Effect of Prestrain on Fatigue Crack Growth in Low-carbon Steel

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Introduction

In many of practical problems of fatigue design of structural components in transport systems of special interest is the design of components which undergo plastic prestrain preceding the service, e.g. in fabrication of tubular components, during installation of marine pipelines by the reeling method, and also in ship hull structures with large shell openings inducing high stress concentrations.

For example, the Rules [2] recommend to consider in design of pipeline components «a prescribed amount of stable crack extensions…» preceding the onset of conditions for unstable fracture. The criteria for failure considered by the rules are those developed in Linear and Non-linear Fracture Mechanics, i.e., the critical value of stress intensity factor, «fracture toughness», J-integral and CTOD criterion. Of special importance is the indication of the plastic strain value assumed by the installation of the pipeline method, equal to 0.03, approximately 20 times the yield strain.

Experimental evaluation of the material resistance characteristics in design has to be based on testing of pre-strained specimens. The principles of manufacturing and testing specimens addressed to evaluation of the fracture criteria given in the standard [2] are not exhaustive, and the crack extensions are related exclusively to behavior of inherent flaws during the pipeline installation causing several cycles of plastic deformation. Meanwhile, nucleation and stable growth of fatigue crack in plastically deformed material caused by environmental variable loads is not considered. The standards [2], [3] only expect inconsistency when the installation cyclic straining may cause the degradation of the crack growth resistance.

Apart from the mentioned in above, the early crack propagation in stress concentration areas in a welded structure can be influenced by residual welding stresses, which may exceed the yield stress. This influence was extensively studied several decades ago [e.g., 7-9]; similar effects were observed when fatigue crack propagation in the presence of residual stress was modeled in PMMA (acrylic glass) structural components [11]. It was found that proper considering of the residual welding stress re-distribution and fatigue crack tracing allowed solution of the problem. The role of overloads in the crack propagation stage was demonstrated by Broek [4] and Davidson and Lankford [5], etc., who showed that the tensile overload results in residual compressive stresses in the unloading phase and subsequent crack retardation. Controversial effects of negative overloads with an existing crack were also studied and displayed. However, the mentioned and similar experiments were carried out using ***cracked coupons***. Respectively, the overloads caused development of plastic zone ahead of the crack tip and sequential development of compressive stress in unloading; the latter reduces the crack tip opening in proceeding cycling and, consequently, the crack growth retardation.

Recently, the influence of pre-strain on fatigue cracking of aluminium alloys was analyzed [1], [6]; depending on the alloy composition, insignificant or negative effects were established. As to structural steels, the effects of relatively large plastic strains on the proceeding crack initiation and propagation are not that certain. Respectively, it seemed necessary to «fill up the gap».

Procedures of testing and analysis

To bring more light into this problem a series of notched plate specimens were tested at cyclic loading and crack propagation was assessed. The specimens were machined from a 10-mm thick plate of low-carbon mild steel in as-rolled condition ($\sigma_y = 240$ MPa). The coupons were preliminary pre-strained under tensile load with the grip displacement control (using the «Instron» testing machine) so that the residual strain in the range of 0-0.15 would be achieved, before the plastic instability would occur. In the pre-strained specimens, dimensions of which were 500x120x10 mm, narrow symmetrical slits were cut in longitudinal edges to initiate fatigue cracks. In order to facilitate crack extension observations (by means of a microscope), a 1 mm –pitch scratches were made ahead of the slit tips, transversely to expected crack paths.

Specimens with a different degree of prestrain were further tested under cyclic loading using the hydraulic pulsator machine, approximately at the same conditions: $\Delta\sigma_n = 0.56\sigma_y$; $R = 0.1$, R is the load ratio. The tests were terminated when the transition of the leading crack normal opening into sliding mode has been observed. This transition was regarded as onset of predominantly shear mechanism of failure provided by material plasticity.

Experiments revealed a marked influence of pre-straining on crack growth rate and transition conditions: the larger was plastic prestrain, the smaller was the crack growth rate observed; at the same time the crack length corresponding to the transition from the opening mode into the out-of-plane deflection of the crack surfaces (sliding mode) increased essentially. Since the prestrains induced considerable strain hardening of material, up to the tensile strength, it was possible to explain the observed effects by the enlarged elastic resistance of the material.

The observations revealed difference in the load cycles necessary to initiate cracks at the slots and different crack growth rates at the both sides of specimen. It was attributed to the wear of the machine grips surfaces, which did not provide the necessary alignment of the load transfer. Strain gage readings had shown nonuniform stress distribution at a distance from the notched section. Respectively, the loading was assessed a combination of axial and bending modes, resulting in different conditions for crack initiation and propagation at the both sides of specimen. In some specimens one of the cracks did not propagate at all due to the load eccentricity, or was arrested in the early stage.

For an approximate analysis of the crack propagation data the non-symmetrical problem was transformed into a problem with symmetrical cracks by applying the coordinate transform illustrated in Fig.1.

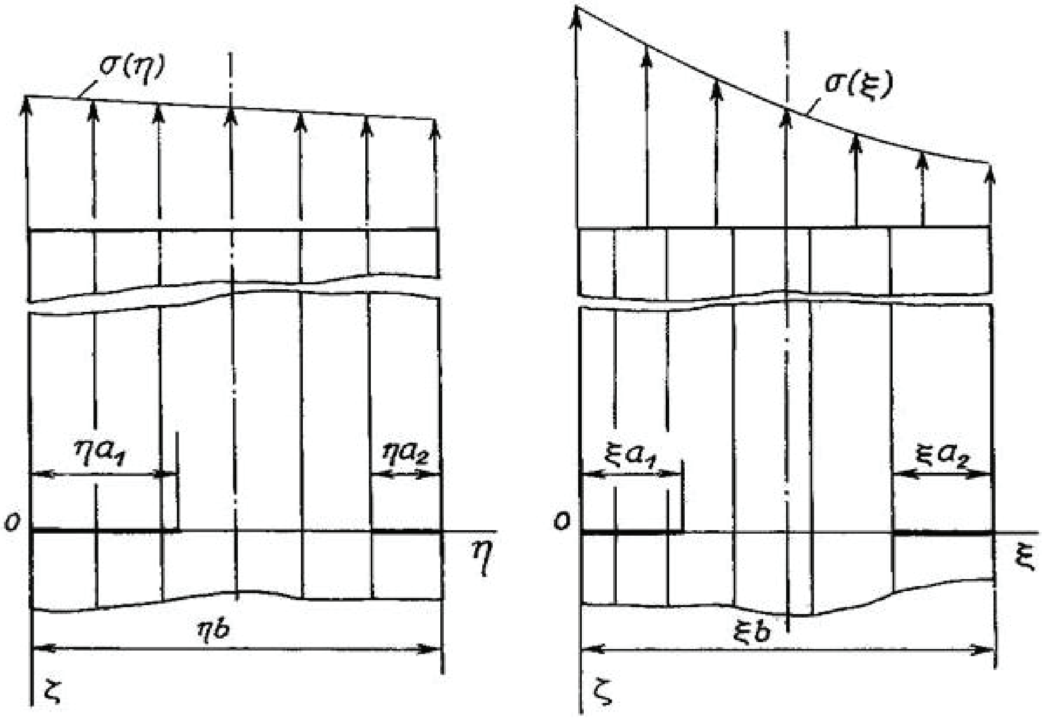

Fig. 1. Transformation of unsymmetrical crack growth scheme into a symmetrical one

A relative coordinate, η, through the width of actual plate with non-symmetrical cracks is transformed into a relative coordinate, ξ, of equivalent plate with symmetrical cracks by the relationship:

$$\xi = \beta\eta + (1-\beta)\eta^2, \tag{1}$$

parameter β of which is found on condition of equality of cracks in equivalent plate. This allows obtaining the non-dimensional crack sizes measured in coordinates ξ:

$$\xi_1 = \frac{\eta_1(1-\eta_1)(1-\eta_2^2) + \eta_1^2\eta_2(1-\eta_2)}{\eta_1(1-\eta_1) + \eta_2(1-\eta_2)}, \tag{2}$$

where $\eta_1 = a_1/b,\quad \eta_2 = a_2/b,$ – non-dimensional crack sizes in actual plate, measured along coordinate η; $\xi_1 = \overline{a}/b;\quad \xi_1 = \xi_2$ in equivalent plate. Parameter β is found from (1):

$$\beta = (\xi_1 - \eta_1^2)/\eta_1(1-\eta_1). \tag{3}$$

The above coordinate transform procedure allowed to respectively adjust applied load. It follows from equivalence of load per elements of plate width that

$$\sigma(\xi)\Delta\xi = \sigma(\eta)\Delta\eta,$$

where $\sigma(\eta)$ is the stress distribution in actual plate close to the grips of testing machine, $\sigma(\xi)$ is the stress distribution in equivalent plate at the same section. Respectively, the stress distribution in the transformed problem is:

$$\sigma(\xi) = \sigma(\eta) / (\beta + 2(1-\beta)\eta), \qquad (4)$$

where $\sigma(\eta)$ is the stress distribution in the basic problem, η is the crack scale parameter (crack length/specimen width) resulting in tension (bending); β is the transformation parameter, $\beta = (\xi_1 - \eta_1{}^2) / (1-\eta_2)\eta_1$.

Consequently, the equivalent plate loading in several steps of crack extensions was assumed a combination of axial tension and bending. This allowed calculating stress intensity factor values using the handbook data [12], separately, in case of uniform tensile loading and in case of bending; further, the results were combined,

$$K_I^{total} = K_I^{axial} + K_I^{bend}.$$

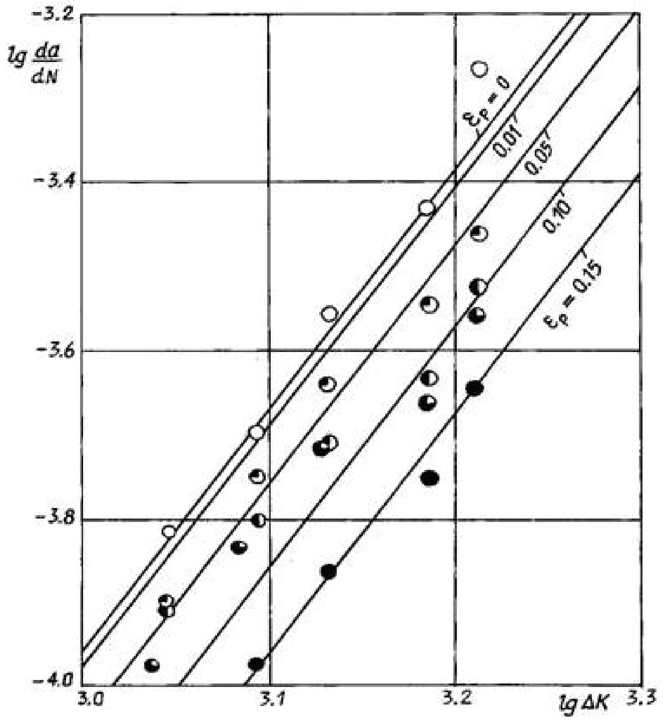

Fig. 2. Effect of prestrain on crack propagation rate in a low carbon steel plate; ε_p is the plastic prestrain

The results were compared to the stress intensities obtained from FEM calculations (using isoparametric singular elements) and fairly good agreement was found. The crack rate observations were related to the crack length and via the relationship «stress intensity-crack length» were applied in subsequent crack growth analysis.

The crack growth data obtained from the experiments and interpreted according to the above approach are shown in Fig.2. It is seen that degree of prestrain practically does not affect the slope of the $da/dN - \Delta K$ curves, essentially differentiate them by the crack propagation rate so that 0.15 pre-strained compared to the «virgin» material is characterized by the almost two times smaller growth rate.

It follows from the analysis that the stable crack propagation in the pre-strained material can be approximated in the form of the Paris-Erdogan equation [10]:

$$da/dN = C_\delta(\Delta K)^{2.88}, \qquad (5)$$

where C_δ is a constant for a given prestrain ε_f, which can be approximated as

$$C_\delta = C_0(1-\delta)^{4.08}; \quad C_0 = 2.504 \cdot 10^{-13}. \qquad (6)$$

It may be concluded that crack growth deceleration for a moderated prestrain (up to $\varepsilon_f = 0.01$) is insignificant; however, this conclusion is based on limited experimental data. Apart from that, as mentioned in above, in all tests the stress range was the same, which allowed examining a relatively narrow range of crack growth rates. These results should be completed by further parametric studies in a range of loading conditions including irregular loading histories typical of wave loading when the pipeline components might be affected.

Conclusion

Experimental investigation of the plastic prestrain effects on the stable fatigue crack propagation in low-carbon steel revealed a notable decrease of the growth rate along with the prestrain degree. A simple and effective procedure of transforming a possible eccentricity of specimen loading into the axial and bending loading modes is suggested addressed to assessment of stress intensity factor values.

Observed crack deceleration in pre-strained steel is found when the nominal stress (load) range was the only in all of the tests. The phenomenon further should be examined in the range of the loading parameters; heath-affected zone and weld material fatigue resistance has to be analyzed when it undergoes plastic straining in manufacturing and installation procedures. Also, the prestrain history should be completed by considering the whole installation loading cycle, when the Bauschinger effect may demonstrate a detrimental influence on the crack propagation features.

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Abstract

The current procedures of fatigue design of marine pipeline components allow for extending service life by considering a certain portion of the crack growth well before it turns into the instable phase. In structural components of transport systems material may undergo plastic pre-strain during the construction. The effect of pre-strain on the crack growth may be different depending on the material properties.

Fatigue crack propagation was examined in testing symmetrically notched specimens machined from pre-strained steel plate coupons. Non-simultaneous crack initiation and propagation at the notches was reduced to symmetrical scheme by a simple coordinate transformation procedure.

It was found that tensile pre-strain up to 0.01 did not substantially change the crack growth rate related to the stress intensity factor scale. Further increase of plastic pre-strain of material up to 0.15 caused almost two-times slowing down the crack growth rate compared to that of virgin material.

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Full text of this article in English: pp. 71-74