A PREDICTION OF AN ENDURANCE OF WELDED STRUCTURES TAKING INTO ACCOUNT AN EFFECT OF TECHNOLOGICAL FACTORS

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ABSTRACT

A method of an initial stage of a cyclic damage propagation in structural members with stress concentrators is suggested. The stressed condition of sections of the most probable fracture of the welded joints vs. technological factors as a function of welding methods is regarded. The design procedure to evaluate the endurance of the welded joints allowing an optimization of the design arrangement of the joints of the welded structures is based on a fracture model and data relating to a stressed condition.

KEYWORDS

Metallic structures, welded joints, stresses, strength, endurance, design.

INTRODUCTION

In general, marine structures are complicated welded metallic structures of many large size members and welded joints. This induces an important requirement to account, in principle, for a design a special character of the structure due to its manufacture methods. The experience of the welded structure performance at cyclic loading shows that a failure, predominantly occurs in the welded joint zones and most frequently in the conjugation zone of welded joint and base metal. This relates to an effect of a combination of factors reducting the performance of the welded joints, the basic factors are: stress concentrators and deformation induced by a geometrical imperfectness of the welded joint cofiguration, residual welding stresses, property inhomogeniety and a fracture resistance in an about joint zone, an inhomogeniety of the geometry of the conjugation zone of the joint and the base metal along the welded joint length. The present paper deals with a development of a design procedure of endurance of the welded structure members taking into account the effect of the above mentioned factors.

A FRACTURE MODEL AT INHOMOGENEOUS STRESSED CONDITION

The present procedure to design the endurance at a stage of a crack initiation are based on a deformation criterion (N.A.Machutov, 1981) and as original data apply an experimental amplitude of a strain, number of cycles to a crack initiation, n_i , relation obtained at the test of unnotched specimens of controlled strain level. The design of the crack propagation stage is based on the equations of the fracture mechanics relating the ΔK_I and K_I^{max} and parameters and a crack growth rate da/dn. The original base for the equations is the test results of precracked specimens. In real structures, welded structures including, a failure is generally induced by the stress concentrators which are not cracks, i.e. a situation is intermediate. It is of special note that a separate application of either design procedure to evaluate the endurance, if sharp concentrators are available, results either in an unrealonably reduced values (if the deformation criteration is used) or in a large unaccurancy due to unreliable values of an initial crack size (a kinetic approach of the fracture mechanics).

Because of this the attempt was made to develop a sufficiently simpe design fracture model of a material at an inhomogeneous stressed condition providing the prediction of an endurance at a random concentrator radius value, ρ, and calculated stress concentration factor, α_σ, and without an application of any kind of supplemented information, $n_i = \varphi(\varepsilon_a)$ and $da/dn = \varphi_1(\Delta K_I)$ curves excluding. The proposed model is based on a calculation of two damage rates: front damage propagation rate v_i , by a shear mechanism being a function of the strain; rate v_k, determined in accordance with the fracture mechanics concepts as a function of ΔK_I and K_I^{max}.
The next approximations are assumed:
- a real rate of the damage propagation , v , is determined as a sum of the rates of two parallel acting processes

$$v = v_i + v_k \qquad (1)$$

- v_i value is a function of a local values at the point where it is calculated and doesn't depend on its depth and mean stresses;
- v_k value can be obtained by standard procedures, i.e.it is identical to da/dn and is a function of a cycle assymetry which is described by known equations;
- Under corrosion medium influence an increase of either v_i or v_k is observed. Based on (1) the endurance , N_Σ, up to crack of a_{max} depth appearence is determined by the equation

$$N_\Sigma = \int_0^{a_{max}} (v_i + v_k)^{-1}\, da \qquad (2)$$

For an unnotched specimens tested under the controlled deformation level (ε_a = const.) v_i doesn't depend on a ,which provides an application of (2) to evaluate v_i, if $v_k(\Delta K_I)$ function is known, a_{max}, value can be 1-2mm. The endurance of the unnotched specimens recorded at the time of the experiment up to the crack initiation is assumed to be N_Σ and v_i values for a given is determined digitally by a subsequent approximation method. Fig.1 shows an example of curves obtained by the method relating to shipbuilding steels. The design of ΔK_I for a crack at a J-step was performed by the equation $(\Delta K_I)_j = 1{,}12 \cdot \varepsilon_{a_j} \cdot E\sqrt{a \cdot \pi}$, i.e. for a load condition of the unnotched specimens (assymetry factor R =-1) a compression part of the cycle was assumed to be of no effect on v_k value.
The application of the desired model to design N_Σ values of the stress concentration zones is a calculation of an integral (2) characterized by a difference represented by v_i being a variable depending on the depth of a location of an analyzed damage point in accordance with an variation of the deformation level, and the design of ΔK_I values seems to be more complicated. To design the endurance up to crack of a_{max} depth initiation at a random parameters of concentrator and algorythms are used realized as a digital procedure including:

1. The design of local, mean and amplitude stress values, $\sigma_m^M(y)$ and $\sigma_a^M(y)$ across the section of the concentrator zone using FEM or Neiber interpolation equation (Hammouda M.M.et al., 1979): $\sigma^M(y) = \alpha_\sigma \cdot \sigma \cdot (\rho/(\rho + 4y))^{0.5}$. In this case an assymetry of nominal stresses, a feasability of residual epure setting, yield strength of a material and increase of a strain concentration factor at elastic-plastic deformation are considered (N.A.Machutov, 1981).

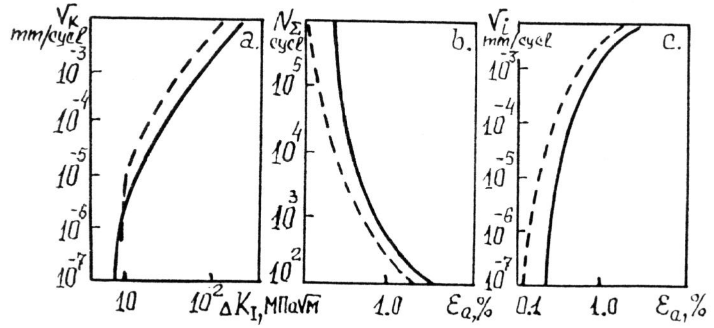

Fig. 1. Kinetic diagramm curves (a), feasability of damage (b),and damage propagation rate, v_i (c)

——— in air _ _ _ in sea water

2. The polynominal approximation of the design epures of the stresses at the maximum and minimum load of the cycle $\sigma(y) = \sum_0^m A_n y_m^n$ required to design K_I^{max}, K_I^{min}, ΔK_I values by Chell method (1976): $K_I = K_0 \cdot \sum_a A_n K_n^* \cdot y^n$ where K_0 is K_I value for a curved or a semielliptical crack in a homogeneous stress field and K_n^* is a tabulated constant.
3. A stepwise integration of the eq.(2) accompanied by the calculation at j-step $(\sigma_a^M)_j$ or $(\varepsilon_a^M)_j$, $(K_I^{max})_j$, $(K_I^{min})_j$ values and a_{min} selection of the v_i and v_k values are given in the tabilated form. At $K_I^{min}/K_I^{max} > 0$ v_k is established by the experimental data relating to the effect of loading assymetry on a crack kinetics.

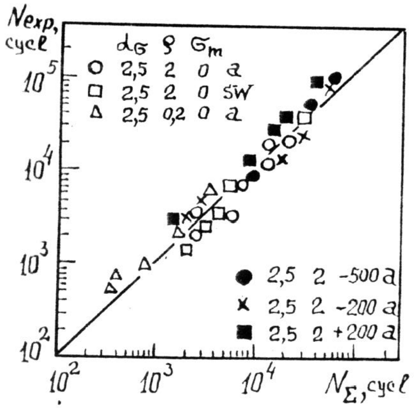

Fig.2. A comparison of the experimental and calculated by the model data of endurance of the specimens with concentrators.

Fig.2 compares the design results of the endurance up to crack of a_{max} = 2 initiation and test results of the specimens with concentrators of a groove type of different ρ and α_σ values. The familiar design model is in good agreement with the experiment and describes a complicated relation of the specimen endurance with concentrators and mean stress value, σ_m.
The application of the regarded design model to predict the endurance of the welded joints requires some additional information:
- data of the interelation of the geometrical parameters of the joint and α_σ

alue;

- data relating to the features of the combined deformation of the parent metal and weld metal of inhomogeneous mechanical properties;
- fracture resistance parameters of metal's sections of structural inhomogeniety of the welded joints;
- parameters characterizing the variation of the welded joint geometry along the joint and the measure to account for the geometrical inhomogeniety. Later on the basic results obtained by the mentioned ways of investigation will be considered.

THE GEOMETRICAL PARAMETERS OF THE WELDED JOINT AS A FUNCTION OF α_σ.

To establish the relation many calculations were performed by the finite element method (FEM). A stress concentration factor of butt and T-joints (Fig.3) can be written as follows:

$$\alpha_\sigma = 1 + A\sqrt{S/\rho} \qquad (3)$$

where ρ is a radius of conjugation of the parent metal and weld metal; s is a thickness of a structural member; A is a factor depending of a butt angle of the weld to the parent metal and a ratio of the rigidities of the conjugated members. For the butt and T-joints the relation (3) can be expressed in the form of an analytical ratio providing the calculation of values using the parameters of the joints, respectively (Carchin V.A., Copelman L.A., 1976; Iljin A.V. et al., 1981)

a) $$\alpha_\sigma = 1 + [\rho(14 \cdot b^{-1} + 1.7 \cdot h^{-1} + 5 \cdot s^{-1})]^{-0.5} \qquad (4)$$

b) $$\alpha_\sigma = 1 + 0.25(S/\rho)^{0.5} \cdot ((T+2b)/S)^{0.25}[1 - \exp(-1.9\sqrt{h/b})] \qquad (5)$$

These equations allow to design the α_σ values with the geometrical parameter variation in the next ranges: $0,03 < \rho/s < 0,75$; $0,2 < h/b < 3$; $0,75 < (T + 2b)/s < 3$. For the two axial loading a correlation factor proposed in (Iljin A.V. et al, 1983) the design by the given formulars is good indicated by the experimental data.

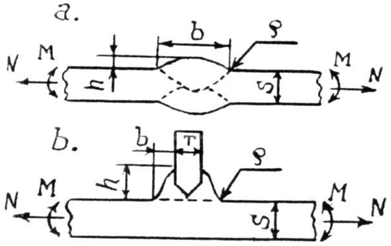

Fig.3: Typical welded joints and their geometrical parameters.

FEATURES OF A COMBINED DEFROMATION OF THE PARENT METAL AND WELD METAL

In a case when an amplitude of local strains in the zones of stress concentrations i.e. zones of the conjugation of the weld metal and parent metal exceeds a yield strength of the less strength metal (of the joint, σ_T^{wm}, or heat affected zone, σ_T^{bm}) a field of a local elastic-plastic deformation occurs. It is known that an increase of the factor of strain concentration K_ε and a reduction of the factor of stress concentration, K_σ, with respect to the original value, α_σ, is observed. To describe a variation of the K_ε and K_σ in a homogeneous metal with the increase loading some equations are proposed, (Machutov N.A., 1981), for example. When a zone of the concentrated interference is isolated by a fusion line of dissimilar materials a picture becomes more complicated (Fig. 4). At coming to the σ_T of less strength metal a localization of the deformation occurs accompanied by a reduction of the deformation rate of a more strong metal. This results in a difference of a strain concentration in the base metal K_ε^{bm} and weld metal K_ε^{wm}, Fig. 4b. On the base of the perfomed designs and analysis some relations are proposed providing a determination K_ε value as a function of an original value, factor of a mechanical inhomogeniety, γ, ($\gamma = \sigma_T^{wm}/\sigma_T^{bm}$) and nominal stresses σ_a^N (Iljin A. V. 1983). For a weld metal:

with $\gamma/\alpha_\sigma > \bar\sigma_a^N$, $K_\varepsilon^{wm} = \alpha_\sigma$ (6)

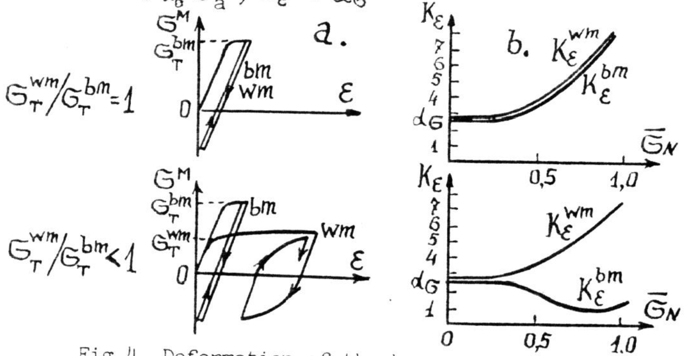

Fig.4. Deformation of the base metal, bm, and weld metal, wm.

$$1 > \sigma_a^N \geq \gamma/\alpha_\sigma, \quad K_\varepsilon^{wm} = \alpha_\sigma^2 \bar\sigma_a^N \left[\gamma(\alpha_\sigma \bar\sigma_a^N/\gamma)^{0.5[1-(\bar\sigma_a^N/\gamma - 1/\alpha_\sigma)]}\right]^{-1} \qquad (7)$$

$$\sigma_a^N \geq 1, \quad K_\varepsilon^{wm} = \alpha_\sigma^2 \left[\gamma(\alpha_\sigma/\gamma)^{0.5[1-(1/\gamma - 1/\alpha_\sigma)]}\right]^{-1} \qquad (8)$$

For a base metal with

$$\gamma/\alpha_\sigma > \sigma_a^N, \quad K_\varepsilon^{bm} = \alpha_\sigma \qquad (9)$$

$$1-\gamma(1-1/\alpha_\sigma) > \bar\sigma_a^N \geq \gamma/\alpha_\sigma, \quad K_\varepsilon^{bm} = 1 + \gamma(1-(1/\alpha_\sigma))/\bar\sigma_a^N \qquad (10)$$

$$1 > \bar\sigma_a^N \geq 1 - \gamma(1 - 1/\alpha_\sigma), \quad K_\varepsilon^{bm} = \alpha_\sigma^2 \bar\sigma_a^N \beta^{-2}(\alpha_\sigma \bar\sigma_a^N/\beta)^{-0.5[1-(\bar\sigma_a^N/\beta - 1/\alpha_\sigma)]} \qquad (11)$$

$$\bar\sigma_a^N \geq 1, \quad K_\varepsilon^{bm} = \alpha_\sigma^2 \beta^{-2}(\alpha_\sigma/\beta)^{-0.5[1-(1/\beta - 1/\alpha_\sigma)]} \qquad (12)$$

where $\bar\sigma_a^N = \sigma_a^N/\sigma_T^{bm}$, $\beta = [\alpha_\sigma(1-\gamma) + \gamma]$.

The amplitude of the local strains in the zones of a feasable fracture of welded joint under cyclic loading is determined by the equation $\varepsilon_a^M = \sigma_a^N \cdot K_\varepsilon/E$ and by any of the equations (6)-(12).

AN ACCOUNT OF AN INHOMOGENIETY OF A GEOMETRY OF THE WELDED JOINTS ALONG THE JOINT LENGTH

A radius value of weld and metal conjugation effecting at the most rate value α_s is generally an uncontrolled parameter of the welded joints and is characterized by a random distribution along the weld length. Fig.5a shows the dispersion with a manual welding by a stick electrode. Due to a large difference of the minimum, ρ_{min} and mean values at a small lenth of the weld section an application of the deformation criteration to predict the endurance seems to be unsufficient-an expected number of cycles to a crack initiation vs is extremely steep (Fig.5b, N_i - curve).

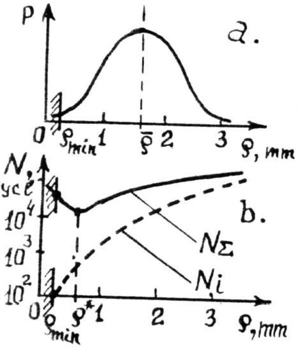

Fig.5. A change of endurance vs conjugation redius.

A different situation occurs if a combined model described above is applied. The endurance design, N_Σ by the instant of a semielliptical crack initiation 2-3 mm in depth shows that value ϱ^* appropriate to the minimum N_Σ is different from ϱ_{min} and $\bar{\varrho}$. In this case the $N_\Sigma(\varrho)$ relation is pronounced more feebly. The present fracture model is applicable to (Fig.6,type 1). Another procedure assumes that due to an initiation, propagation and coalescence of individual semielliptical crack along the weld joint, an edge crack generates. (Fig.6 type 2). An analysis of this fracture model shows that it can be applied for low cycle field and in this case the endurance design can be performed similar to weld joint with the constant $\varrho = \bar{\varrho}$ value along the weld length. The performed analysis shows that to determine allowable conditions (stresses) it is reasonable to regard two fracture types: 1) a propogation along the welded joint of acountinuos edge crack generated due to damage initiation over 50 % of the weld length; 2) a propagation of a semielliptical crack starting from a weld section with ϱ_{min} or ϱ^*. The design performed on the base of the above mentioned data shows that a transition from the first fracture type to the second occurs at the endurance exceeding 10^4 cycles in air and 5.10^5 cycles in sea water.

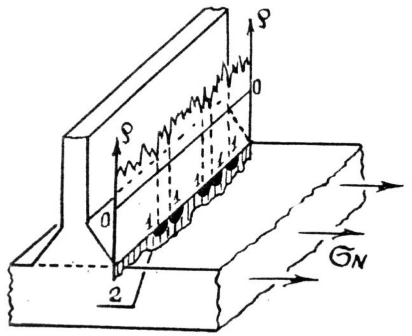

Fig.6. Features of a fatigue failure in a welded joint
1 - local cracks, large number cycle loading
2 - front of a generated crack ,low cycle loading

DETERMINATION OF FIELDS OF THE RESIDUAL WELDING STRESSES

The existance of the fields of the residual welding stresses (rws) in the welded joints is a base factor inducing a cyclic strength of a structure. The rws distribution in a weld metal-base metal conjugation zone, physicomechanical inhomogeniety and structural transformations are investigated unsufficiently. Common enough results (Fig.7) were obtained when an investigation based on FEM digital simulation of the thermodeformation cycle of a welding was performed. At the time of $\gamma \rightarrow \alpha$ transformation at temperatures below 400°C (Fig.7a) zones of compression transversal stresses can generate. However, these zones are highly localized. The pronounced compression zones can occur at $\gamma \rightarrow \alpha$ transformation at temperature below 200°C. When $\gamma \rightarrow \alpha$ transformation occurs at cooling at temperatures over 400 - 500 °C in an about weld zone tensile rws approaching about σ_T are formed.

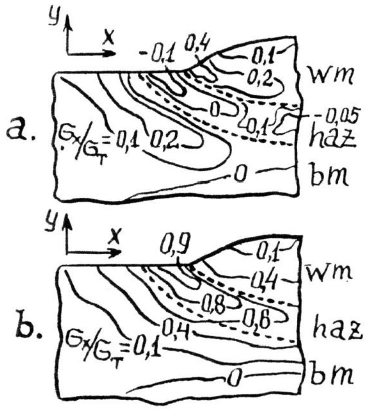

Fig.7. Transversal rws at availability (a) and non-existance of structural transformation (b)

Thus, rws in the weld base metal conjugation zone is characterized by an essential inhomogeniety which results in the requirement to analyze in detail the most "dangerous" cycle of material deformation in different points of the welded joint and design of $\sigma_m(y) = f(\sigma_m^N, \alpha_\sigma, \sigma_x/\sigma_T)$ accounting for them: in detail the problem is regarded in a paper by Ardentov V.V.et al., 1985. The proposed model allows to account an existance of this complicated relation.

THE DESIGN PROCEDURE TO EVALUATE ENDURANCE TAKING INTO ACCOUNT TECHNOLOGICAL FACTORS

The desing procedure is as follows:

1. Based on the $\bar{\varrho}$ and ϱ_{min} values inherent to a given technology and the geometrical parameters of the welded joint appropriate $\bar{\alpha}_\sigma$ and $\alpha_{\sigma max}$ values are established.
2. In accordance with the described above results the design and polynomina approximation of destribution of amplitude $\sigma_a(y)$ and mean $\sigma_m(y)$ values of local stresses are performed. The required information is the rws distribution cyclic parameters of operating stresses, yield strength of the material.
3. The relations $N_\Sigma(\sigma_a)$ for two limit types of cyclic fracture is design: propagation of a semielliptical crack in a field of local stresses corresponding to α_σ^*, i.e. $\sigma_a = f(N_\Sigma)$ for $\varrho = \varrho^*$ (Fig.8a,curve 1) and an edge crack in field of local stresses corresponding to $\bar{\alpha}_\sigma$, i.e. $\sigma_a = f(N_\Sigma)$ for $\varrho = \bar{\varrho}$ (Fig. 8a, curve 2).
4. The generalized curve of allowable stress curve representing a lower envelope of the two $N_\Sigma(\sigma_a)$ relations design by item 3 (Fig. 8a,curve 3).Each similar curve of the allowable stresses appropriates to a certain type of the welded joints Fig.8b shows as an example, curves of the allowable stresses of a butt joint produced by different manufacture method: α_σ = 1,1- 1,5 - argon arc fusion of a conjugation zone; 2,5 -automatic welding;3,5 - manual welding. To analyze if the described design procedure can be regarded as a method to design the endurance of the welded joint at an initial stage of a damage propagation some special experiments were performed. The endurance design by the developed procedure of the welded joints and structural members loaded by 10^3 -10^6 cycles doesn't result in errors exceeding in 95% the experimental data by a factor of 2-3.

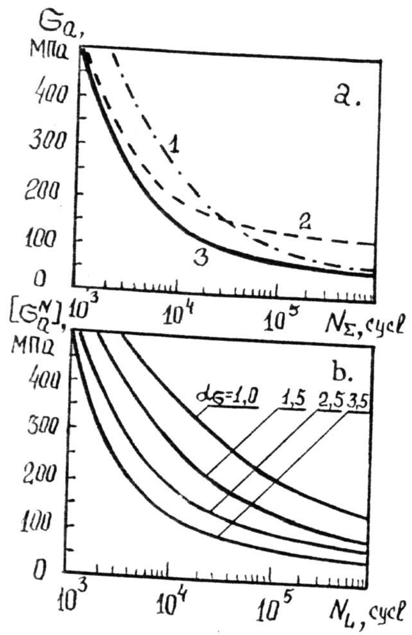

Fig.8. Allowable stresses with cyclic loading: a-plotting procedure; b-standard curve for butt joint

CONCLUSION

A rather simple design procedure providing a prediction of the endurance of the structural members with stress concentrators of a random geometry based on the standard fracture resistance parameters of the material under cyclic loading is suggested. The application of the design procedure to predict the endurance of the welded joints allow to account in tis scope the basic technological factors generating at welding and reasonable approach to the plotting of the curves of the allowable stresses by an engineering criteration - initiation of a visually recorded crack. The design of the cyclic strength of the welded joints or structural members by the developed procedure allows to increase the reliability of the design procedure and safety of the structures.

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