ANALOGY BETWEEN LOW TEMPERATURE AND FATIGUE EFFECTS

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Wide-spread use of welding multiplied the number of brittle or fatigue fractures in steel structures, giving new initiatives for research on prevention measures.

Several methods have been developed for the elimination of brittle fracture, among them that by PELLINI [1], [2] is the closest to traditional engineering approach.

PELLINI's diagram known in the literature as FAD (Fracture Analysis Diagram) indicates mean strength of low-grade steel specimens exhibiting the adverse conditions of real welded structures as a function of temperature T and fault size a (Fig. 1), permitting the engineer to apply structural engineering formulae at low temperatures hence for brittle or less tough material conditions.

σ_c values of PELLINI's diagram are between an upper and a lower boundary curve in the $T-\sigma_c$ co-ordinate system. Obviously, the upper boundary curve involves a minimum fault size value $a_{\min}$ still likely of impairing the specimen's mean strength. Where this diagram intersects the yield curve σ_F of the faultless material, elements including the fault undergo brittle fracture in any case. This point of temperature is NDT (Nil Ductility Transition Temperature). The lower boundary curve termed CAT (Crack Arrest Temperature Curve) points to a given mean stress value required to produce failure even for big fault sizes. Thus, CAT may be considered as a minimum σ_c belonging to a fault $a_{\max}$ or over. As a matter of fact, for wide and thin members, the two boundary curves meet the tensile strength diagram σ_B of the faultless material at a sufficiently high temperature FTP (Fracture Transition Plastic Temperature). Its physical purport is obvious: with increasing temperature, the material grows in toughness, hence the effect of practically encountered faults becomes increasingly negligible.

FAD has been composed by PELLINI and al. on the basis of test results but the correctness of this conception is also supported by fracture mechanics.

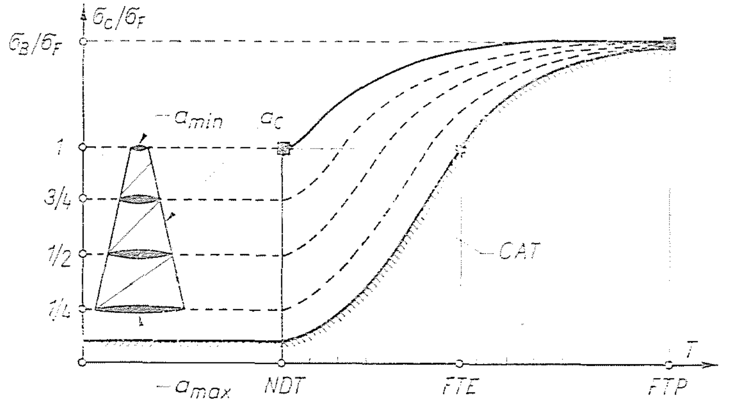

Fig. 1. Pellini's diagram (FAD)

For a material of brittle behaviour at point NDT, its condition of fracture is, according to fracture mechanics:

$$K = K_c = \sigma_c \sqrt{\pi a}$$

where K_c is a critical stress intensity factor, to be determined empirically. This condition yields the ultimate stress at failure:

$$\sigma_c = \frac{K_c}{\sqrt{\pi a}} .$$

On the other hand, at FTP, the failure condition for any fault size a:

$$\sigma = \sigma_c = \sigma_B .$$

Knowledge of σ_c at NDT and FTP permits a solution by interaction. Based on test results by PELLINI and bearing in mind the still existing uncertainties, the simplest, linear relationship may be assumed (Fig. 2a). Of course, because of the relativity of practical failure diagrams, the problem may be solved by fictitious stress intensity factors [3]. Introducing e.g. for the transition zone between NDT and FTP the notation:

$$\overline{K}_c = \sigma_c \sqrt{\pi a}$$

yields a transformed PELLINI diagram (Fig. 2b).

An interesting feature of the simplified PELLINI diagram is its striking analogy to fatigue test results by BARSOM and MCNICOL (United Steel Corporation) [4].

In steel specimens 6″ (152.4 mm) wide and 0.125″ (0.3 mm) thick of Barsom and McNicol, bilateral notches (artificial cracks) $a_0 = 0.9''$ (22.9 mm) with various curvatures of radii ϱ at roots were made to investigate the relationship between the cyclic stress amplitude $\Delta\sigma = \sigma_{max} - \sigma_{min}$ and the number of cycles ΔN_0 initiating further cracks in the notch. Tests were made at room temperature and at stress amplitude

$$R = \frac{\sigma_{min}}{\sigma_{max}} \cong 0 .$$

Test results by Barsom and McNicol are seen in a log-log diagram, Fig. 3. Points for case ϱ = const. are seen to define inclined straight lines in the left side of the diagram, continued by curves in the right side to presumably tend to horizontal asymptotes. Since in the tests $R = 0$, and ordinatae $\Delta\sigma$ were practically equal to σ_{max}, it is not surprising that extension of the inclined

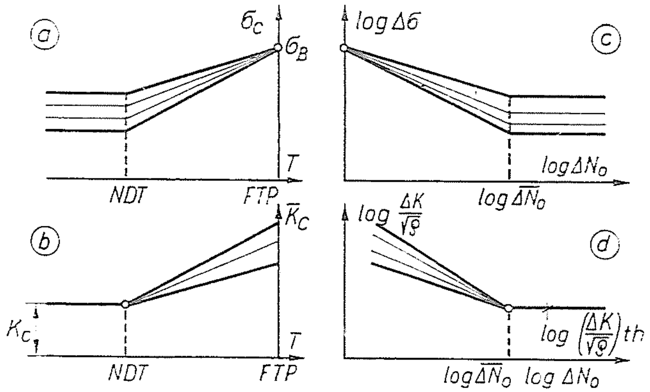

Fig. 2. a) Simplified Pellini diagram; b) Transformed Pellini diagram; c) Simplified diagram of test results by Barsom and McNicol; d) Transformed diagram of test results by Barsom and McNicol

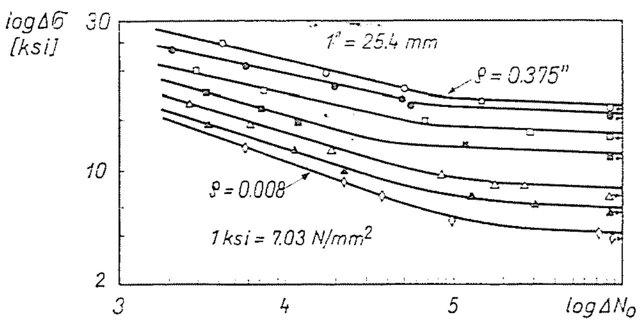

Fig. 3. Test results by Barsom and McNicol according to [4]

straight lines to the left meets vertical $\Delta N_0 = 1$ exactly at $\Delta\sigma = \sigma_B$ while horizontal asymptotes yield approximately the pulsating fatigue strengths of specimens. The diagram gives a hint that inclined straight lines cut horizontal asymptotes approximately along one vertical, thus, with simplifications generally accepted for fatigue test results, the data can be summarized according to Fig. 2c.

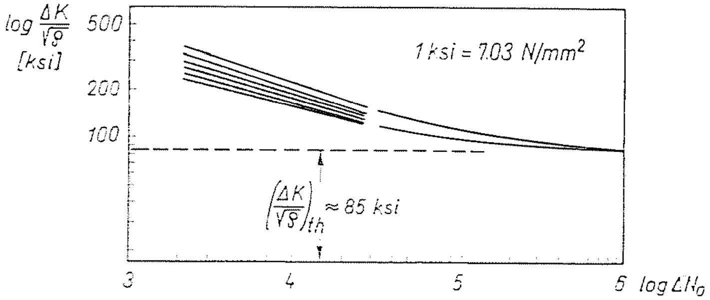

Fig. 4. Threshold value of test results by Barsom and McNicol according to [4]

Referring to JACK and PRICE [5], BARSOM and MCNICOL plotted test results in the reference frame:

$$\log \Delta N_0 - \log \frac{\Delta K}{\sqrt{\varrho}} \, .$$

where ΔK is the cyclic stress intensity factor according to the linear fracture mechanism. In the quoted system, the diagrams for the different values were found to be initially about linear, to unite in a single curve with increasing ΔN_0 and to tend to a horizontal asymptote with an ordinate to be considered as characteristic material threshold; in the examined case (Fig. 4):

$$\left(\frac{\Delta K}{\sqrt{\varrho}}\right)_{th} = \text{const.} \approx 85 \text{ ksi.}$$

The same threshold value has been demonstrated by CLARK [6].

Applying the linear approximation for Fig. 4 causes lines belonging to different ϱ values to meet at a point of abscissa $\overline{\Delta N_0}$ in level with the threshold value

$$\left(\frac{\Delta K}{\sqrt{\varrho}}\right)_{th}$$

(Fig. 2d), supporting our previous assumption that failure points are along a vertical in Fig. 2c.

The physical purport of the demonstrated threshold value is obvious. According to the IRWIN equations [7], in the actual case,

$$\frac{\Delta K}{\sqrt{\varrho}} \approx \frac{\bar{K}_{\max}}{\sqrt{\varrho}}$$

is proportional to the stress peak at the crack end, as known from the theory of elasticity. Thus, the threshold value means that for given a_0 and ϱ values there is a material-dependent highest mean fatigue stress $\sigma_{\max}$ still not causing permanent deformation such as to generate fatigue crack at the end of the initial crack, that is, where the specimen is still in practically elastic condition. In the actual case, this $\sigma_{\max}$ is identical to the pulsating strength $\sigma_{1\text{ü},\text{i}}$ of the specimen.

Tests by BARSOM and MCNICOL also confirmed the existence of a limit value ϱ_0 for the notch radius of curvature revealed by JACK and PRICE, below that fatigue continues as for ϱ_0. Taking it into consideration and assuming that for the most dangerous initial hair cracks $\varrho \leq \varrho_0$, a threshold value for "sharp" cracks

$$(\bar{K}_{\max})_{th} = K_{th} = \sqrt{\varrho_0} \left(\frac{\bar{K}_{\max}}{\sqrt{\varrho}} \right)_{th} = \text{const.}$$

may be established, to be defined for infinitely wide (practically, compared to the fault) specimens, in view of the elastic condition, by the formula:

$$K_{th} = \sigma_{1\text{ü},\text{i}} \sqrt{\pi a_0} \, .$$

Accordingly, taking also Fig. 2, combining the simplified PELLINI diagram and the diagram of the test results by BARSOM and MCNICOL, it is obvious that the K_{th} value of faulty (cracked) steel specimens is closely related to the critical stress intensity factor K_c of the PELLINI diagram. Both represent the pulsating stress of the material in the corresponding (tough or brittle) state, only that K_c represents at the same time the static strength of the faulty, brittle material, because of its nature. This means that in cooling, the K_{th} value will tend to K_c, and in brittle material condition (at NDT):

$$K_{th} = K_c .$$

At the same time, necessarily:

$$\bar{K}_{\max} = K_c .$$

The K_{th} to K_c relationship permits to develop a new model likely of help in a uniform discussion of the brittle and fatigue failure modes, simplifying and making more reliable the practical design method [8], [9].

Summary

Pellini's Fracture Analysis Diagram and fatigue test results by Barsom and McNicol show a striking analogy, hinting to a close relation between the critical intensity factor K_c and the fatigue threshold value K_{th}.

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