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Fatigue strength determination of ship structural joints

Part I
Analytical methods for determining fatigue strength of ship structures

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ABSTRACT

Spectacular accidents at sea which have happened for a few last years show that hull structures of contemporary sea-going ships are not perfect and must be systematically improved. Fatigue strength is one of the groups of strength problems which affect design of contemporary ship's structures and greatly contribute in their improvement process. In this paper several approaches to estimation of fatigue life of hull structural elements are presented. In practice the some approaches based on nominal stresses, „hot spot" stresses or notch stresses which constitute the basis for fatigue life determination by using σ-N design curves are applied. In this paper the existing proposals have been critically analyzed and their drawbacks (often hidden) presented.

Keywords: fatigue of ship structure; cumulative damage; fatigue life analysis

INTRODUCTION

Contemporary merchant ships (especially VLCC and ULCC tankers and containerships (whose hulls reach ~400m in length, more than 50m in breadth and 30m in depth), as well as ocean engineering objects such as semi-submersible drilling rigs are ones of the largest technical objects worldwide. Their structures are to comply with many criteria considered crucial such as: of safety, reliability, mass, operational economy, producibility, ergonomy and esthetics. In many cases technical parameters which represent given criteria interact to each other and the interaction may be - on the one hand - of amplifying character and - on the other hand - of mutually opposing one.

From the point of view of operational conditions the structures are used in extreme conditions, i.e. they are subjected to loads generated by waves, sequential loading –unloading operations, temperature changes (day-night, crossing climatic zones during a given period of service), vibrations etc, as well as action of highly corrosive environment. It leads to determinate consequences. Firstly: occurrence of failures of hull structures usually leads to lowering their technical operational capability by limiting their functions (decreasing load-carrying capacity, occurrence of leaks etc). Secondly: in an extreme case it may lead to catastrophic collapse of the whole structure. As a rule the failures are of kind of corrosion wear or form of cracks.

The detected cracks are analyzed by classification societies as to their location and causes of occurrence [1]. As results from the reports, hull structure cracks constitute almost a half of total number of failures occurring in hull structure due to various causes. Most of the detected cracks have been qualified as fatigue cracks, that is in compliance with other data [2] where operational failures of ship structures have been divided into brittle fractures, fatigue cracks, immediate tensile as well as buckling failures, and ~75% of the cracks were considered to be generated by material fatigue.

In Fig. 1÷4 are presented examples of fatigue cracks detected on various ships and located in different zones of their structure [3, 4, 5, 6].

This paper initiates the series of publications devoted to the determining of fatigue strength of ship structure joints, in which problems of fatigue cracking and estimation of fatigue life of ship structure joints will be successively discussed both on local and zone level.

METHODS FOR ANALYZING FATIGUE OF SHIP STRUCTURES

Analysis of the modeling of fatigue phenomena in ship structures

Fatigue analysis of ship structures is a very complex problem. It results from many factors among which the following are most important:

a) the material fatigue phenomenon itself has been not sufficiently recognized so far due to complex influence, on run of fatigue changes, of such factors as: kind of

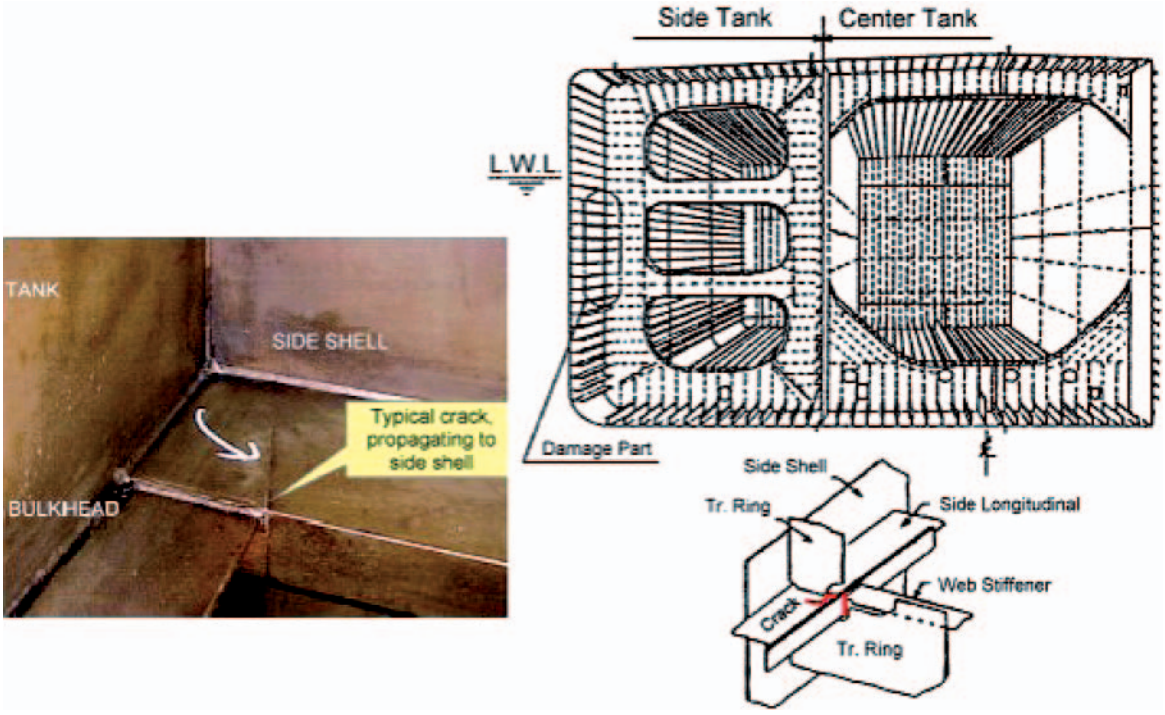

Fig. 1. *Example of fatigue cracks in tankers [3]*

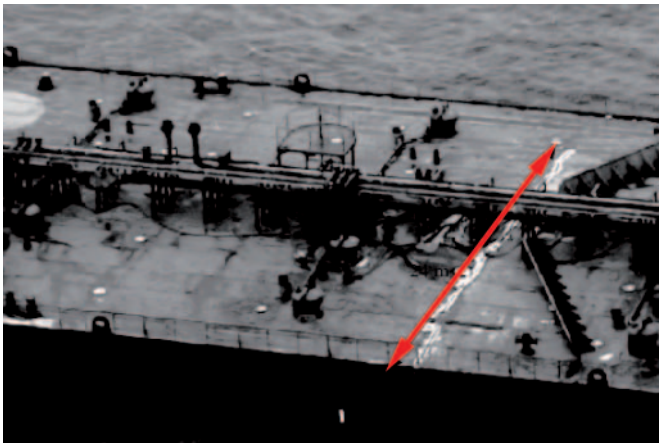

Fig. 2. *Fatigue - cracked deck of the tanker Castor [4], (Crack length of about 24 m)*

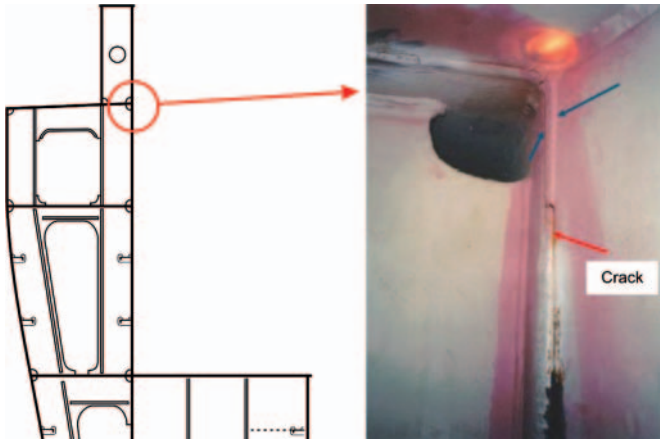

Fig. 3. *Example of fatigue crack in welded joint of ship structure detail of a containership [3]*

Fig. 4. *Example of fatigue crack in base plate of ship structure detail [5]*

Fig. 5. *Example of fatigue crack in welded joint of ship structure detail [6]*

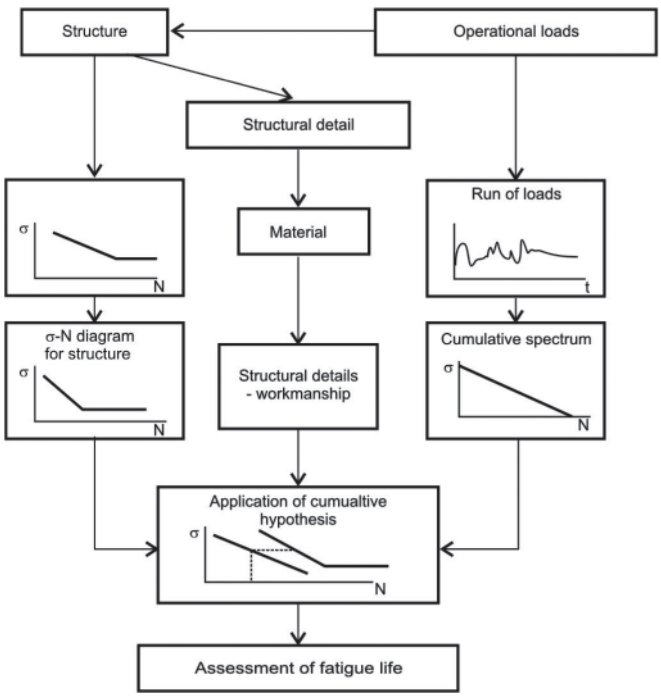

Fig. 6. „Safe-life" approach to fatigue analysis [8]

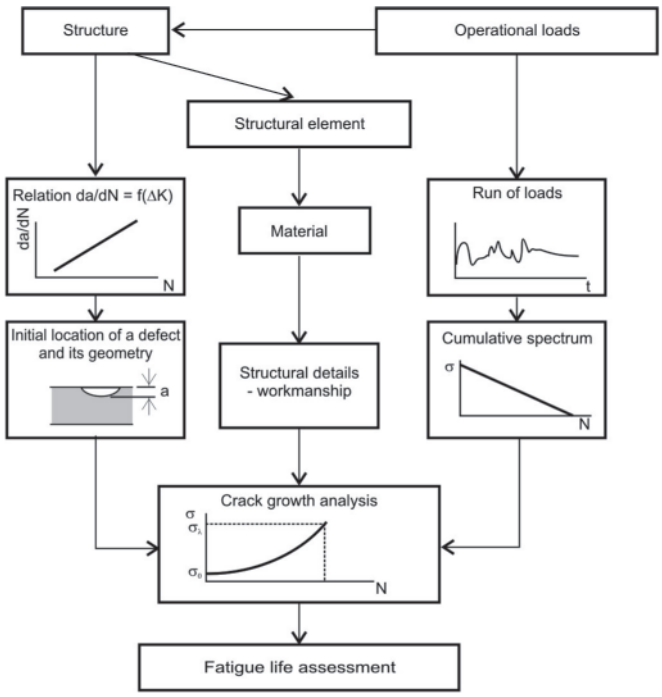

Fig. 7. „Fail safe" approach to fatigue analysis [8]

material (its structure, mechanical properties, chemical composition), loading mode (its magnitude, effect of mean stresses), structural element geometry, impact of environmental conditions etc [7],

b) difficulties in unambiguous determining loads applied to the entire hull structure and its particular elements (zones, joints) as well, both as to load components, their directions and simultaneity of action,
c) different state of protective coating in particular ship zones, which may cause different run of phenomena because of a different degree of environmental influence,
d) interaction of geometrical, technological and material notches.

As a result of the above described situation, fatigue analyses of ship structures are performed under many simplifying assumptions, by using different procedures depending on aim and degree of accuracy of a given analysis.

As a result of action of variable loads in ship structures fatigue cracks appear in structural zones especially susceptible to the kind of loading, namely, in stress concentration areas to which belong regions of changeable shape of structural element (geometrical discontinuities – see Fig. 1, 3, 4 and 5), sometimes additionally amplified by presence of welds.

Fatigue failure of an analyzed ship structural element (like other elements of welded structures and/or machinery parts) and the total fatigue life (NC) corresponding to the process and measured by number of fatigue load cycles can be split into the initiation period (NI) and the propagation period (NP) of fatigue failure, as follows:

$$N_C = N_I + N_P \tag{1}$$

Determination of fatigue life for a given load level (usually represented by stresses, and sometimes by strains) or inversely – determination of an allowable load level for a given fatigue life are the main tasks of fatigue analysis in the domain of the so called limited fatigue life. Such analysis may be conducted by applying two fundamental approaches to design (selection of scantlings) of structures, namely: according to „safe life" criterion, i.e. safe duration time (which does not allow to initiate a fatigue crack in a considered structure or its chosen elements) – or „fail safe" criterion, i.e. safe cracking (which allows to initiate a fatigue crack in a considered structure or its chosen elements and to continue its stable growth within controlled limits up to the so called critical length (see e.g. Fig. 2).

Fig. 6 and 7 show the simplified schematic diagrams of the fatigue analyses carried out in accordance with the above mentioned criteria [8].

In the case of complex welded structures among which ship hull structures are numbered, analysis of their fatigue properties, by performing calculations of fatigue strength or fatigue life of analyzed structural joints, can be realized by means of one of the approaches making use of many possibilities of carrying out the calculations, presented in Fig. 8, [9], and Fig. 12, [10].

Choice of a given approach results from the aim attributed to the analysis to be performed. Basing on the relation (1) one is able to present complete fatigue characteristics of a given structural element in the form of sum of partial characteristics corresponding to two phases of fatigue failure, namely:

a) the initiation phase – period up to appearance of a fatigue crack,
b) the propagation phase – period of further stable growth of the crack up to the instant of triggering unstable crack propagation, that corresponds to the complete fatigue life.

Lack of an unambiguous criterion of the end of fatigue crack initiation phase (depending on aims of performed analysis there are distinguished [9]) the so called scientific and engineering criteria for the end of the initiation phase) results in arbitrary choice of an approach to fatigue analysis, which this way affects its final results.

In engineering practice of conducting fatigue analyses depending on a considered type and place of ship structure as well as consequences resulting from a mode of fatigue crack growth the notion of the „visible crack" of about 2 inches (50 mm) in length was adopted as the limit value for the crack initiation phase. The so defined „visible crack" length equal to 2 inches was confirmed as that practically distinguishable during surveys of real ship hull structures conducted by det Norske Veritas, as shown in Fig. 9 [1].

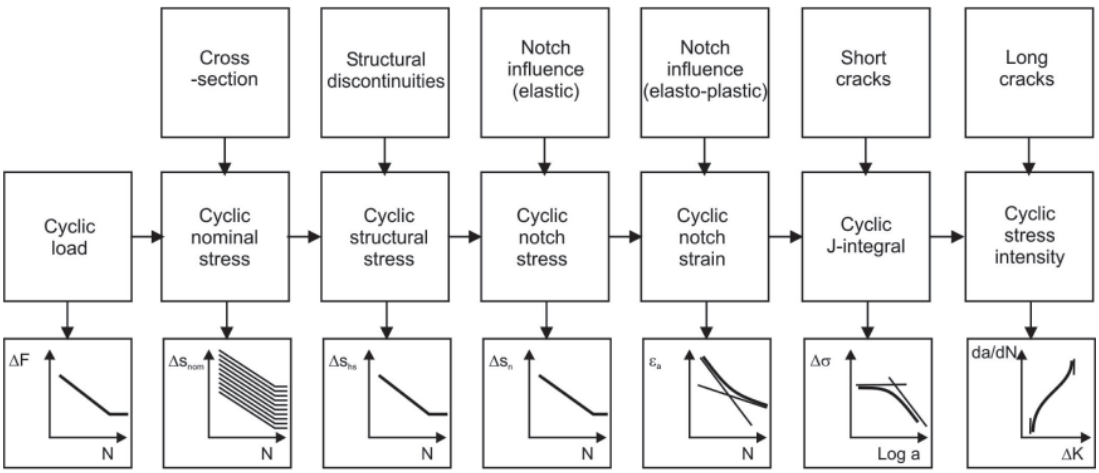

Fig. 8. *Overview of approaches to fatigue analyses for determining fatigue strength or fatigue life of welded structures [8]*

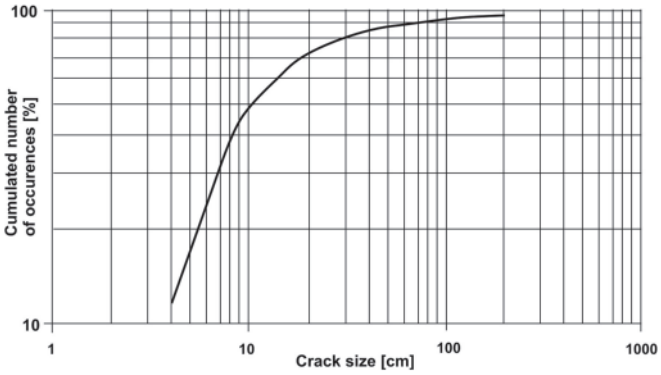

Fig. 9. *Cumulative length distribution of the cracks detected in ship structures by det Norske Veritas (DNV) [1]*

Depending on aims of fatigue analysis, in the case of calculation of fatigue life corresponding to the fatigue crack initiation period on the basis of the relations σ = f(N), are most often used Wőhler diagrams recommended in the rules of classification societies [11], IIW [12] and /or one's own research. In practical performing such analysis it is necessary to represent an analyzed structural fragment by means of the simplified models for which the relations σ = f(N), obtained from the same specimens as those analyzed, are known, see for instance [11] and [12].

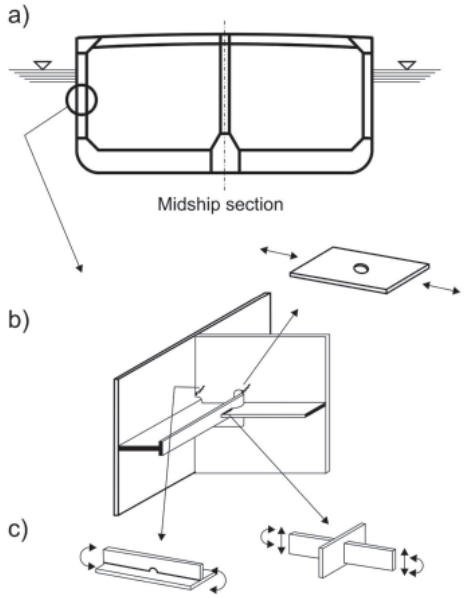

Fig. 10. *Example of representing real ship hull structure joints by using models of elementary joints [13]:* ***a)*** *on global level,* ***b)*** *on local level,* ***c)*** *on elementary joint's level*

Fig.10 schematically illustrates the modeling process of elementary joints used in ship structures, and Fig. 11 [13] shows the example of the relation σ = f(N) recommended by IACS in their common structural rules [11]. Letters B,C,D… denotes here given class of curve related to type of structural element.

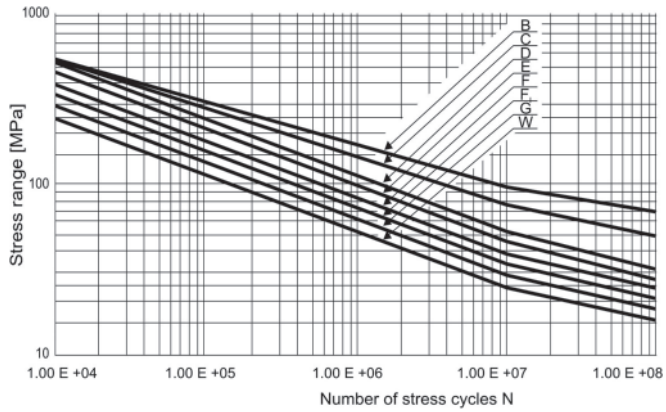

Fig. 11. *Wőhler diagrams for parent material and welded joints, recommended by IACS [11]*

In the case of fatigue analyses of ship structures when dimensioning their elements on the basis of the „safe life" approach, out of those presented in Fig. 8, are used the methods based on the nominal stresses σn, the „hot spot" stresses σhs, or the local notch stresses σk. In the case of determination of fatigue properties by applying the „fail safe" approach the principles resulting from fracture mechanics (FM) and dealing with fatigue crack growth (FCG) are used, Fig. 12 [14].

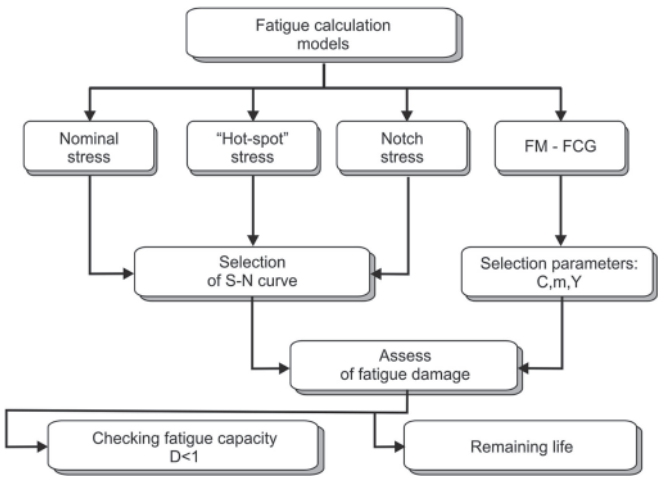

Fig. 12. *Schematic diagram of practical fatigue assessment procedure [14]*

Fatigue analysis based on the σ-N fatigue diagrams

a) Concept of the nominal stresses σ_n

The concept of performing strength calculations on the basis of nominal stresses is widely applied to welded structures. Analysis of such complex structural joint is conducted on the basis of the so called „elementary joints" distinguished in a considered structure (Fig. 10c). Loading state of such elementary joint is defined by its nominal stresses, i.e. stress values which can be determined in an elementary way on the basis of known internal tensile, compressive and shear forces and bending, twisting and other moments as well as known geometry of the considered structure [15]. If necessary, also influence of effective plate flanges are accounted for. But such effects as stress concentration resulting from geometrical discontinuities, e.g. brackets, cutouts, influence of local notches such as fusion penetration lines, initial deformations or manufacturing imperfections are not taken into account. In the approach in question the effects are accounted for in the σ -N curve representative for a given category of elements and mode of loading. The so determined stress values are considered an independent variable for fatigue life determining on the basis the relations σ = f(N) collected in various rules, standards, codes etc [11, 12, 16, 17, 18] and given in the form of diagrams or analytical functions containing the experimentally determined coefficients m and A:

$$N \cdot \sigma^m = A \tag{2}$$

where:
N – fatigue life of element under the stress σ_n,
A – constant,
m – material constant.

Worth mentioning that the coefficient m is of a constant value for a given type of joint, and the coefficient A is randomly varying and described by means of logarithmic - normal distribution. After finding logarithms of both sides of the expression (2) the basic curve equation in the logarithmic reference system is obtained:

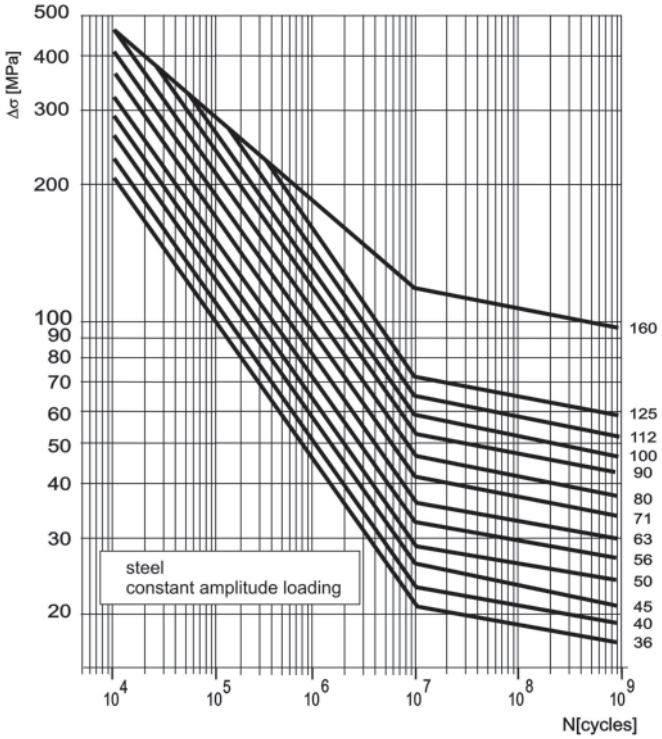

Fig. 13. Example of the σ_n – N design curves (FAT), [12]

$$\log N = \log A - m \cdot \log \sigma \tag{3}$$

The design curve Np – considered as a line which defines fatigue life up to a given phase of cracking (usually up to complete damage of a joint) - is defined as a line parallel to the basic one, shifted to the left by a multiple of the standard deviation d, namely:

$$\log N_p = \log A - m \cdot \log \sigma - k \cdot d \tag{4}$$

where:
N_p – fatigue life of element under the stress σ,
A – constant which describes the curve σ-N,
d – standard deviation of $\log(N_p)$ value,
m – material constant,
k – coefficient.

In shipbuilding practice k = 2 is usually assumed, that corresponds to 97,5% level of probability that no failure will occur [11,12]. Class of a given joint is determined, according to the curves, by a load value which usually corresponds to the fatigue life N = 2·106 cycles of load changes, Fig. 13. The curves presented in the figure are also determined on the probability level equal to 97,5%.

b) Concept of the „hot spot" (structural, geometrical) stresses σ_{hs}

In contrast to the nominal stress the structural stress is that which contains impact of local stress concentrations resulting from changes in structure geometry except those introduced by welds. Therefore the effect of stress concentration due to weld notch is not taken into account in the approach in question. Only stress raise resulting from changes in geometry of structural elements and possible initial deformations are accounted for. Such stress determined for the point of potential fatigue crack initiation (usually taken as a border line between fusion penetration and parent material) is called the „hot - spot stress" or geometrical (structural) stress, Fig. 14 [18].

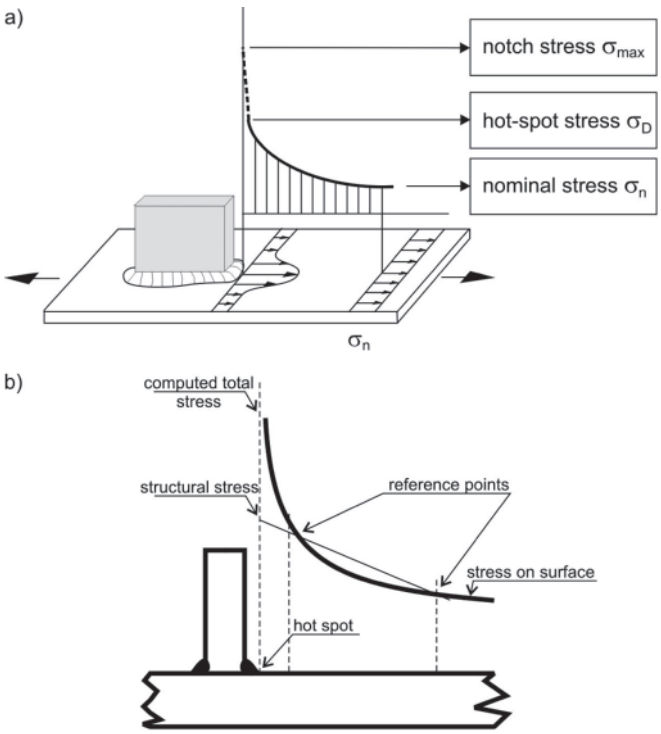

Fig. 14. Definition of structural hot- spot stress: ***a)*** *stress representatives;* ***b)*** *determination of the hot-spot stress*

The fatigue calculation procedure based on the approach in question was described in detail in [15, 18]. In the approach it is assumed that it suffices, in fatigue analysis algorithms, to account for only the component of macro-geometrical stresses because of its variability and individual character depending on an analyzed geometry. The weld geometry effect is already contained in the design curves used for the analysis – as a rule the two: one for butt welds, the other for fillet welds – based on test results of elementary joints. It means that the structural stress in the critical point („hot spot"), together with the curve σhs-N which is valid for a given kind of material and form of weld – make it possible to assess fatigue behaviour of an analyzed joint.

The stresses resulting from geometry of a joint („hot spot") can be determined by:

- making use of appropriate coefficients of stress concentration associated with geometry of a considered element,
- applying the finite element method and processing the so obtained results to determine stresses in the point of their concentration [19].

In applying the second approach it is important to appropriately choose the reference points for determining the stress in the point of concentration: stress values used for extrapolation should be taken so much distant from weld as not to account for weld notch effect and so much close to it as to account for effect of geometry change, Fig. 14b. Certain considerations as to choice of reference points for plate elements are given in [20]. In present the selection procedure for the reference points is defined differently by various institutions, for instance [1]:

- International Institute of Welding recommends the linear extrapolation of stress values from the points located in the distance of 0,4·t and t from the point of weld penetration into parent material (where t – plate thickness) [21], on the other hand Yagi [22] shows that making use of the stresses in the points located respectively in the distance of $1.57\sqrt[4]{t^3}$ and $4.9\sqrt[4]{t^3}$ from the fusion penetration point, gives very good conformity with experimental data.
- Det Norske Veritas and Germanischer Lloyd recommend the linear extrapolation of stresses up to the section of weld fusion penetration into parent material on the basis of stress values taken for the points located in the distance of 0,5·t and 1,5·t from the fusion penetration point (where t – plate thickness), Fig. 15, [23, 24].
- Bureau Veritas recommends using, for geometrical peculiarity places, the linear extrapolation of two closest stress values calculated by using the finite element method [25].
- In some publications the stresses in the 0.3xt distant point is indicated as the reference values.

The stress value calculated in the stress concentration area is next used as the input data to the design curve σ-N to determine number of cycles to failure. In order to be able to consider the so obtained fatigue life values reliable it is important to ensure that values of the calculated stresses and reference stresses for the used curve σ-N correspond to each other as to geometry, material and loading conditions. In particular, the same procedure of determining stresses in the „hot spot" point should be used for the process of defining the reference stresses intended for elaboration of the design curve σ-N on the basis of laboratory test results, as well as for the calculations themselves.

The „hot spot" approach is often criticized. Especially the problem of ambiguity in selecting the reference points used for extrapolation triggers many discussions. There are several rules and guidelines which recommend different procedures for determining the „hot spot" stresses. As above presented, even for ship and offshore structures the procedures issued by some classification societies and other institutions differ from each other (Fig.15).

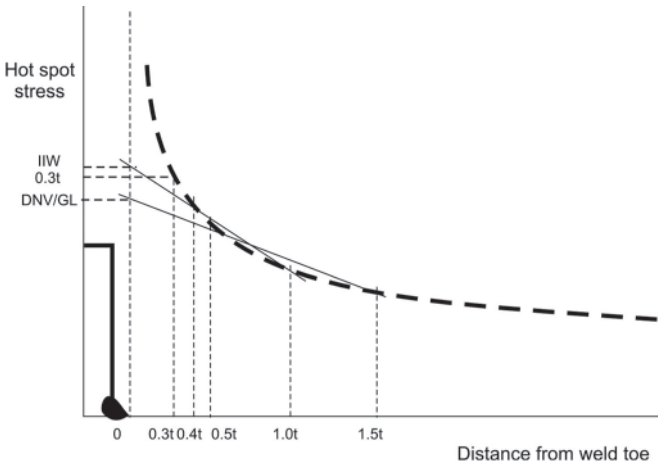

Fig. 15. *Differences in obtained „hot-spot" stress values depending on the points chosen for extrapolation*

Designers of welded structures consider the „hot spot" approach very useful for practical applications and providing better possibilities as compared with the approach based on the concept of nominal stresses, which leads, because of very different geometry of joints in ship and offshore structures, to inaccurate characteristics of stresses in the joints. The problem of itself is the proper modelling of weld and fusion penetration zone for calculations by using the finite element method. Wide possibilities of contemporary calculation programs and a great number of types of elements involve risk of obtaining different results for the same geometry only as an effect of different way of modelling a given task. Additionally it should be mentioned that the approach is not applicable in the case of fatigue cracks initiated at weld root and propagating across the weld. The range of application of the „hot spot" approach is limited to the cases (a) through (e) presented in Fig. 16. For the cases (f) through (j) it is not applicable at all.

c) Concept of the notch stresses σ_k

The notion of „notch stresses" defines the stresses which locally undergo concentration in a notch such as cutout edge or fusion penetration line.

As in the fusion penetration line sudden changes in geometry always occur, in consequence material yield point is as a rule exceeded locally under design load (which generates lower stresses beyond the weld). Simultaneously, the load is considered to be taken over by the surrounding material since the plastic zone is generally small and the surrounding structure still remains elastic that ensures blocking excessive raise of local deformations in the stress concentration zone. Hence the stress concentration coefficient K_t as well as the maximum notch stress σk is not a representative parameter for assessing fatigue strength. Occurrence of the effect of load taking - over by the surrounding area is accounted for in the effective fatigue notch coefficient K_f of a reduced value as compared with Kt. For sharp notches the value can be determined on the basis of effective notch stresses if only a suitably large radius of notch root is assumed, Fig. 17.

Various approaches are proposed in this case. In [26] application of the radius r = 1 mm is suggested on the basis of

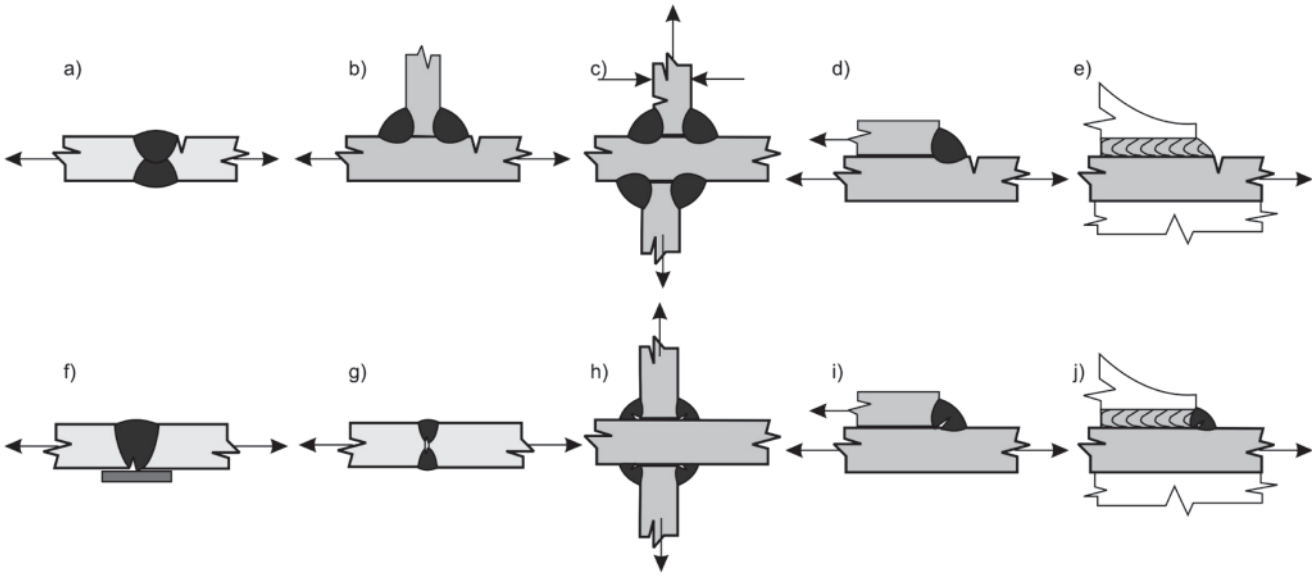

Fig. 16. *Various locations of cracks in welded joints*

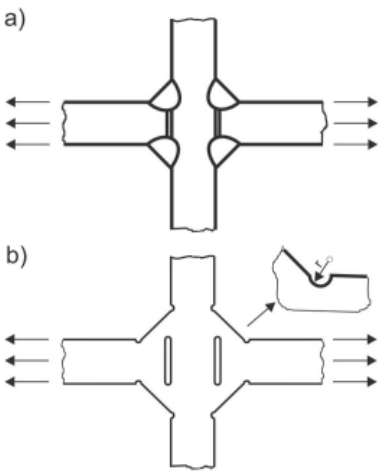

Fig. 17. a) *cruciform joint;*
b) *model of the joint for calculating effective notch stresses*

the effect of micro-support given to the intermediate structure between the weld and parent material. The similarly justified method was proposed in [13]; it leads to smaller values of the radius, depending on a given case, and requires additional transformation to be performed from K_t to K_f. An additional factor which greatly affects stress value in the fusion penetration zone and the weld itself - and may raise it many times – are various workmanship imperfections such as non-axiality and angular deformations of a joint or departures from its ideal geometry [26].

Disadvantages and merits of application of particular models of fatigue analysis based on the fatigue diagrams σ-N were discussed in [27] and [28]. Basing on [29] one can present general guidelines for application of a given fatigue assessment method (strategy of realization of a given approach), as shown in Tab. 1.

d) <u>Application of fracture mechanics to analyzing fatigue of ship structures</u>

As commonly considered, occurrence of geometrical notch in a structural element, which may cause significant stress concentration (e.g. a weld together with micro-defects contained in it), leads to shortening crack initiation phase and this is crack propagation phase which decides on total fatigue life of the element, i.e. Nc ≈ Np [7, 8, 29, 30, 31].

Therefore the information on fatigue crack growth rate in a given material as well as welded joint zones (HAZ, weld – deposited metal) corresponding to it becomes especially important as it makes it possible to classify materials as to its capability of resisting the so called final fatigue under given loading conditions [7] and to determine fatigue life of structural element especially in the limited fatigue life range.

Tab. 1. *Strategy for the fatigue assessment [29]*

Type	Stress raisers	Stress determined	Assessment procedure
A	General analysis of sectional forces using general theories e.g. beam theory, no stress riser considered	Gross average stress from sectional forces	Not applicable for fatigue analysis, only for component testing
B	A + macrogeometrical effects due to design of the component, but excluding stress risers due to the welded joint itself	Range of nominal stress (also modified or local nominal stress)	Nominal stress approach
C	A + B + structural discontinuities due to the structural detail of the welded joint, but excluding the notch effect of the weld toe transition	Range of structural hot-spot stress	Structural hot-spot stress approach
D	A + B + C + notch stress concentration due to the weld bead notches a) actual notch stress b) effective notch stress	Range of elastic notch stress (total stress)	a) Fracture mechanics approach b) Effective notch stress approach

The growth rate at a given crack length l, i.e. dl/dN, is expressed by the crack length increase dl per one cycle (in m/cycle or mm/cycle). The rate can be determined from slope of tangent line to fatigue crack growth curve in a considered point of the curve, which is schematically demonstrated by the point A in Fig. 18. The particular curves of the diagram l - f(N) are associated with different values of the stress amplitude σ_a (Ni stands for number of cycles corresponding to the fatigue crack beginning).

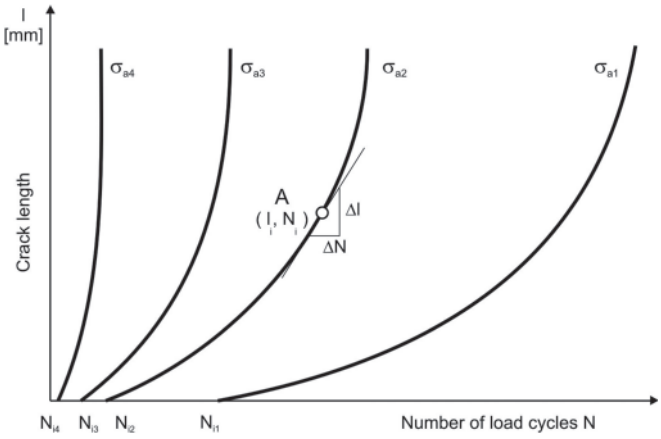

Fig. 18. Schematic diagram of growth of fatigue cracks at various stress amplitudes: $\sigma_{a1} < \sigma_{a2} < \sigma_{a3} < \sigma_{a4}$

The fatigue crack growth rate can be expressed in a very general form as follows:

$$\frac{dl}{dN} = f(\sigma, l, C, R,) \tag{5}$$

where:

σ – stress,
l – current crack length,
C – material constant,
R – stress ratio.

The functional relations (5) have been elaborated in various forms, however in practical applications those based on fracture mechanics have appeared most useful. It results from that the crack growth rate is controlled by the state of stress just ahead the fatigue crack root and the state can be unambiguously determined by the stress intensity factor K. Nonetheless the changeability range of stress intensity factor, $\mathbf{\Delta K = K_{max} - K_{min}}$, is most often used for describing the fatigue crack growth rate. The diagram of the relation dl/dN = f(ΔK) has a characteristic signoidal form (Fig. 19);

From the diagram of Fig. 19 it can be observed that the fatigue crack growth can be split into three ranges:

- Range I - the range of fatigue crack initiation and its slow growth, and, as assumed, if $\Delta K < \Delta K_{th}$ the crack will not propagate,
- Range II - the range of stable fatigue crack propagation,
- Range III - the range of unstable, sudden propagation of fatigue crack preceding fatigue damage of structural element.

The range of stable fatigue crack propagation is as a rule the longest period, usually described by the so called Paris law:

$$\frac{dl}{dN} = C(\Delta K)^m \tag{6}$$

where:

C and m – experimentally determined coefficients - the so called material constants, and the changeability range of stress intensity factor is determined in the following form:

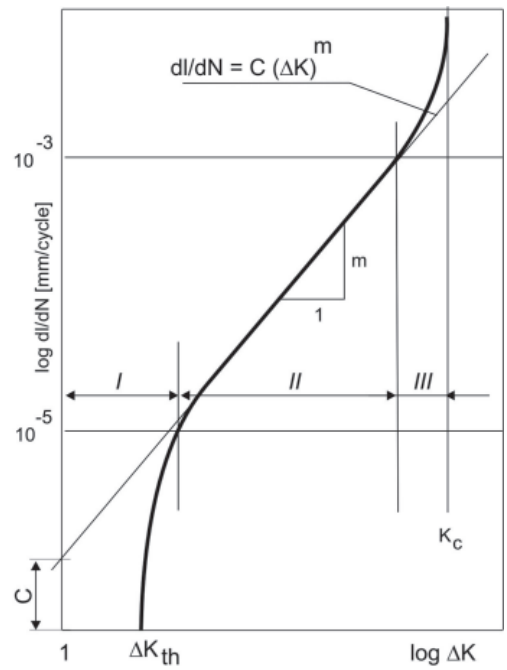

Fig. 19. Diagram of the fatigue crack growth rate in function of the changeability range of stress intensity factor ΔK

$$\Delta K = \Delta\sigma \cdot \sqrt{l} \cdot Y \tag{7}$$

where:

$\Delta\sigma = \sigma_{max} - \sigma_{min;}\ \sigma_{min} \geq 0,$

l – crack length,
Y – shape correcting function dependent on a crack length and type.

By making use of Paris relation between dl/dN and ΔK, (Eq. 6), it is possible to determine fatigue life by integrating the relation (6), i.e.:

$$N = \int_{l_0}^{l_{kr}} \frac{dl}{C(\Delta K)^m} \tag{8}$$

where:

l_0 – initial length of a crack, assumed – in the case of welded joints – equal to size of an existing defect (e.g. size of weld non-penetration) or the smallest dimension of a hidden defect which can be detected by using non-destructive test methods;
l_{kr} – critical length of a crack, at which ultimate damage of an element will take place or - in accordance with other criterion - its unserviceability, e.g. leakage, will occur.

The application of fracture mechanics to fatigue analysis of ship structures may concern the following issues:

a) the determining of the fatigue curve S-N for an analyzed element of ship structure (e.g. a joint etc) by integrating the Paris equation (8),
b) the determining of the critical crack length l_{kr} after reaching of which the following may occur e.g.: lack of tightness, drop of load-carrying capacity of a structural fragment,
c) the determining of permissible size of initial defect whose value can be taken as an initial fatigue crack length,
d) the estimating of the so called residual fatigue life for an existing crack of determined length.

RECAPITULATION

Spectacular accidents at sea which have happened for a few last years show that hull structures of contemporary sea-going ships are imperfect and must be systematically improved. It can be done by improving the existing solutions or applying entirely novel design and technological ideas. One of the groups of strength problems which affect design of contemporary ship's structures and greatly contribute in their improvement process is that of fatigue strength. Rules of classification societies contain procedures for estimating fatigue strength of hull structural elements. They are based on the approach in which nominal stresses, „hot spot" stress or notch stress, being the base for determining fatigue life by using the design curves σ-N, are applied. For summation of effects of load action on various levels the Palmgren-Miner damage cummulation hypothesis is most often used. Though the proposed procedures have been intensively developed for a few last years, degree of compliance of results obtained with their use with real behaviour of structures remains still unsatisfactory. The reason is that many factors are not taken into account; these are among other such as: influence of load sequence both in the scale of entire structure life and in the instant of load level change, not always precisely defined reference stresses for using the design curves σ-N (because of different forms, mean values or stress ratio in test cycle, different specimen dimensions). This is also contributed by: unambiguous influence of life under small loads, imperfection of the hypothesis on linear cummulation of damages, very weakly accounted for influence of cycle mean stress, lack of a clear definition and differentiation between initiation phase and propagation phase in the scale of entire ship hull, unambiguous definitions of ways for determining stresses in „hot-spot" approach, influence of a way of modelling used in finite element method on resulting stress values, lack of differentiation of damage mechanism influence on choice of appropriate design curve, as well as many other factors. It means that the procedures have not been finally elaborated so far and hence they must be continuously improved.

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