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Fatigue of Welded Structures at Low Temperatures

Fatigue des constructions soudées à basse température

Ermüdung geschweisster Konstruktionen bei tiefen Temperaturen

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SUMMARY

The results of integrated investigations of the low temperature (to – 70 °C) influence on the characteristics of static, dynamic and cyclic strength and crack resistance of welded joints in structural steels are presented, which are used as initial data for the design of cyclic-loaded metal structures by the existing design methods, based on deformation criteria of low-cycle fatigue as well as using the parameters and criteria of the fracture mechanics.

RÉSUMÉ

Les résultats des études globales de l'influence de basses températures (jusqu'à – 70 °C) sur les caractéristiques de la résistance statique, dynamique et cyclique, et la résistance à la fissuration des joints soudés en aciers de construction son présentés. Ces caractéristiques servent de base au dimensionnement des structures métalliques, soumises aux sollicitations cycliques, dans le cadre des méthodes actuelles, basées sur les critères de déformation, la fatigue avec un faible nombre de cycles, ainsi que les critères de la mécanique de la rupture.

ZUSAMMENFASSUNG

Es werden Ergebnisse komplexer Untersuchungen zum Einfluss tiefer Temperaturen (bis – 70 °C) auf die Kennwerte statischer, dynamischer und zyklischer Festigkeit und die Rissfestigkeit geschweisster Baustahlverbindungen dargestellt. Diese werden als Bezugswerte bei der nach üblichen Verfahren durchgeführten Berechnung zyklisch beanspruchter Metallkonstruktionen verwendet, wobei diesen Verfahren, welche Parameter und Kriterien der Bruchmechanik benutzen, die Verformungskriterien kleinzyklischer Ermüdung als Grundlage dienen.

1. ANALYSIS OF THE PROBLEM AND AIMS OF INVESTIGATION

A number of important metal structures work under low temperature conditions. Tanks and gas-holders, knock-down metal bridges and crane girders, transport galleries and overpasses, bins and silos, main pipelines, floating and stationary offshore drilling platforms are referred to such structures. These structures are subjected to both static cyclic loading (movement of a live load, periodic tank emptying and filling, product pressure variation in gas-holders and pipelines, wind pressure pulsation, wavy sea) and impulse (impact)loading.

Thus repeatedly loaded structures under severe climatic conditions are especially susceptible to brittle fracture, since for their manufacture mild and low-alloyed steels are primarily used, the critical brittleness temperature of which coincides with climatic temperatures interval. Besides, the non-isothermicity of the loading specific for these structures (sometimes with sharp temperature difference) also increases the danger of brittle fracture. It is the influence of cyclic (repeated static and impact) loading under low-temperature conditions that is often the reason of numerous failures. Under the influence of such loads cracks initiate in zones of increased stress concentration and non-uniformity of the material mechanical characteristics: either in the metal of the weld-adjacent zone of welded joints, close to weld intersection points or in butt welds with a lack of penetration or some other welding defects. At a dangerous influence of low temperatures indicates the fact that the failure intensity considerably increases (2 to 7 times) in winter periods.

Practice showed that the cracks may be formed already in the manufacturing phase or at rather early stages of operation and nevertheless the structures with such cracks may safely work. Depending on the purpose of a structure the structural limit state may be assumed as a development of an admissible crack (detected by non-destructive testing methods or specified in the manufacturing codes) or its critical length development characterized by a possibility of the structure brittle fracture (for a surface or through crack) or the structure depressurization (for a surface crack).

Thus, the limit state design of metal structures for cyclic strength should comprise two stages of structural behaviour - the stage of the fatigue crack initiation and the stage of its safe development. However, the existing codes for welded structures design for cyclic and brittle strength either don't take into consideration the effect of low (climatic) operation temperatures on the structure cyclic strength, or ignor the effect of the loading cyclicity at the evaluation of the structure load-carrying capacity by brittle fracture criteria. The effect of low temperatures is evaluated only through variations in the characteristic of fracture resistance under static loading (K_c). Besides, the difference between the static, cyclic and dynamic crack resistance of the main zones of the welded joint isn't taken into account, and only through cracks are considered, though surface and inner defects may be most probable.

On the basis of the found mechanism of welded joints in structural steels resistance to low-temperature static and low-cycle loading, initial data for cyclic loaded welded metal structures design by the criteria of low-cycle and brittle fracture were obtained.

2. EXPERIMENTAL INVESTIGATIONS RESULTS

2.1. Investigation procedure

For specimens cooling the contact method was used, that is, a refrigerant (liquid nitrogen vapour) contacted with a specimen surface. The advantage of the technique is in a free access to the zone being examined and in the possibility of installing the instruments to measure its stressed-strained state. The procedure developed allows to provide on large-scale models local cooling of their individual zones, simulating accidental leaking of a refrigerant directly on bearing structures due to damage of the structure insulating layers (liquid ammonia storage).

2.2 Physical and mechanical properties

The correct transition from measured strains to stresses is connected with the use of actual values of the materials elastic characteristics E and μ at design temperatures. The function of transverse deformation coefficient $\mu(\varepsilon_i)$ allows to take into account the peculiarities of deformation of relatively ductile steels, but being in a quasi-brittle state at decreased temperatures. The material loosening processes and, consequently, non-linearity of the relationship between average stress σ_{cp} and average strain ε_{cp} can be described by means of the modulus of cubic strain by formula:

$$K_{\varepsilon_i} = \frac{2\sigma_i[1+\mu(\varepsilon_i)]}{9\varepsilon_i[1-\mu(\varepsilon_i)]}$$

Experimental data for $\mu^T(\varepsilon_i)$ for some structural steels (with contrast mechanical properties) show that the temperature decrease can reduce the value $\mu^T(\varepsilon_i)$ at elasto-plastic behaviour of the material (up to 3%) by 15 to 20%. Given in the Report experimentally found actual value of the static (secant) modulus of elasticity E_c^T and dynamic modulus of elasticity E_g^T showed their considerable difference. Due to this fact, at the design of metal structures when a limit state is determined according to the criterion of deformativity and at the refined design of static and repeated (low-cyclic) strength at the stage of a crack initiation and propagation (these processes take place with low deformation rates), it is suggested to use an actual value of E_c^T. The actual values of E_g^T with regard for their statistic parameters of spread are found at determination of brittle fracture properties (as well as at the design of dynamically loaded structures), characterised by a high rate at which microplastic deformations, reducing the modulus of elasticity have no time to propagate in large material volumes. In the climatic range of temperatures for specimens made of mild and low-alloy steels, subjected to a long period static and cyclic loading, it was found out that E_g^T was increased by 3% at a spread 1.4%, while E_c^T was increased by 10% and 14%, respectively (maximum values are given).

2.3 Characteristics of static and cyclic strength

The test temperature reduction doesn't alter cyclic elasto-plastic properties of structural steels and their welded joints and a static deformation is plotted at a common curve on relative coordinates ($\bar{\sigma}=\sigma/\sigma_{0,2}$ — $\bar{e}=e/e_{0,2}$) and is restricted by an initial value of plasticity ψ^T at a given temperature. Due to this fact, the influence of low temperatures at the kinetics of a stressed-strained state in the zone of structural stress concentrators is insignificant.

The climatic range of low temperatures practically doesn't reduce the low-cycle strength of structural steels and of separate zones of the welded joint at the stage up to a crack initiation, the strength of the whole welded joint at a rigid loading being limited by the metal of the adjacent to the weld zone (AWZ) or by weld metal (WM). An empirical relationship of the exponent m_e^T from ψ^T in the Coffin's equation is suggested, experimentally verified for a wide range of low temperatures

$$m_e^T = m_e^{20°C} - 0{,}047\left(\psi^{20°C} - \psi^T\right)$$

2.4 Characteristics of static, dynamic and cyclic crack resistance

The analysis of graphical relationships of the fatigue crack propagation rate (FCP) to temperature for structural steels of various strength levels and their welded joints confirms a general tendency to reduction of FCP rate with the test temperature drop, metal of AWZ and WM of low-alloyed steels having the lowest cyclic crack resistance. For some grades of low-alloyed steels a temperature range was experimentally determined (-20C for steel 20ХГСА of increased strength and -20...-40C for steel 09Г2С of medium strength), in which the rate of FCP was 1.3 and 2 times, respectively, increased. At a further temperature decreasing the FCP rate slowed down: for steel 20ХГСА by 1.3 times at -40C and 2 times at -70C, for steel 09Г2С by 2 times at -70C. It has been found out that test temperature reduction slows down the process of a surface crack growth without any influence on its shape. However, at the same time reduction of the critical defect size occurs, that might result in the structural member failure before the crack reaches a stable shape, besides the plastic zone size reduction takes place by 1.8-2.1 times for the deepest point of the surface crack and by 1.5-1.8 times - on its surface.

At temperature decrease down to -70C the values of K_c for ductile steels (low strength low-carbon steel 20K) decreased by more than 2.5 times and for less ductile steels (such as low-alloyed steel 09Г2С of a medium strength) - only by 1.9 times. Lower values of K_c were obtained for the metal of AWZ (20K) and WM (09Г2С), however, the difference between the separate zones of the welded joint is small. At -40C for high-strength steels (20ХГСА and 07Х3ГНМЮА) the value of K_{fc} for the weld metal having pronounced characteristics of a cyclic loss of strength was lower than that of the base metal by 1.7-2.6 times.

It has been established that the test temperature drop down to -70C and increasing of the loading intensity (by 10^6 times) resulted in reduction of resistance to the crack initiation in metal of all welded joint zones ($K_c^{20°C}/K_{gc}^{-70°C} \approx 5$). However, at an embrittled state of steel due to the temperature drop, the additional reduction in fracture toughness caused by high-rate loading, is only 15-40%.

3. CONCLUSIONS

The experimental results obtained are initial data for design of low-temperature cyclic durability of welded structures both in the absence of initial crack-like imperfections, and in the presence of such imperfections as lack of penetration, undercuts, non-metallic inclusions, gas cavities, etc. and structural-technological concentrators having high values of stress gradients. In the first case between cycle numbers prior to final failure N and crack initiation N_0 in the absence of stress concentration there is an experimentally found Manson's relationship

$$N/N_0 = 1 - 2{,}5\, N^{-1/3}$$

at $N = 10^5$ the ratio $N/N_c = 0.95$, while at $N = 10^4$ the ratio $N/N_0 = 0.88$. In this case the stage of crack propagation can be considered as a negligible one. With available stress concentrators of defects these ratios undergo significant changes since the crack appears earlier, the higher is stress and concentration. Thus, the useful life of structural elements after damage detection may be 75-90% of their total durability, depending on the level and the gradient of stresses in the section considered with this contribution increasing as the stress concentration rises.

Design evaluation of the useful life of the cyclic loaded welded structures at the stage of fatigue crack growth showed that using of crack resistance parameters C, n, K_{gc} and K_{fc} with regard for their temperature dependence changed the value of durability from 30 to 50% in comparison with the design based on the constant values of these parameters.

Thus, for the purpose of fuller use of the material bearing capacity and reduction of the amount of metal per structure a possibility is presented to ensure an equal strength from the standpoint of simultaneous failure of differently stressed assemblies, connections and elements of the given structure. One of the ways of creating an equally reliable structure can be a design method based on a probabilistic approach, and allowing at the design stage to take into account real structural stress concentration and technological defects of design sections with the aim to ensure approximately equal durability by crack development criteria or its critical value with regard for temperature dependence of the design parameters.

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