions of the applicable rules.

2.3 Local bending stress

2.3.1 Stress due to stiffener bending

The hot spot stress σ_L , in N/mm², due to the local dynamic pressure is obtained from the following formula, or from the formula prescribed by the applicable rules:

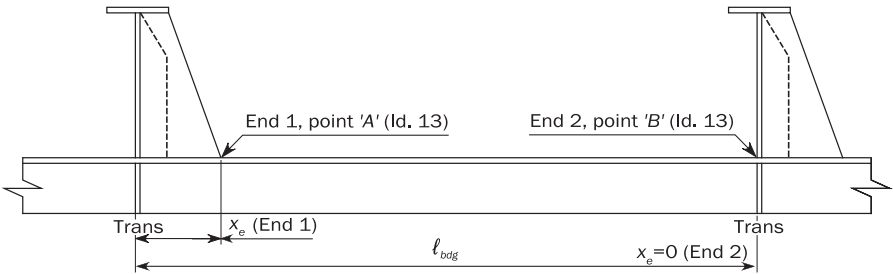
$$\sigma_L = f_{c-b} \cdot K_{gb} \cdot \left[K_n \cdot s \cdot \ell_{bdg}^2 \cdot P_{LT} \cdot \left(1 - \frac{6x_e}{\ell_{bdg}} + \frac{6x_e^2}{\ell_{bdg}^2} \right) \right] / (12 \cdot Z_{eff})$$

where:

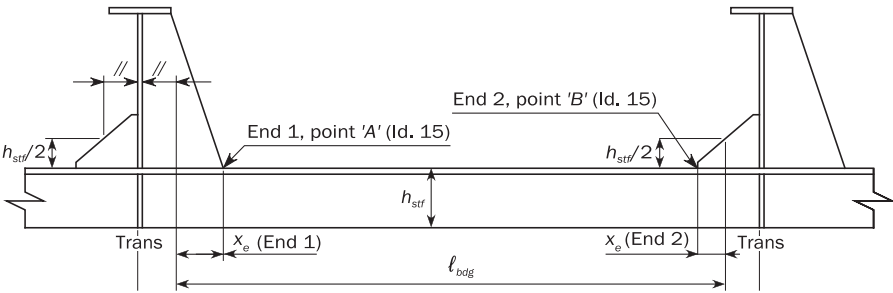
- ℓ_{bdg} : Effective bending span of stiffener, in m, as defined in Fig 6, unless otherwise specified in the applicable rules
- s : Stiffener spacing, in m
- K_n : Additional stress concentration factor due to unsymmetrical stiffener geometry, as defined in [3.2]
- P_{LT} : Total local pressure at mid span, in kN/m², as defined in [2.3.2]
- x_e : Distance, in m, to the hot spot from the closest end of the bending span, as defined in Fig 6
- Z_{eff} : Section modulus, in cm³, of the considered stiffener calculated, considering an effective breadth b_{eff} of the attached plating
- K_{gb} : Geometric stress concentration factor due to lateral pressure given in [3.1] or determined as per [3.3]

- $f_{c,b}$: Correction factor for the effect of corrosion, applied on the local bending stress:
- in case the single structural model approach described in Sec 1, [3.3.3] has been selected: the value of $f_{c,b}$ is given in the applicable rules
 - otherwise: $f_{c,b} = 1,0$

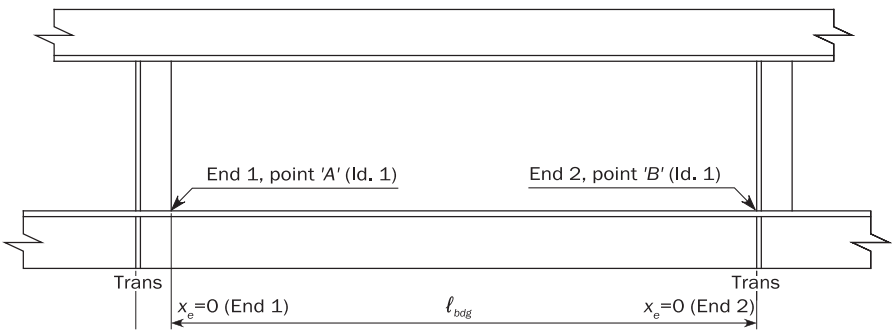
Figure 6 : Definition of effective span (ℓ_{bdg}) and distance (x_e) to the hot spot



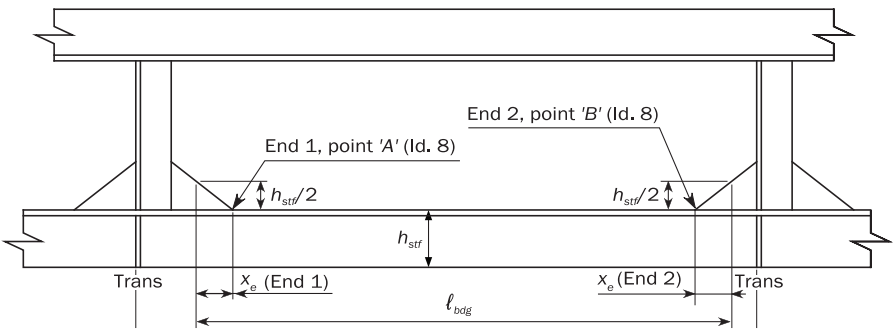
Supported by free flange transverses



Supported by free flange transverses



Supported by double skin/transverse bulkheads



Supported by double skin/transverse bulkheads

2.3.2 Total local pressure

The total pressure acting on the stiffener attached plate is given by:

$$P_{LT} = P_{L_Stif} - P_{L_Opp}$$

where:

P_{L_Stif} : Pressure at mid span, in kN/m², applied on the stiffener side of the attached plating

P_{L_Opp} : Pressure at mid span, in kN/m², applied on the plating side opposite to the stiffener side.

2.3.3 Effective breadth

The effective breadth b_{eff} , in mm, of the attached plating to be used for the computation of the effective stiffener modulus is given by:

- for $\frac{\ell_{bdg}}{s} \left(1 - \frac{1}{\sqrt{3}}\right) \cdot 10^3 \geq 1$:

$$b_{eff} = s \cdot \text{Min} \left\{ 1, 04 / \left[1 + 3 \left(\frac{\ell_{bdg}}{s} \left(1 - \frac{1}{\sqrt{3}}\right) \cdot 10^3 \right)^{-1,35} \right] ; 1, 0 \right\}$$

- for $\frac{\ell_{bdg}}{s} \left(1 - \frac{1}{\sqrt{3}}\right) \cdot 10^3 < 1$:

$$b_{eff} = 0, 26 \cdot \ell_{bdg} \cdot \left(1 - \frac{1}{\sqrt{3}}\right) \cdot 10^3$$

where:

ℓ_{bdg} : Effective bending span of stiffener, as defined in [2.3.1]

s : Stiffener spacing, in m.

2.4 Stress due to relative displacements of primary supporting members

2.4.1 General

The additional hot spot stress due to the relative displacement of primary supporting members is to be considered for longitudinal stiffener end connections fitted on transverse web frames or floors located:

- in way of plane transverse bulkheads (including swash bulkheads in cargo holds), or
- in way of transverse stools and cofferdam bulkheads.

2.4.2 Displacement of primary supporting members

The displacement of primary supporting members is to be evaluated using a finite element model that satisfies the prescriptions given in the applicable rules.

The displacement of a primary supporting member is the displacement of the point located at the intersection of the stiffener flange, the stiffener web and the supporting member web. This displacement is measured along the line defined by the intersection between the stiffener web and the primary supporting member web in the non-deformed state of the finite element model.

The displacement is counted positive in the direction from the stiffener flange towards the attached plating.

2.4.3 Relative displacements of primary supporting members

For the primary supporting members where the longitudinal stiffener fatigue details are located, two values of relative displacement are computed (see Fig 7):

- the relative displacement δ_{Fwd} for the stiffener span in the forward direction, corresponding to the displacement of the first primary supporting member forward minus the displacement of the considered primary supporting member, and
- the relative displacement δ_{Aft} for the stiffener span in the aft direction, corresponding to the displacement of the first primary supporting member aftward minus the displacement of the considered primary supporting member.

2.4.4 Relative displacements in way of transverse stools, cofferdam bulkheads and container carrier transverse bulkheads

For longitudinal stiffener connection details located in way of a transverse stool, a cofferdam bulkhead, or a container carrier transverse bulkhead, four different primary supporting members come into play: the two web frames in way of the transverse stool or bulkhead, and the two adjacent web frames in the forward and aft directions.

The longitudinal stiffener connection details located on the two web frames in way of the transverse stool are to be considered:

- For the details located on the foremost web frame in way of the stool:
 - the relative displacement δ_{Fwd} is the displacement of the first adjacent web frame forward of the stool minus the displacement of the foremost stool web frame
 - the relative displacement δ_{Aft} is the displacement of the aftmost stool web frame minus the displacement of the foremost stool web frame
- For the details located on the aftmost web frame in way of the stool:
 - the relative displacement δ_{Aft} is the displacement of the first adjacent web frame aft of the stool minus the displacement of the aftmost stool web frame
 - the relative displacement δ_{Fwd} is the displacement of the foremost stool web frame minus the displacement of the aftmost stool web frame.

2.4.5 Stress due to relative displacement

The stress due to relative displacements, in N/mm², for both locations 'a' and 'f' shown on Fig 7, is to be obtained directly from the following formulae:

- for location 'a':

$$\sigma_D = f_{c,b} \cdot K_{gb} \cdot (\sigma_{d_{Fwd,a}} + \sigma_{d_{Aft,a}})$$

- for location 'f':

$$\sigma_D = f_{c,b} \cdot K_{gb} \cdot (\sigma_{d_{Fwd,f}} + \sigma_{d_{Aft,f}})$$

where:

K_{gb} : Geometric stress concentration factor for stiffener bending stress for the location 'a' or 'f'. Each location 'a' or 'f' may correspond to point 'A' or 'B' as defined in Tab 1 depending on the stiffener end connection design

$f_{c,b}$: Correction factor for the effect of corrosion, applied on the local bending stress, as defined in [2.3.1]

$\sigma_{d_{Fwd,a}}, \sigma_{d_{Aft,a}}$: Additional stresses at location 'a', in N/mm², due to the relative displacements of the primary supporting members, obtained from the following formulae:

$$\sigma_{d_{Fwd,a}} = \frac{3,9\delta_{Fwd} \cdot E \cdot I_{Aft} \cdot I_{Fwd}}{Z_{Aft} \cdot \ell_{Fwd} \cdot (\ell_{Aft} \cdot I_{Fwd} + \ell_{Fwd} \cdot I_{Aft})} \left(1 - 1,15 \frac{|x_{e,Aft}|}{\ell_{Aft}}\right) 10^{-5}$$

$$\sigma_{d_{Aft,a}} = \left[\frac{3,9\delta_{Aft} \cdot E \cdot I_{Aft} \cdot I_{Fwd}}{Z_{Aft} \cdot \ell_{Aft} \cdot (\ell_{Aft} \cdot I_{Fwd} + \ell_{Fwd} \cdot I_{Aft})} \left(1 - 1,15 \frac{|x_{e,Aft}|}{\ell_{Aft}}\right) - \frac{0,9\delta_{Aft} \cdot E \cdot I_{Aft} \cdot |x_{e,Aft}|}{Z_{Aft} \cdot \ell_{Aft}^3} \right] 10^{-5}$$

$\sigma_{d_{Fwd,f}}, \sigma_{d_{Aft,f}}$: Additional stresses at location 'f', in N/mm², due to the relative displacements of the primary supporting members, obtained from the following formulae:

$$\sigma_{d_{Fwd,f}} = \left[\frac{3,9\delta_{Fwd} \cdot E \cdot I_{Aft} \cdot I_{Fwd}}{Z_{Fwd} \cdot \ell_{Fwd} \cdot (\ell_{Aft} \cdot I_{Fwd} + \ell_{Fwd} \cdot I_{Aft})} \left(1 - 1,15 \frac{|x_{e,Fwd}|}{\ell_{Fwd}}\right) - \frac{0,9\delta_{Fwd} \cdot E \cdot I_{Fwd} \cdot |x_{e,Fwd}|}{Z_{Fwd} \cdot \ell_{Fwd}^3} \right] 10^{-5}$$

$$\sigma_{d_{Aft,f}} = \frac{3,9\delta_{Aft} \cdot E \cdot I_{Aft} \cdot I_{Fwd}}{Z_{Fwd} \cdot \ell_{Aft} \cdot (\ell_{Aft} \cdot I_{Fwd} + \ell_{Fwd} \cdot I_{Aft})} \left(1 - 1,15 \frac{|x_{e,Fwd}|}{\ell_{Fwd}}\right) 10^{-5}$$

where:

I_{Fwd}, I_{Aft} : Moments of inertia, in net scantlings, of the forward and aftward longitudinals, in cm⁴

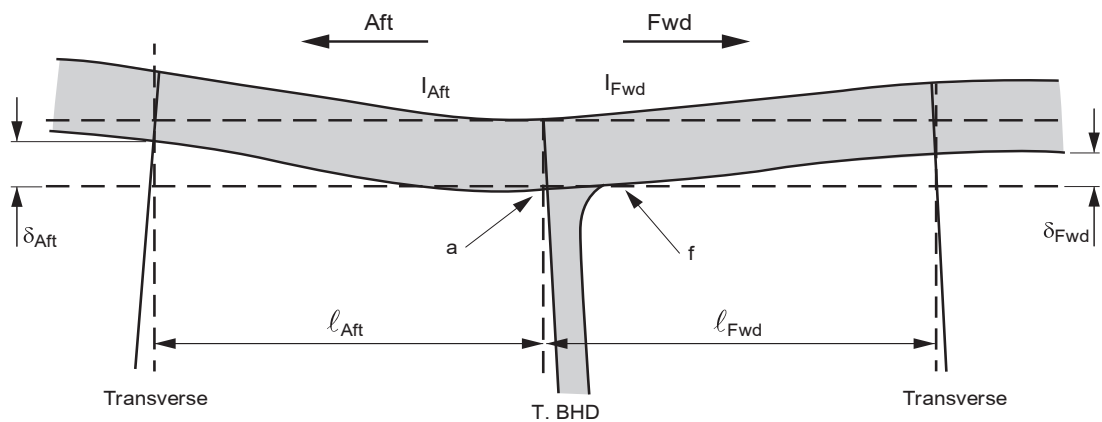
Z_{Fwd}, Z_{Aft} : Section moduli, in net scantlings, of the forward and aftward stiffeners, in cm³

ℓ_{Fwd}, ℓ_{Aft} : Spans, in m, of the forward and aftward longitudinals, as shown in Fig 7

$x_{e,Fwd}, x_{e,Aft}$: Distances, in m, to the hot spot in location 'a' or 'f', from the closest end of the forward and aftward longitudinal spans, respectively, as shown in Fig 6

$\delta_{Fwd}, \delta_{Aft}$: Relative displacements, in mm, between the transverse bulkhead (or floor) and the forward or aftward web frame (or floor) determined according to [2.4.3] or [2.4.4].

Figure 7 : Definition of the relative displacement (ordinary transverse bulkhead)



3 Stress concentration factors (SCF)

3.1 Stress concentration factors for longitudinal stiffener end connections

3.1.1 Standard connection types

Stress concentration factors K_{ga} and K_{gb} are given in Tab 1 for end connection of stiffeners subjected to axial and lateral loads. The values for soft toe given in Tab 1 are valid provided that the toe geometry of web stiffener and backing bracket complies with the following requirements:

$\theta \leq 20$

$h_{toe} \leq \text{Max} (t_{bkt_gr} ; 15)$

where:

θ : Angle of the bracket toe, in deg, as shown in Fig 8 and Fig 9

h_{toe} : Height of the bracket toe, in mm

t_{bkt_gr} : Gross thickness of the bracket, in mm.

3.1.2 Other connection types

When the connection types are different from those given in Tab 1, the stress concentration factors should be determined using FEM analysis according to the requirements in [3.3].

Otherwise, the hot spot stress can be directly obtained as described in Sec 5.

Figure 8 : Detail design for soft toes and backing brackets

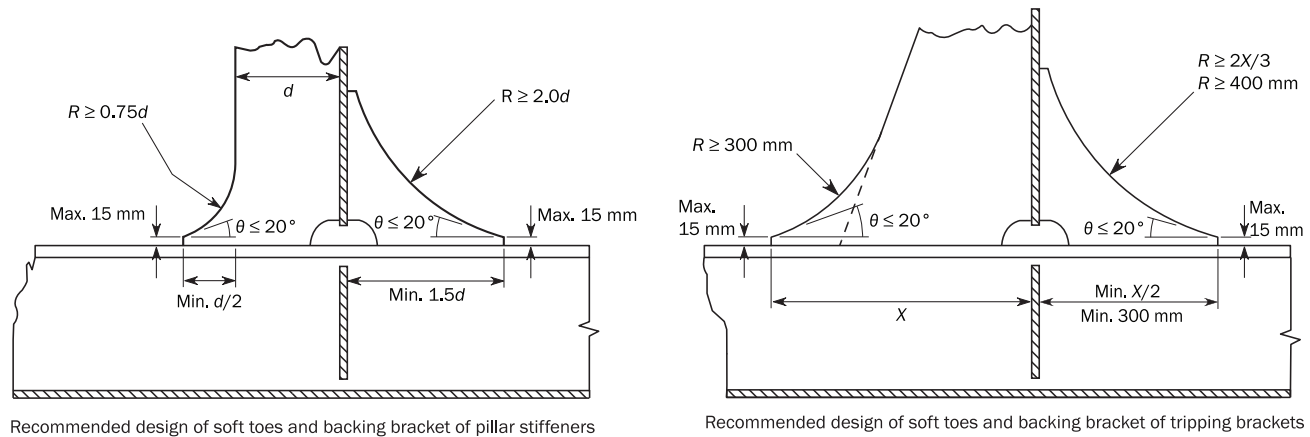


Figure 9 : Recommended alternative design of soft toes of tripping brackets

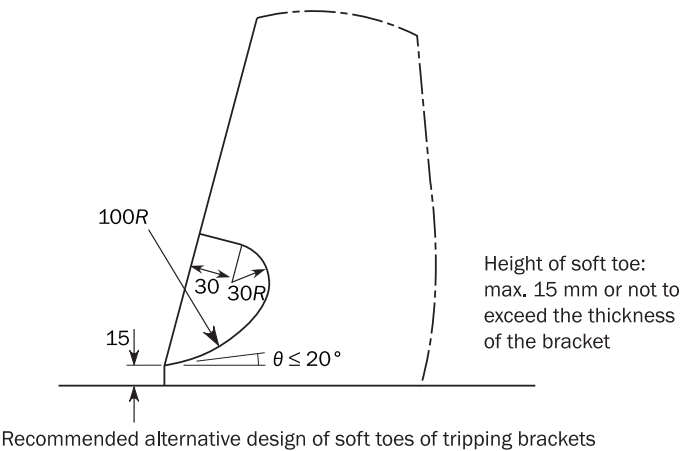
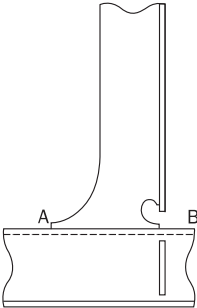
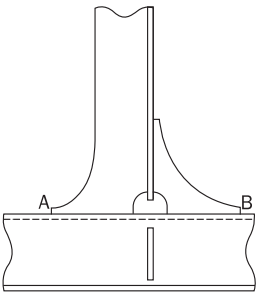
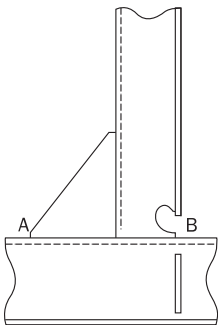
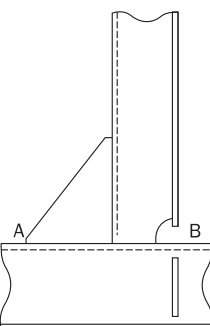
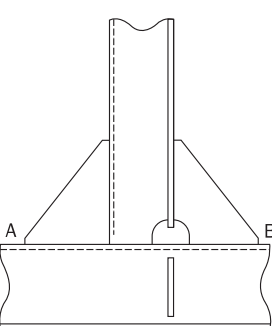
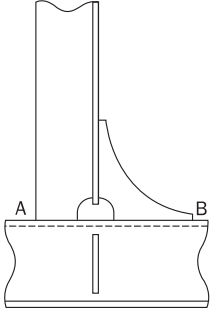
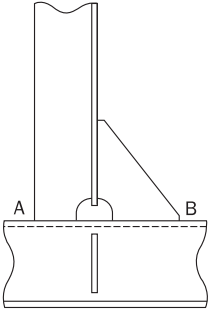
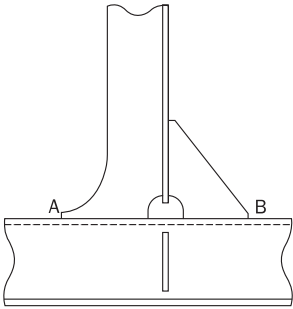
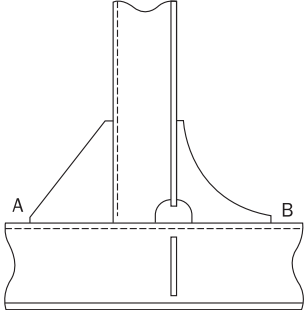
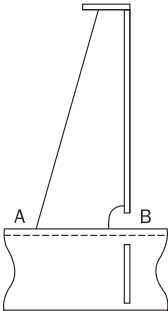
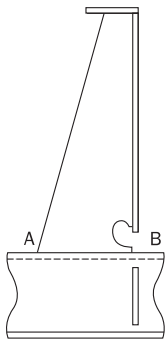
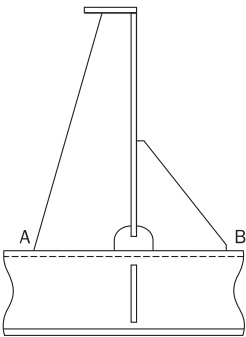
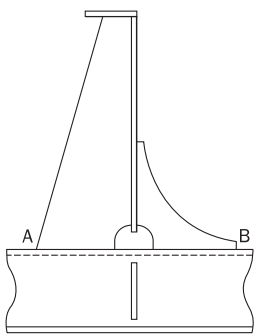
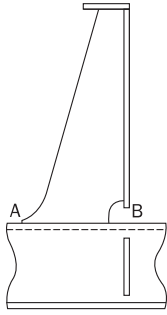
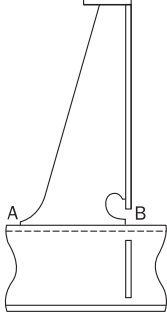


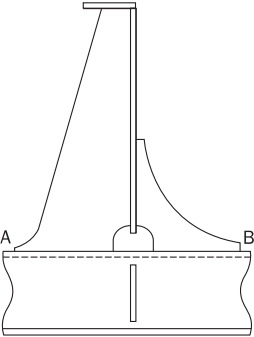
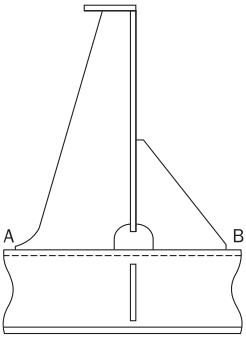
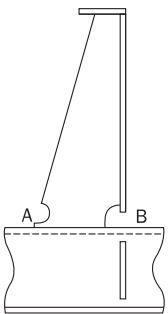
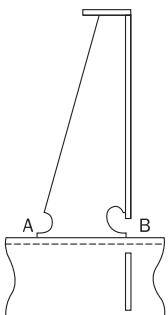
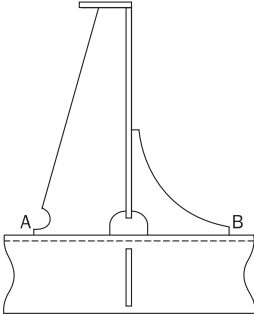
Table 1 : Geometric stress concentration factors K_{ga} and K_{gb}

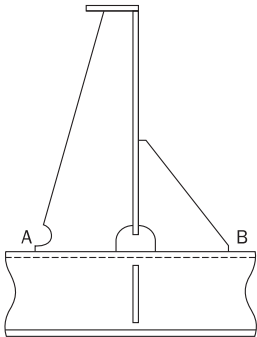
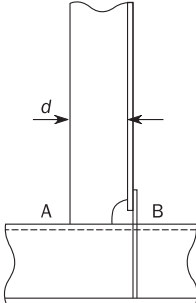
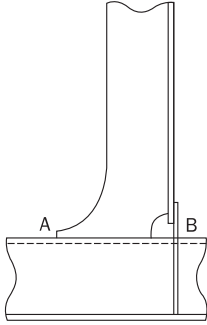
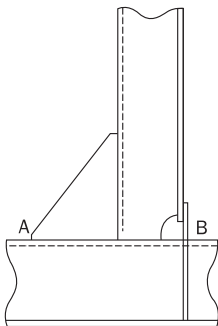
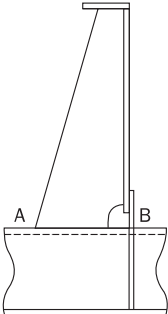
ID	Connection type (1)	Point 'A'		Point 'B'	
		K_{ga}	K_{gb}	K_{ga}	K_{gb}
1 (2)		- for $d \leq 150$: $K_{ga} = 1,28$ - for $150 < d \leq 250$: $K_{ga} = 1,36$ - for $d > 250$: $K_{ga} = 1,45$	- for $d \leq 150$: $K_{gb} = 1,40$ - for $150 < d \leq 250$: $K_{gb} = 1,50$ - for $d > 250$: $K_{gb} = 1,60$	- for $d \leq 150$: $K_{ga} = 1,28$ - for $150 < d \leq 250$: $K_{ga} = 1,36$ - for $d > 250$: $K_{ga} = 1,45$	$K_{gb} = 1,60$
2 (2)		- for $d \leq 150$: $K_{ga} = 1,28$ - for $150 < d \leq 250$: $K_{ga} = 1,36$ - for $d > 250$: $K_{ga} = 1,45$	- for $d \leq 150$: $K_{gb} = 1,40$ - for $150 < d \leq 250$: $K_{gb} = 1,50$ - for $d > 250$: $K_{gb} = 1,60$	- for $d \leq 150$: $K_{ga} = 1,14$ - for $150 < d \leq 250$: $K_{ga} = 1,24$ - for $d > 250$: $K_{ga} = 1,34$	$K_{gb} = 1,27$
3		$K_{ga} = 1,28$	$K_{gb} = 1,34$	$K_{ga} = 1,52$	$K_{gb} = 1,67$

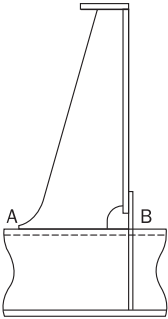
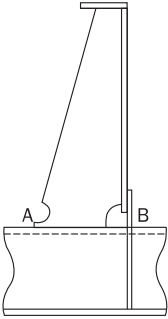
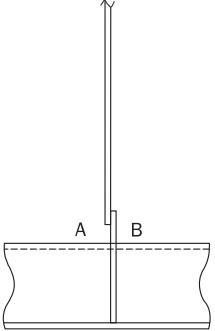
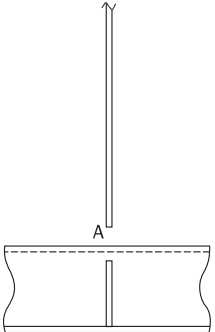
ID	Connection type (1)	Point 'A'		Point 'B'	
		K_{ga}	K_{gb}	K_{ga}	K_{gb}
4		$K_{ga} = 1,28$	$K_{gb} = 1,34$	$K_{ga} = 1,34$	$K_{gb} = 1,34$
5		$K_{ga} = 1,28$	$K_{gb} = 1,34$	$K_{ga} = 1,28$	$K_{gb} = 1,34$
6		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,34$	$K_{gb} = 1,34$
7		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
8		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,52$	$K_{gb} = 1,67$

ID	Connection type (1)	Point 'A'		Point 'B'	
		K_{ga}	K_{gb}	K_{ga}	K_{gb}
9		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,28$	$K_{gb} = 1,34$
10		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
11		$K_{ga} = 1,28$	$K_{gb} = 1,34$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
12		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,28$	$K_{gb} = 1,34$
13		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,52$	$K_{gb} = 1,67$

ID	Connection type (1)	Point 'A'		Point 'B'	
		K_{ga}	K_{gb}	K_{ga}	K_{gb}
14		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,34$	$K_{gb} = 1,34$
15		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
16		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,28$	$K_{gb} = 1,34$
17		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
18		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,34$	$K_{gb} = 1,34$

ID	Connection type (1)	Point 'A'		Point 'B'	
		K_{ga}	K_{gb}	K_{ga}	K_{gb}
19		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,28$	$K_{gb} = 1,34$
20		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
21		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
22		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,34$	$K_{gb} = 1,34$
23		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,28$	$K_{gb} = 1,34$

ID	Connection type (1)	Point 'A'		Point 'B'	
		K_{ga}	K_{gb}	K_{ga}	K_{gb}
24		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,52$	$K_{gb} = 1,67$
25 (2)		- for $d \leq 150$: $K_{ga} = 1,28$ - for $150 < d \leq 250$: $K_{ga} = 1,36$ - for $d > 250$: $K_{ga} = 1,45$	- for $d \leq 150$: $K_{gb} = 1,40$ - for $150 < d \leq 250$: $K_{gb} = 1,50$ - for $d > 250$: $K_{gb} = 1,60$	- for $d \leq 150$: $K_{ga} = 1,14$ - for $150 < d \leq 250$: $K_{ga} = 1,24$ - for $d > 250$: $K_{ga} = 1,34$	- for $d \leq 150$: $K_{gb} = 1,25$ - for $150 < d \leq 250$: $K_{gb} = 1,36$ - for $d > 250$: $K_{gb} = 1,47$
26		$K_{ga} = 1,28$	$K_{gb} = 1,34$	$K_{ga} = 1,34$	$K_{gb} = 1,47$
27		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,34$	$K_{gb} = 1,47$
28		$K_{ga} = 1,52$	$K_{gb} = 1,67$	$K_{ga} = 1,34$	$K_{gb} = 1,47$

ID	Connection type (1)	Point 'A'		Point 'B'	
		K_{ga}	K_{gb}	K_{ga}	K_{gb}
29		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,34$	$K_{gb} = 1,47$
30		$K_{ga} = 1,34$	$K_{gb} = 1,34$	$K_{ga} = 1,34$	$K_{gb} = 1,47$
31		$K_{ga} = 1,13$	$K_{gb} = 1,20$	$K_{ga} = 1,13$	$K_{gb} = 1,20$
32 (3) (4)		$K_{ga} = 1,13$	$K_{gb} = 1,14$	—	—

- (1) Where the longitudinal stiffener is a flat bar and there is a web stiffener/bracket welded to the flat bar stiffener, the stress concentration factor listed in the Table is to be multiplied by a factor of 1,12 when the thickness of attachment is thicker than the 0,7 times thickness of flat bar stiffener. This also applies to unsymmetrical profiles where there is less than 8 mm clearance between the edge of the stiffener flange and the attachment, e.g. bulb or angle profiles where the clearance of 8 mm cannot be achieved.
- (2) The attachment length d , in mm, is defined as the length of the welded attachment on the longitudinal stiffener flange without deduction of scallop.
- (3) For connection type ID 32 with no collar and/or web plate welded to the flange, the stress concentration factors provided in this Table are to be used irrespective of slot configuration.
- (4) The fatigue assessment point 'A' is located at the connection between the stiffener web and the transverse web frame or lug plate.

3.2 SCF for unsymmetrical stiffeners

3.2.1 Angle profiles

The stress concentration factor K_n for unsymmetrical flange of built-up and rolled angle stiffeners under lateral load, calculated at the web mid-thickness position, as shown in Fig 10, is given by:

$$K_n = \frac{1 + \lambda \cdot \beta^2}{1 + \lambda \cdot \beta^2 \cdot \Psi_z}$$

where:

$$\lambda = \frac{3 \left(1 + \frac{\eta}{280} \right)}{1 + \frac{\eta}{40}}$$

$$\beta = 1 - \frac{2 \cdot b_g}{b_f} \quad \text{for built-up profiles}$$

$$\beta = 1 - \frac{t_w}{b_f} \quad \text{for rolled angle profiles}$$

$$\Psi_z = \frac{h_w^2 \cdot t_w}{4 \cdot Z} \cdot 10^{-3}$$

with:

$$\eta = \frac{\ell_{bdg}^4 \cdot 10^{12}}{b_f^3 \cdot t_f \cdot h_{stf}^2 \cdot \left(\frac{4 \cdot h_{stf}}{t_w^3} + \frac{s}{t_p^3} \right)}$$

- b_g : Eccentricity of the stiffener, equal to the distance from the flange edge to the web centreline, in mm, as shown in Fig 11
- b_f : Flange breadth, in mm, as shown in Fig 11
- t_w : Web thickness, in mm, as shown in Fig 11
- t_f : Flange thickness, in mm, as shown in Fig 11
- h_{stf} : Stiffener height, including the face plate, in mm, as shown in Fig 11
- t_p : Thickness of the attached plating, in mm, as shown in Fig 11
- h_w : Web height, in mm, as shown in Fig 11
- Z : Section modulus, in cm^3 , of the stiffener with an attached plating breadth equal to the stiffener spacing.

Figure 10 : Bending stress in stiffener with symmetrical or unsymmetrical flange

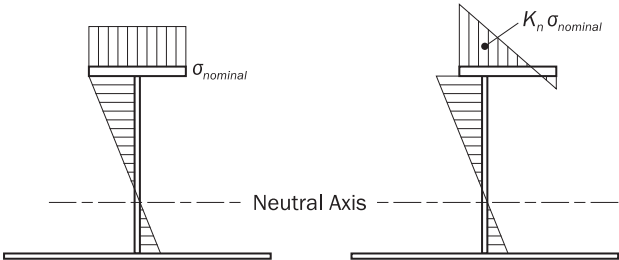
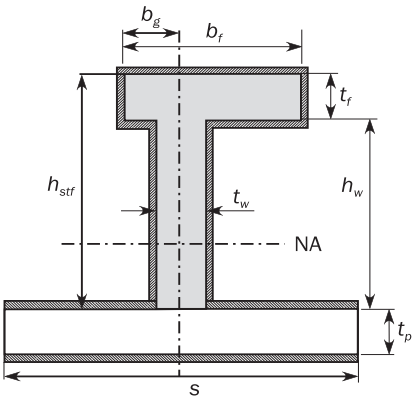


Figure 11 : Stiffener - Net scantling



3.2.2 Bulb profiles

For bulb profiles, factor K_n may be calculated using an equivalent built-up profile.

The equivalent built-up profile is to have the same properties as the bulb profile, i.e. the same:

- cross-sectional area
- moment of inertia of the profile about the horizontal neutral axis position, and
- moment of inertia of the profile about the vertical neutral axis position.

In addition, torsional constant and shear centre position of the equivalent built-up profile are to be checked.

Attention should be paid to the accuracy of this calculation. More accurate results can be obtained by determining the stress concentration factors by means of a FEM model as described in [3.3].

3.3 SCF for longitudinal stiffener end connections - Calculation by FEM

3.3.1 General

Upon agreement by the Society, the stress concentration factors for alternative designs are to be calculated by a very fine mesh FE analysis according to the requirements given in Sec 5.

Additional requirements for the derivation of stress concentration factors for stiffener end connections using very fine mesh FE analysis are given in this sub-article.

3.3.2 FE model extent

The FE model (see Fig 12) is to cover at least four web frame spacings in the longitudinal stiffener direction. The considered detail is to be located at the middle frame. The same type of end connection is to be modelled at all web frames. In the transverse direction, the model may be limited to one stiffener spacing.

3.3.3 Load application

In general, two loading cases are to be considered:

- axial loading, by enforced displacement applied to the model ends, and
- lateral loading, by unit pressure load applied to the shell plating.

3.3.4 Boundary conditions

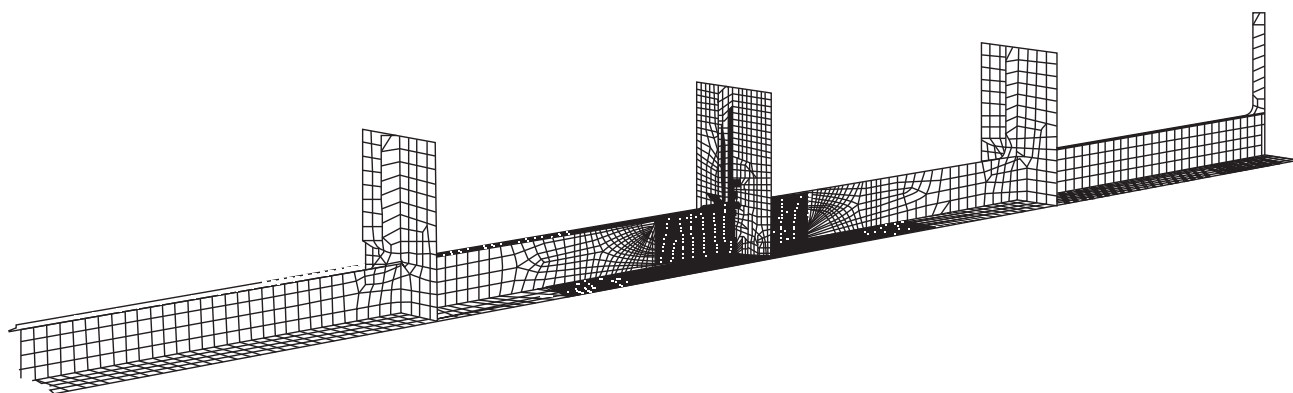
The following boundary conditions are to be applied on the FEM model:

- Symmetry conditions are applied along the longitudinal cut of the plate flange, along transverse and vertical cuts on web frames and on top of the web stiffener
- The model is to be fixed:
 - for lateral pressure loading: at both forward and aft ends in all degrees of freedom
 - for axial loading: at the aft end of the model for displacement in the longitudinal direction while enforced axial displacement is applied at the forward end, or vice versa.

3.3.5 FE mesh density

At the location of the hot spots under consideration, the element size shall be in the range of the thickness of the stiffener flange. In the remaining part of the model, the element size shall be in the range of $s/10$, where s is the stiffener spacing.

Figure 12 : Example of fine mesh finite element model for the derivation of geometrical stress concentration factor



3.3.6 Bulb profiles

When computing the stress concentration factors for a bulb profile, a solid elements FE model is recommended to improve the results. In order to capture the torsional properties of bulb sections, it is recommended to use a sufficient number of solid elements for modelling the bulb section.

3.3.7 Calculation of the geometric stress concentration

Two geometric stress concentration factors K_{ga} and K_{gb} are to be determined, for each load case mentioned in [3.3.3].

The geometric stress concentration factor is defined as the ratio of the hot spot stress derived from FE analysis on the nominal stress calculated according to analytical stress analysis for longitudinal stiffener connections.

The hot spot stress calculation is based on the procedure given in Sec 5, [3.3], Sec 5, [3.4] or Sec 5, [3.5].

The nominal stress is to be calculated according to analytical formulae based on unit load (i.e. the same loads than those used in the FEA).

- For the axial load case:

$$K_{ga} = \frac{\sigma_{HS_AXIAL}}{\sigma_{nom_AXIAL}}$$

where:

σ_{HS_AXIAL} : Hot spot stress determined by FE analysis at stiffener flange for the axial load

σ_{nom_AXIAL} : Nominal stress calculated at stiffener flange according to [2.2] for the same axial load applied in the FE analysis

- For the bending load case:

$$K_{gb} = \frac{\sigma_{HS_Bending}}{\sigma_{nom_Bending}}$$

where:

$\sigma_{HS_Bending}$: Hot spot stress determined by FE analysis at stiffener flange for the pressure load

$\sigma_{nom_Bending}$: Nominal stress calculated at stiffener flange according to [2.3] for the same pressure load applied in the FE analysis.

The K_{gb} value determined through this procedure includes the effect of the stiffener asymmetry, if any. Therefore, this value is generally to be associated with $K_n = 1,0$.

4 Hot spot stress

4.1 Hot spot stress range and mean value for rule based approach

4.1.1 General

For the rule based approach, the hot spot stress is to be calculated separately from the load cases i1 and i2 of loading condition j as defined in Sec 11, [2.1].

Then the hot spot stress range is obtained as described in [4.1.2] and the associated hot spot mean stress is obtained as prescribed in [4.1.3].

4.1.2 Hot spot stress range

The hot spot stress range due to dynamic loads, for load case (i) of loading condition (j), is obtained from the following formula:

$$\Delta\sigma_{HS,i(j)} = |(\sigma_{G,i1(j)} + \sigma_{\Omega,i1(j)} + \sigma_{L,i1(j)} + \sigma_{D,i1(j)}) - (\sigma_{G,i2(j)} + \sigma_{\Omega,i2(j)} + \sigma_{L,i2(j)} + \sigma_{D,i2(j)})|$$

where:

$\sigma_{G,i1(j)}$, $\sigma_{G,i2(j)}$: Global hull girder bending hot spot stress for load case i1 and i2 of loading condition j, calculated as prescribed in [2.2.1]

$\sigma_{\Omega,i1(j)}$, $\sigma_{\Omega,i2(j)}$: Global hull girder warping hot spot stress for load case i1 and i2 of loading condition j, calculated as prescribed in [2.2.2], if relevant

$\sigma_{L,i1(j)}$, $\sigma_{L,i2(j)}$: Local stiffener bending hot spot stress for load case i1 and i2 of loading condition j, calculated as prescribed in [2.3]

$\sigma_{D,i1(j)}$, $\sigma_{D,i2(j)}$: Hot spot stress induced by the primary supporting members relative displacement, for load case i1 and i2 of loading condition j, calculated as prescribed in [2.4].

4.1.3 Hot spot mean stress

The hot spot mean stress due to static and dynamic loads, for load case (i) of loading condition (j), is obtained from the following formula:

$$\sigma_{\text{meanHS},i(j)} = \frac{1}{2}[(\sigma_{G,i1(j)} + \sigma_{\Omega,i1(j)} + \sigma_{L,i1(j)} + \sigma_{D,i1(j)}) + (\sigma_{G,i2(j)} + \sigma_{\Omega,i2(j)} + \sigma_{L,i2(j)} + \sigma_{D,i2(j)})]$$

4.2 Hot spot stress for direct calculation approach

4.2.1 For the direct calculation approach, the hot spot stresses are combined as follows, either in frequency domain or in time domain:

$$\sigma_{\text{HS}} = (\sigma_G + \sigma_{\Omega} + \sigma_L + \sigma_D)$$

where:

- σ_G : Global hull girder bending hot spot stress calculated as prescribed in [2.2.1]
- σ_{Ω} : Global hull girder warping hot spot stress calculated as prescribed in [2.2.2], if relevant
- σ_L : Local stiffener bending hot spot stress calculated as prescribed in [2.3.1]
- σ_D : Hot spot stress induced by the relative displacement of the primary supporting members, calculated as prescribed in [2.4.5].

SECTION 4

HOT SPOT STRESS BASED ON ANALYTICAL
APPROACH FOR TUBULAR JOINTS

1 General

1.1 Principles

1.1.1 This Section deals with the determination of the hot spot stress in tubular node welded joints and tubular butt welded joints with an analytical approach. In this approach, the hot spot stress at the weld toe is derived from the nominal stress corrected by a geometric stress concentration factor K_g .

Partially penetrated tubular node joints and tubular butt joints are not permitted. Only fully penetrated tubular node joints and tubular butt joints are considered in this Section.

The nominal stress may be obtained from beam theory analytical calculations or from finite element models.

Geometric stress concentration factors may be already established (e.g. catalogue of details) or may be derived from FEA.

2 Tubular node welded joints

2.1 General

2.1.1 Scope

This Article deals with the fatigue of tubular node welded joints (i.e brace to chord connection) at weld toe (see Fig 1), based on hot spot stress obtained using the nominal stresses and the geometric stress concentration factor K_g .

K_g is given by either parametric formulae (see [2.3.3]) or local FE analysis (see Sec 6, [2] for assessment methodology).

2.1.2 Nominal stress calculation

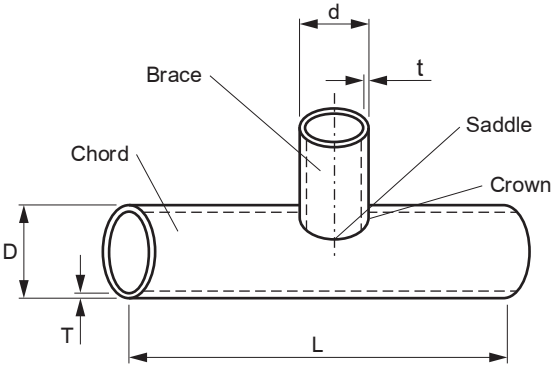
The nominal stresses are to be calculated by a space frame analysis, using a beam finite elements model. The calculations provide sectional forces and moments in the beam elements that represent the members of the structure. By definition, the corresponding stresses are nominal stresses.

The relevant nominal stresses to be considered for fatigue analysis are the following:

- axial stress
- in-plane bending stress
- out-of-plane bending stresses (see ISO 19902, par. 16.5).

The stress variations of these three nominal stress components shall be kept separate and shall not be combined. Shear stresses and torsional stresses may be neglected.

Figure 1 : Geometrical definitions for tubular joints



2.1.3 Hot spot stress calculation

For tubular joints, the geometric (hot-spot) stress ranges are to be determined at the connection, first by multiplying the brace nominal stress components by the associated geometric stress concentration factors (K_g associated to axial, in-plane bending, out-of-plane bending loading mode), and then by combining the geometric stress components.

The locations at which the geometric (hot spot) stress is to be assessed are given in [2.3.5].

2.2 Joint modelling

2.2.1 General

The modelling choices and the performance of the space frame analyses are not in the scope of the present Guidance Note. Guidance on the modelling of a joint structure is given in par. 12.3 of ISO 19902. However, the influence of joint modelling is mentioned due to its significant impact on the calculated nominal stresses.

2.2.2 Space frame model

The space frame model consists of members that are connected at nodes. The modelling of members is based on beam elements representing the axial, bending, shear and torsional stiffnesses of the structural members.

2.2.3 Simple node modelling

The simplest way of modelling tubular joints is to consider a node-to-node connection at the intersection of the centre lines of the brace and chord members, and to retrieve the nominal stresses at the intersection point.

2.2.4 Advanced node modelling

The node modelling can be refined by introducing joint flexibilities, which allows redistribution of the bending moments and retrieval of the nominal stresses at the actual weld position. Flexibilities modelling for fatigue analyses is accepted but shall be implemented with care for multi-braced joints due to cross terms contributions that may entail non-linear effects.

2.3 Simple tubular joints

2.3.1 Design hot spot stress

The design hot spot stress range $\Delta\sigma_{HS}$ to be considered for fatigue analysis is the maximum value among the geometric stress ranges $\Delta\sigma_G$ calculated at the specific locations around the tubular joint circumference defined in [2.3.5].

2.3.2 Joint classification

For the purpose of the evaluation of the geometric stress concentration factor K_g , tubular joints are usually classified into planar joints of T/Y, K, KT or X type (see typical examples in Fig 2).

Further details can be found in ISO 19902 (see section A.16.10.2.1.3).

The tubular joints classification is based on geometrical considerations (chord diameter, chord thickness, brace diameter, brace thickness), keeping in mind that the classification actually depends on the force flow in the framed structure and that the multi-planar effects are disregarded.

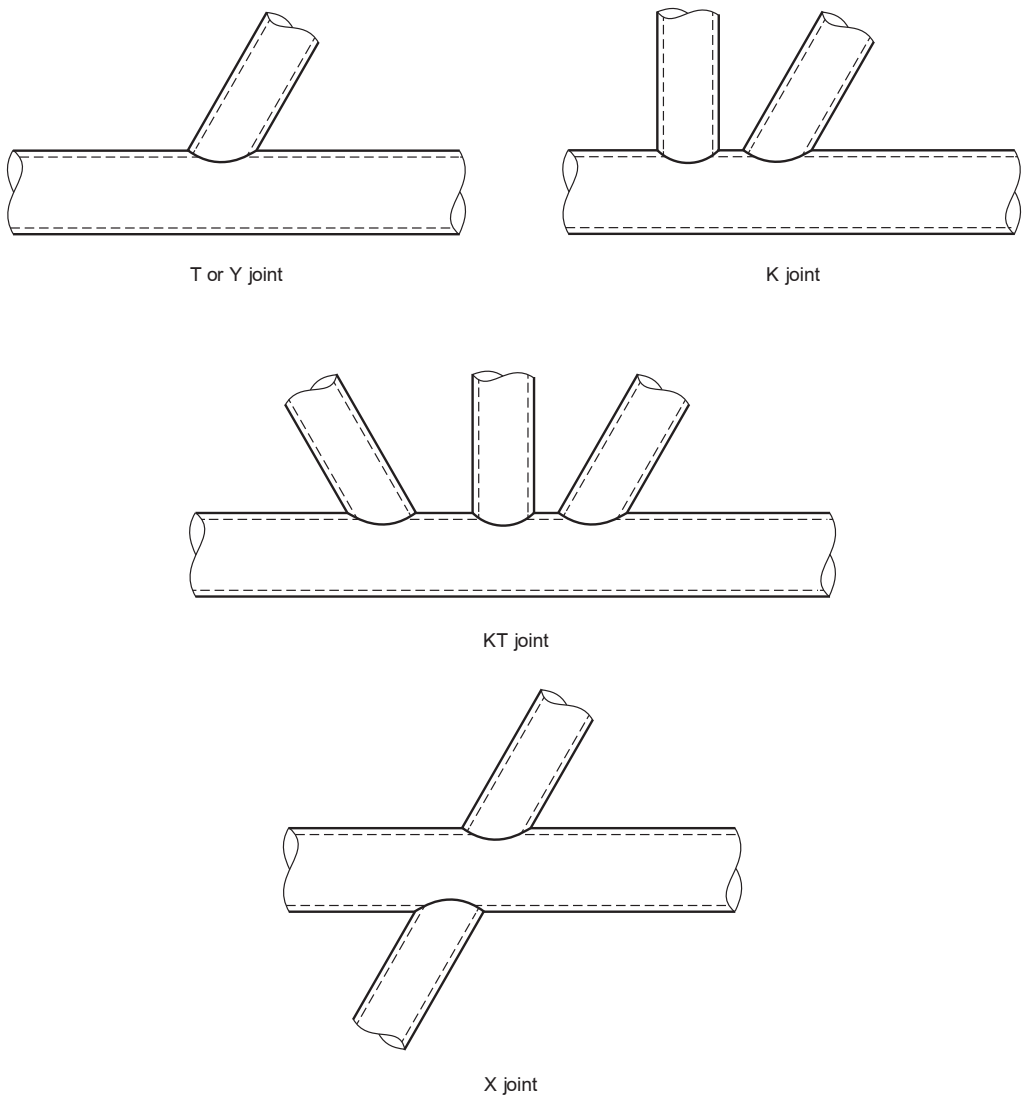
2.3.3 Geometric stress concentration factors

For simple planar joints (T/Y, K, KT, X) and simple loading mode (axial, in plane bending, out of plane bending), parametric K_g expressions have been developed. These equations are based on Efthymiou formulations and are detailed in ISO 19902, section A.16.10.2.2.2. These equations provide K_g for crown and saddle points of simple tubular joints at chord and brace side, as defined in Fig 1.

For crown and saddle locations, on both chord and brace sides, K_g is to be determined using Efthymiou equations and taking into account the chord length as prescribed in [2.3.4]. A minimum K_g value of 1,5 shall be considered (see ISO 19902, section 16.10.2.1).

Alternatively, or when the joint geometry does not allow the use of Efthymiou formulations, the geometric stress concentration factors K_g may be calculated at the locations defined in [2.3.5] by finite element analysis, as defined in Sec 6.

Figure 2 : Planar joint types



2.3.4 Influence of the chord length on the stress concentration factors

For fatigue assessment of the weld toe at chord side crown positions, the chord nominal bending stress should be considered and added to the hot spot stress due to the brace nominal loading. Actually, the chord bending stress is already included in the Efthymiou formulae via the parameter α . The choice of this parameter is however not straight forward as it is linked to the chord length which has to be defined by the user.

As the chord nominal bending stress is already known from the space frame analysis, an alternative approach is to disregard the chord bending effect in Efthymiou formulae (i.e. by setting $\alpha = 12$, $C = 0,5$) and add the chord nominal bending stress obtained from the space frame analysis to the calculated hot spot stress.

In order to account for the presence of the welded brace, the chord bending stress to be added shall be multiplied by a K_g taken equal to 1,25 (see ISO 19902 A.16.10.2.1.5).

2.3.5 Combination of axial and bending stresses

The geometric stresses are to be calculated at eight locations around the circumference of the joint, at the chord side and at the brace side. Relevant locations shall include, as a minimum (see Fig 3):

- the chord sides at two crown positions
- the brace sides at two crown positions
- the chord sides at two saddle positions, and
- the brace sides at two saddles positions.

The geometric stresses at these points are derived by the combination of axial, in-plane bending and out-of-plane bending stresses.

When no K_g value is available at a given location, it can be estimated, considering:

- linear interpolation of the K_g values for axial loading, and
- sinusoidal interpolation of the K_g values for bending loading as detailed hereafter (see also Fig 3).

The geometric (hot spot) stress as a function of the circumferential location ϕ can be expressed as follows:

$$\sigma_G(\phi) = K_{g_{AX}}(\phi) \sigma_{AX} + K_{g_{IPB}}(\phi) \sigma_{IPB} + K_{g_{OPB}}(\phi) \sigma_{OPB}$$

where:

ϕ : Angle around the chord to brace intersection, with $\phi = 0$ at crown location (point 1 on Fig 3)

σ_{AX} , σ_{IPB} , σ_{OPB} : Respectively the nominal maximum axial stress, in-plane bending stress and out-of-plane bending stress in the adjoining brace member

$K_{g_{AX}}(\phi)$, $K_{g_{IPB}}(\phi)$, $K_{g_{OPB}}(\phi)$: π -periodic functions, defined as follows:

- for $0 \leq \phi < \pi/2$:

$$K_{g_{AX}}(\phi) = K_{g_{AX,crown}} + 2 (\phi/\pi) (K_{g_{AX,saddle}} - K_{g_{AX,crown}})$$

- for $\pi/2 \leq \phi < \pi$:

$$K_{g_{AX}}(\phi) = K_{g_{AX,saddle}} - K_{g_{AX,crown}} - 2 (\phi/\pi) (K_{g_{AX,saddle}} - K_{g_{AX,crown}})$$

$$K_{g_{IPB}}(\phi) = -K_{g_{IPB,crown}} \cos(\phi)$$

$$K_{g_{OPB}}(\phi) = K_{g_{OPB,saddle}} \sin(\phi)$$

with:

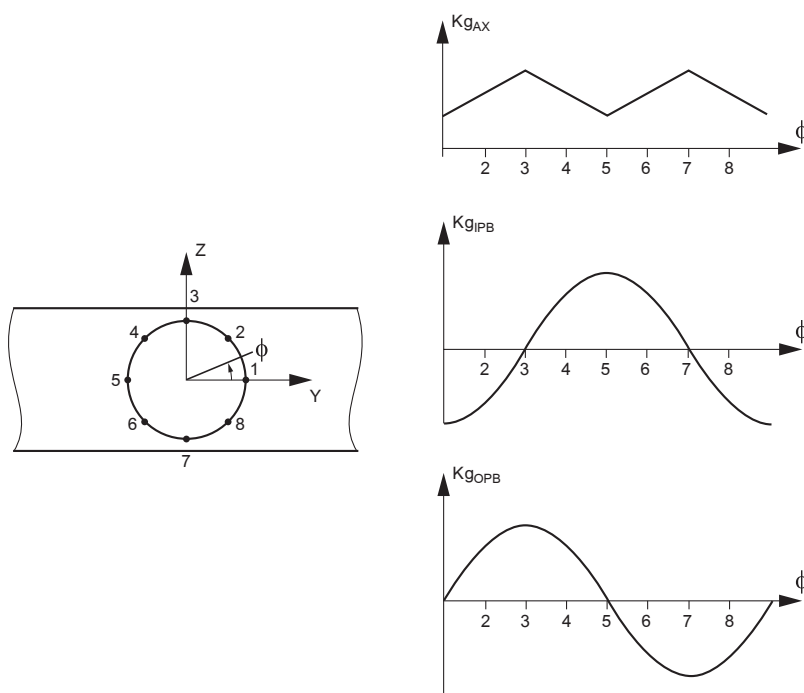
$K_{g_{AX,crown}}$, $K_{g_{IPB,crown}}$: Geometric stress concentration factors at crown, for axial stress and in plane bending

$K_{g_{AX,saddle}}$, $K_{g_{OPB,saddle}}$: Geometric stress concentration factors at saddle, for axial stress and out of plane bending.

These factors can be obtained according to Efthymiou equations or by finite element analysis (see [2.3.3]). In the later case, the finite element model may also provide directly $K_{g_{AX}}(\phi)$, $K_{g_{IPB}}(\phi)$ and $K_{g_{OPB}}(\phi)$.

The above procedure is to be applied independently for chord and brace sides.

Figure 3 : Stress calculation locations and SCF (K_g) periodic functions



2.3.6 Alternative methods for geometric stress calculation

For more accurate calculations of geometric stresses, one of the following alternative methods can be adopted:

- to use the generalized concept of influence functions developed by Efthymiou
- to perform the global analyses integrating a detailed sub-model of the tubular joint according to Sec 6.

The influence function method is more accurate than the SCF approach because it can handle generalized forces and moments on the braces forming the joint, as opposed to the Kg approach which is based on individual planes and joint classification.

Moreover, the influence function method has several advantages:

- it avoids the need to classify joints and hence is more convenient to use than Kg method. It handles classification automatically on the basis of the actual load paths
- it allows to handle multiplanar joints for the important case of axial brace forces.

2.3.7 Geometric stress range

The geometric stress range $\Delta\sigma_G$ is the range of σ_G calculated during a wave load cycle according to [2.3.5].

2.3.8 Applicable S-N curve

The tubular joints shall be checked versus toe cracking considering the 'T' curve as per ISO 19902.

The basic 'T' S-N curves to be used in air environment and in seawater with corrosion protection are given in Sec 9, [2.2]. These curves may need to be modified due to factors affecting the fatigue strength, as described in Sec 10.

2.4 Other tubular joints

2.4.1 Geometric stress concentration factors

For the following types of tubular joints, a detailed local FE analysis as per Sec 6 is required in order to determine the applicable Kg values:

- overlapping joints
- ring-stiffened joints
- cast joints.

A minimum Kg value of 2,0 shall be considered for these joints (see ISO 19902, section 16.10.2.1).

2.4.2 Applicable S-N curve

The casted joint shall be checked versus toe cracking considering the 'CJ' curve as per ISO 19902.

The 'CJ' S-N curve to be used in air environment is given in Sec 9, [2.3].

3 Tubular butt welded joints

3.1 General

3.1.1 Local nominal stress

Tubular butt welded joints shall be designed based on the assessment of nominal stresses and the use of appropriate stress concentration factor due to eccentricity between welded members in order to obtain the local nominal stress given by:

$$\sigma_{\text{Loc Nom}} = K_m \sigma_{\text{nom}}$$

where:

K_m : Stress concentration factor due to eccentricity defined in Sec 10, [5.5]

σ_{nom} : Cyclic nominal stresses defined in [2.1.2].

3.1.2 Nominal stress

The relevant cyclic nominal stresses σ_{nom} to be considered for fatigue analysis are the ones produced by axial loads and bending moments, the stress components of which are normal to the weld toe.

The nominal stresses within the tubular members can be obtained by space frame finite element model where the members of the model are represented by beam elements and no eccentricities are modelled.

When the butt welded joint involves a thickness transition, the nominal stress to be considered is the stress calculated in the weakest member.

3.2 Classification of tubular butt welded joints

3.2.1 Tab 1 defines different tubular butt welded joint geometries and the potential hot spots at weld toe and weld root. Both single-sided joints and double-sided joints are considered, with or without thickness difference. Thickness transition between members may be located inside or outside the members.

The applicable formula of stress concentration due to eccentricity are given in Sec 10, [5.5] for each hot spot.

Each constructional detail incorporates local weld effects but not gross geometrical discontinuities which shall be considered using the appropriate geometric stress concentration factors.

For double-sided joints, hot spots are exclusively located at weld toe.

For single-sided joints, hot spots are located at both the weld toe and the weld root. In addition to the weld toe crack initiation checking, special consideration is to be given to the potential fatigue failure originated at the weld root which exhibits lower fatigue performances (see Sec 7, [2.2]).

3.3 Applicable S-N curves

3.3.1 Toe cracking

The applicable S-N curves for weld toe checking of tubular butt welded joints in air and in seawater with corrosion protection are given in Sec 9, [2.4].

3.3.2 Root cracking

The applicable S-N curves for weld root checking of tubular butt welded joints in air and in seawater with corrosion protection are given in Sec 9, [3.4].

Table 1 : Classification of tubular butt welded joints

Position of thickness transition	Type of weld	Hot spot 1	Hot spot 2	Illustration
Inside	single-sided	weld toe	weld root	
	double-sided	weld toe	weld toe	
Outside	single-sided	weld toe	weld root	
	double-sided	weld toe	weld toe	
Equal thickness	single-sided	weld toe	weld root	
	double-sided	weld toe	weld toe	

SECTION 5

FEA HOT SPOT STRESS FOR PLATED WELDED JOINTS AND FEA LOCAL NOMINAL STRESS FOR NON-WELDED DETAILS

1 General

1.1 Application

1.1.1 General

The aim of this Section is the determination of the hot spot stress for plated welded joints and of the local nominal stress for non-welded details such as cut plate edge from shell finite element models.

The stress at hot spot for welded joints is generally highly dependent on the finite element model used for the representation of the structure. Therefore the method for determination of hot spot stress is to be accurately specified.

The local nominal stress for non-welded area at cut plate edge requires a specific finite element model and a well specified method for the calculation.

Where other methods than those described in this Section are adopted for calculation of FEA based hot spot stress, these methods are to be submitted to the Society for review.

1.1.2 Rule based approach

When simplified rule based approach (see Sec 1, [5.2.1]) is used, according to the type of detail, the dedicated stress (hot spot or local nominal) analysis is to be carried out for each rule load case i1 and i2 associated to the loading condition (j) (see Sec 2, [1.2], Sec 2, [1.3], and Sec 11, [2.1.4]). Depending on the type of detail, the prescriptions in [3], [4] or [6] are to be followed.

The procedure to obtain the dedicated stress range and associated mean stress is then given in [7].

1.1.3 Direct calculation approach

When a direct calculation approach is used according to the type of detail, the prescriptions given in [3], [4], [5] or [6] are to be used to derive the dedicated stress transfer functions or dedicated stress time series.

The prescriptions in [7] are not applicable to direct calculation approaches.

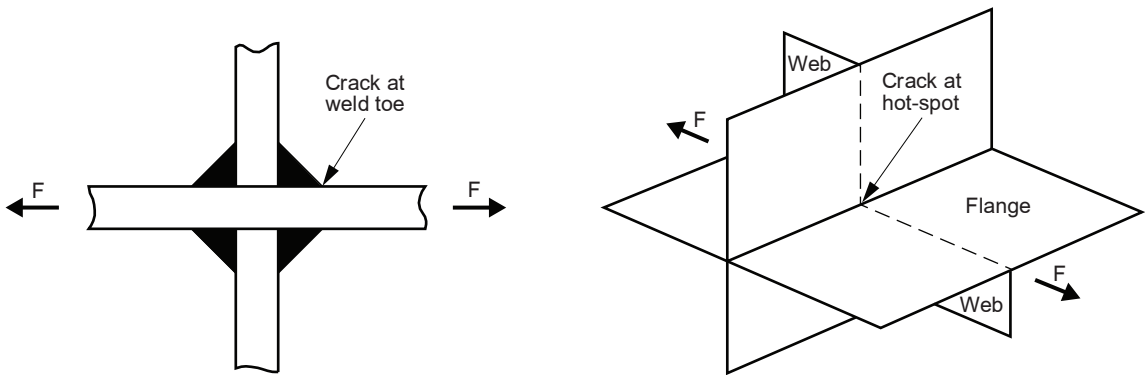
1.2 Type of details

1.2.1 Web-stiffened cruciform joints

A standard cruciform joint corresponds to the intersection of two plates (see Fig 1). A web-stiffened cruciform joint corresponds to a cruciform joint where the two plates are stiffened by another plate perpendicular to the first ones and acting as a web (see Fig 1).

The method for the calculation of the hot spot stress at the weld toes of web-stiffened cruciform joints is given in [4].

Figure 1 : Standard cruciform joint (left hand side) and web-stiffened cruciform joint (right hand side)



1.2.2 Bent hopper knuckle details

Prescriptions for the calculation of the hot spot stresses for bent hopper knuckles are given in [5].

1.2.3 Ordinary welded details

Ordinary welded details are commonly used welded details other than web-stiffened cruciform joints and bent hopper knuckle details such as simple butt welds, simple fillet welds of T joints and ordinary cruciform joints.

The method for calculation of hot spot stress for ordinary welded details is described in [3].

1.2.4 Non welded details

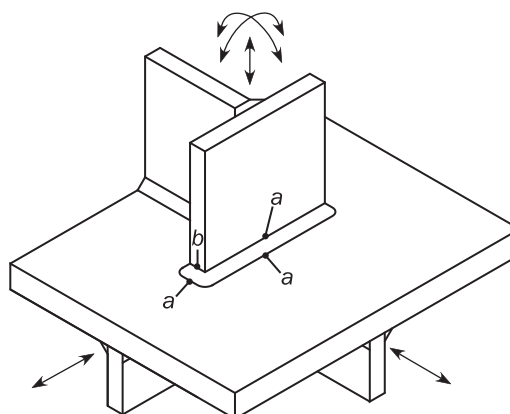
Prescriptions for the calculation of the local nominal stress for non-welded area such as cut plate edges, cut-outs for stiffeners connections at web frames, hatch corners, etc. are given in [6].

1.3 Types of hot spots for ordinary welded joints

1.3.1 Two types of hot spots ('a' and 'b') at weld toe of ordinary welded joints are defined depending on their position on the plate, as follows (see Fig 2):

- Hot spot type 'a': weld toe on plate surface
- Hot spot type 'b': weld toe on plate edge.

Figure 2 : Types of hot spots



2 Finite element models

2.1 General

2.1.1 General

The evaluation of the hot spot stresses for fatigue assessment requires the use of very fine mesh in way of high stress concentration areas.

These very fine mesh zones may be incorporated into the global FEM model as shown in Fig 3. Alternatively, the very fine mesh analysis may be carried out by means of separate local finite element models with very fine mesh zones to which boundary conditions obtained from a global model are applied. A typical local separate model of a hopper knuckle connection is shown in Fig 4.

2.1.2 Corrosion

The FEM models used for fatigue assessment are based on the net scantling concept (see Sec 1, [3.3]).

2.2 Global FEM model

2.2.1 General

The global FEM model is used to compute the structural response of the ship or offshore unit as a whole and at the scale of the primary supporting members. The typical element size is equal to the spacing between ordinary stiffeners.

The global FEM model may be either a full length FEM model or a partial FEM model. The type and the extent of the global FEM model is to be adapted to the considered ship or offshore unit, and to the considered fatigue detail, in such a way that the structural response is correctly captured.

Figure 3 : Very fine mesh zones included into the cargo hold model

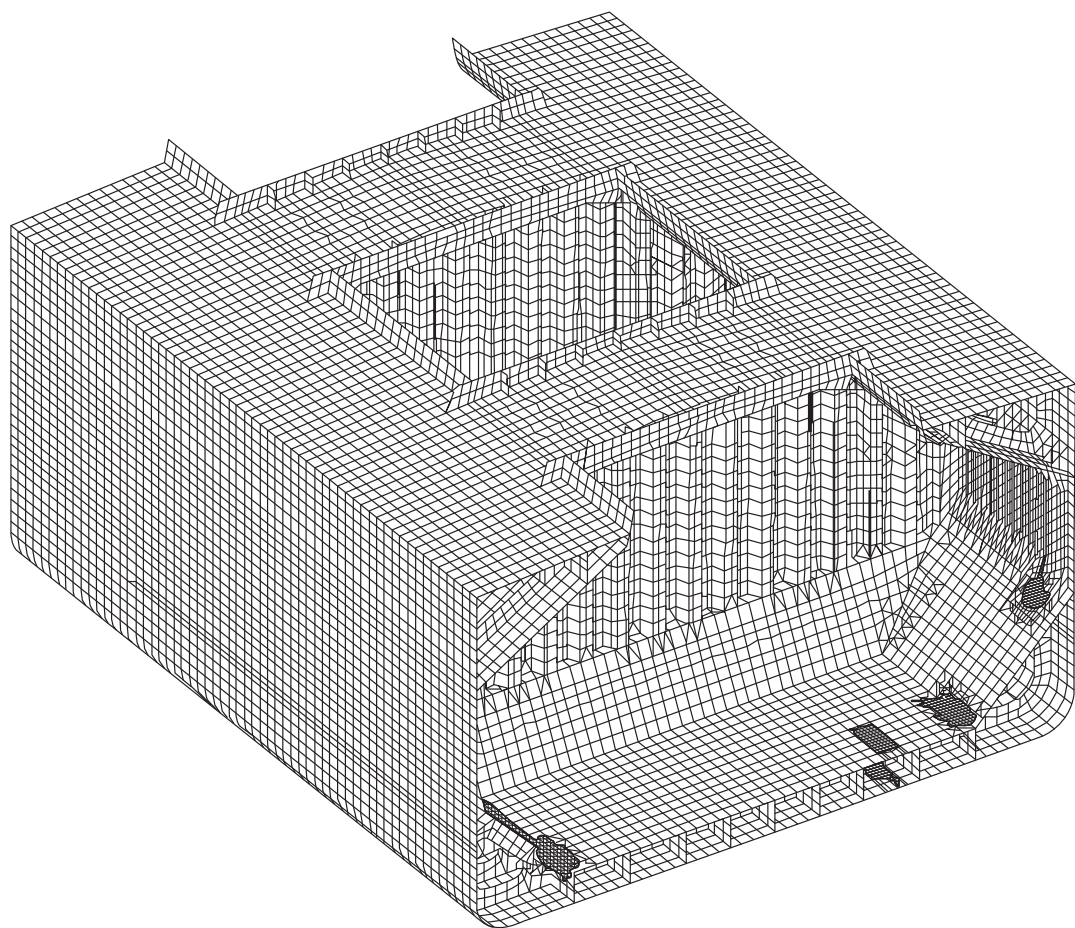
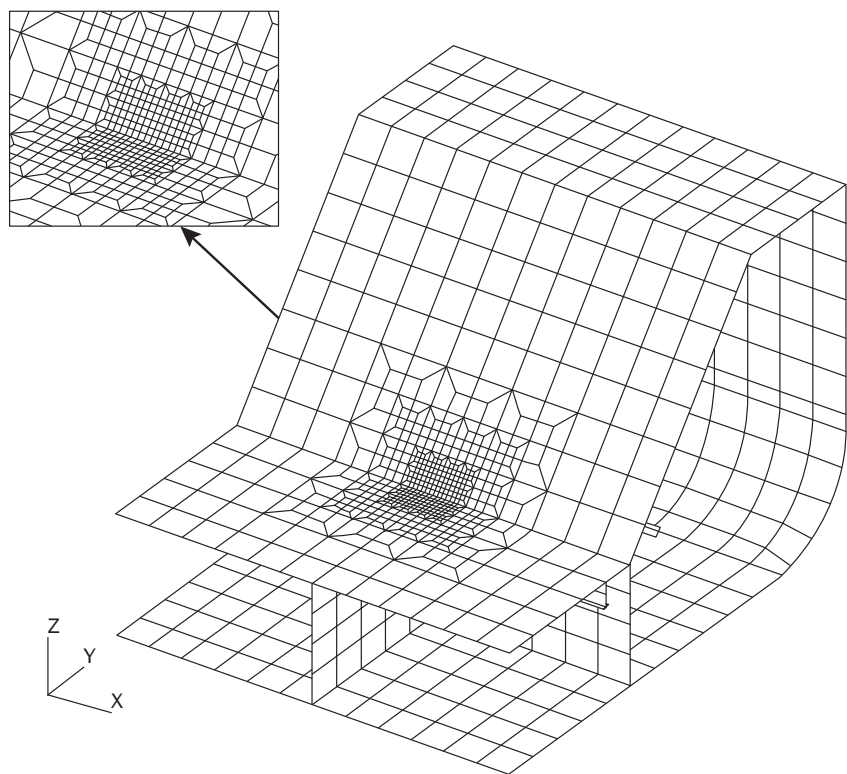


Figure 4 : Local separate FE model of hopper knuckle connection including very fine mesh zone



2.2.2 Full length FEM model

The structural model can be a “full length FEM model” where the entire structure of the vessel is included in the model. This type of model is suitable for any type of structure but is more demanding than partial models described in [2.2.3].

The modelling rules and boundary conditions are to be in accordance with the applicable requirements of the applicable rules.

Full length models need to be analysed through procedures that guarantee an accurate balance of the model under all wave induced loads, such as the direct calculation methods described in Sec 11, [3.2.5].

2.2.3 Partial FEM model

For some types of structures, a full length FEM model is not necessary for the correct evaluation of the structural response in the area of interest. In this case the extent of the FEM structural model can be reduced to a subpart of the structure.

The considered structural subpart has to be isostatic (i.e. statically determinate), thus limiting the applicability to slender structures. The structural response within the extent of the FEM model must not be significantly influenced by the distortion of the non-modelled parts, which excludes structures prone to warping or shear lag. This method is typically used for “three holds models” of ships and ship shaped units.

The modelling rules, model extent and boundary conditions are to be as prescribed in the applicable rules.

If a partial structural model is used, the forces and moments exerted by the structure parts not included in the FEM model need to be applied at the boundaries of the structural model.

2.3 Finite element modelling for hot spot stress calculation

2.3.1 Separate local FE model

Where a separate local finite element model is used, the extent of the local FE model is to be chosen so that the imposed boundary conditions and the applied loads are far enough from the very fine mesh zones in order not to affect the calculated stresses.

Boundaries of the fine mesh model are to be taken at adjacent primary supporting members such as girders, stringers and floors, as far as practicable. Transverse web frames, stringer plates and girders at the boundaries of the local model shall not be represented in the local model.

Other prescriptions that may be given in the applicable rules have to be applied.

2.3.2 Shell elements

In shell element models, the elements are arranged in the mid-plane of the structural components. For practical purposes, adjoining plates of different thickness may be assumed to be median line aligned, i.e. no staggering in way of thickness change is required. Workmanship misalignment is not required to be modelled.

2.3.3 Modelling of welds

The welds are usually not modelled except for cases where the results are affected by local bending, e. g. due to an offset between plates or due to a small free plate length between adjacent welds such as at collar plate. For those cases, hot spot stress calculation is to be performed according to suitable methods, to the satisfaction of the Society.

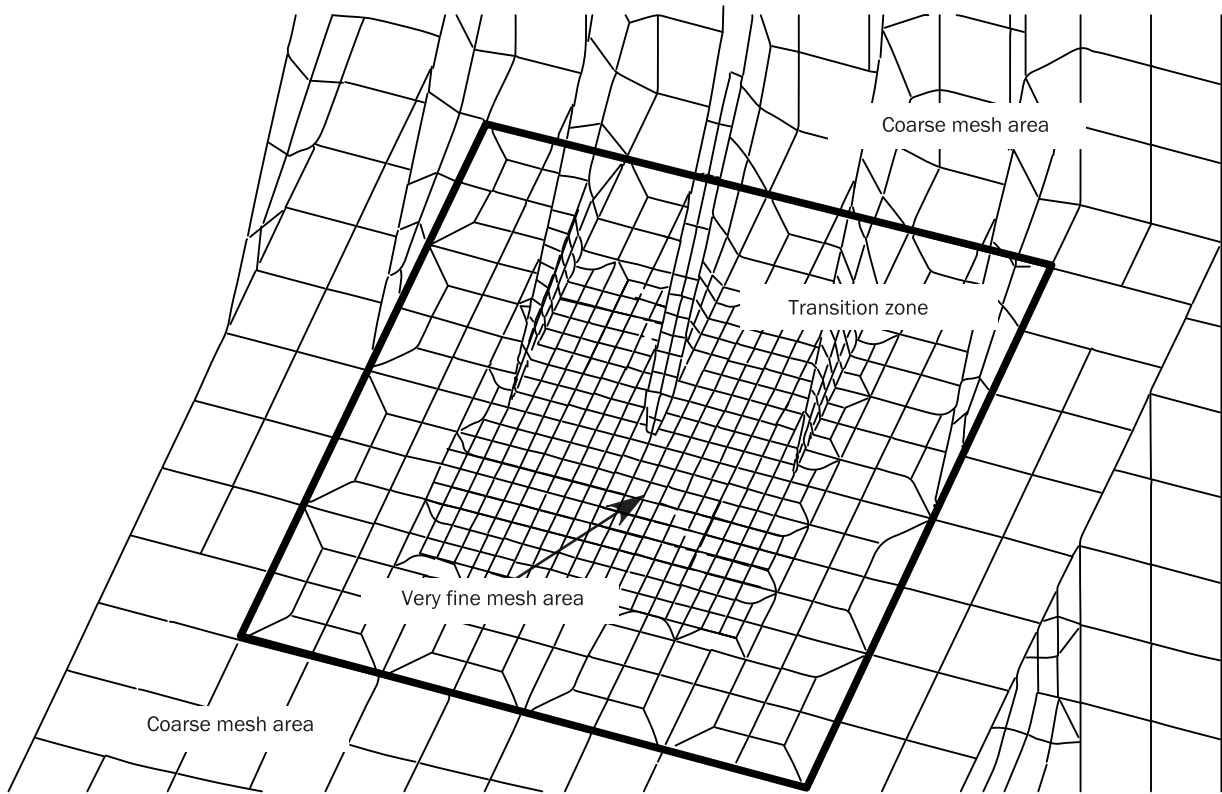
2.3.4 Mesh size

For type ‘a’ hot spots (see [1.3.1]), the very fine mesh density is to be based on shell element of mesh size t_n by t_n , where t_n is the net thickness of the plate in way of the considered hot spot.

For type ‘b’ hot spots (see [1.3.1]), the very fine mesh density is to be based on shell element of mesh size 10 by 10 mm.

The aforementioned mesh size is to be maintained within the very fine mesh zone, extending over at least ten elements in all directions from the fatigue hot spot position. The transition of element size between the fine mesh and the very fine mesh zone is to be done gradually and an acceptable mesh quality is to be maintained. An example of mesh transition in way of the side frame bracket toe is shown in Fig 5.

Figure 5 : Transition area between fine mesh and very fine mesh



2.3.5 Element type

Quadrilateral shell elements are to be used inside the very fine mesh zone. Shell elements with midside nodes are recommended particularly in case of steep stress gradients.

2.3.6 Transition mesh

Use of linear triangular elements is to be avoided as much as possible in close proximity to the very fine mesh zones. Quadrilateral elements are to have 90 degrees angles as much as possible or angles between 60 degrees and 120 degrees. The aspect ratio is to be close to 1. When the use of a linear triangular elements cannot be avoided, edges aspect ratio is to be as close as possible to unity.

2.3.7 Beam elements for edge stress evaluation

For type ‘b’ hot spots (see [1.3.1]) or for non-welded cut edge details, such as cut-outs for stiffeners connections at web frames, edge plating and hatch corners, stresses are to be evaluated on the plate edge. In such a case, the stress may be read out directly in beam elements put along the plate edge. In order to capture both the axial and bending stresses, such beam elements should have a rectangular section, with one side equal to the thickness of the plate along which they are fitted. The other section side is to be made very small in order to have a negligible beam element stiffness.

3 Hot spot stress for ordinary welded details

3.1 General

3.1.1 Types of welded details

The prescriptions in [3] apply to ordinary welded details: butt welds, fillet welds of T joints and ordinary cruciform joints. They do not apply to web-stiffened cruciform joints and bent hopper knuckles.

3.1.2 Types of FE mesh

The prescriptions in [3] apply to FEM model based on shell elements, in which the welds are not explicitly modelled. For other types of meshes, other methods are to be used.