UDC 539.4

Method of Prevention of Fracture of Welded Metal Structural Elements Subjected to Single Dynamic Loads

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УДК 539.4

Методика предупреждения разрушений элементов сварных металлоконструкций при однократном динамическом нагружении

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На основе критерия нелинейной механики разрушения δ_{cr}^{D} (CTOD) предложена методика оценки вязкости разрушения конструкционных материалов и их сварных соединений в условиях однократного динамического нагружения. Установлены закономерности влияния скорости нагружения, определяемой параметром δ' (скорость раскрытия вершины трещины), на вязкость разрушения. Рекомендована методика предупреждения разрушений элементов сварных конструкций при высокоскоростном деформировании.

Ключевые слова: конструкционные стали, сварные соединения, однократное динамическое нагружение, вязкость разрушения, методика, предупреждение разрушений.

Introduction. Under dynamic loading conditions, the level of nominal stresses increases relative to design static stresses due to forces of inertia and transformation of kinetic energy of moving bodies to the potential energy of deformation. To make allowance for this effect, the dynamic coefficient K_D is introduced during designing of metal structures. As a result, the nominal dynamic tensile stresses σ_D are determined by design static stresses σ_S ($\sigma_D = K_D \sigma_S$). The coefficient K_D is set theoretically or experimentally depending on the type of loading of a definite design element. In this case, the condition of strength design takes a form $\sigma_S \le [\sigma_D]/K_D$, if the allowable values of normal stresses at dynamic $[\sigma_D]$ and static $[\sigma_S]$ loading are assumed to be equal ($[\sigma_D] = [\sigma_S]$). Thus, the dynamic design of strength is replaced by a static design.

In addition to increasing the nominal stresses, the dynamic loading leads to changes in the mechanical properties of metal, caused by its plastic deformation. This is stipulated by the material improved resistance to plastic deformations due to the inertia factor. As the investigations showed, with increase of a loading rate on flat structural steel specimens, the yield strength σ_{YS} is significantly increased, while the ultimate strength σ_{US} is increased to a less degree [1]. This leads to the decrease in the relation σ_{YS}/σ_{US}. As to the characteristics of plasticity (such as elongation and cross-section area reduction), these change even less noticeably and not always adequately. It is quite evident that the change in elongation and reduction in area of the specimens, as well as in σ_{US}, is determined not only by the resistance to a plastic deformation, but to the fracture as well. The fracture resistance depends, in turn, on the level of stress concentration, degree of restriction and localizing of plastic deformations, metal microstructure, fracture mechanism, etc. The cases of fractures of welded metal structures described in literature, which occurred under the extreme conditions of a dynamic loading (earthquake), proved the hazard of stress concentrators, which were not critical at static loading [2, 3]. Hence, to prevent fractures under the conditions of a high-rate deformation, the selection of a proper design of connections, type and shape of welded joints from the point of view of reduction of stress concentrations has a primary importance. The butt-welded joints are preferable in this case. The next step in the way of prevention of fractures is the application of the "fitness-for-purpose" concept based on the fracture mechanics approaches and criteria.

Method of Assessment of Fracture Toughness under the Dynamic Loading Conditions. This method has been developed at the Paton Electric Welding Institute of National Academy of Sciences of Ukraine [1, 4]. It is based on the determination of a critical crack tip opening displacement (CTOD) – δ_{cr}^{D}. This selection of the criterion was due to the necessity in establishment of fracture toughness within the wide range of its variation, including brittle, quasi-brittle and tough states of the material. Moreover, in this case it is not necessary to record and calculate the actual forces acting on the specimen which are difficult to realize at dynamic tests from the point of view of procedure. In accordance with the procedure developed, the tests of standard specimens under the conditions of a three-point bending at the rates of loading Λ' up to 10 m/s are performed in a vertical drop-weight impact machine. The preset rate Λ' is attained by an appropriate height of lifting of the loading hammer head, and its relative constancy during all the stage of the specimen deforming is reached by a selection of a weight mass using the following condition: the impact energy should exceed the energy required for the specimen deformation by more than three times. The significant increase in the loading rate Λ' (approximately up to 120 m/s) is attained by a shock wave of a cumulative charge of an explosive in a special device. To determine δ_{cr}^{D}, a series (5 or 6) of specimens is tested at a preset temperature T and rate Λ' up to different levels of bending. This is provided by a stop of the loading head in fixed positions during the process of the specimen deforming. It is noteworthy that this procedure makes it possible to arrest the propagation of both brittle and tough cracks. The plastic constituent of the current opening of the crack tip δ_p, for which the specimen was deformed, is determined by varying the distance between the crack lips near its tip. The elastic constituent δ_e was approximately in accordance with the relation "opening during loading δ – opening after loading δ_p," plotted at static loading for the test specimen, similar by sizes and mechanical properties with allowance for the dynamics: ($\delta_e = \delta - \delta_p$). After the complete fracture of specimens with a changeover in its mode, the value of crack growth l' formed at the preliminary deformation is measured. Relation $\delta^D - l'$ is plotted from these data and CTOD is determined at the stage of initiating of the brittle (quasi-brittle) fracture δ_c^D (Fig. 1a) or tough fracture δ_i^D (Fig. 1b).

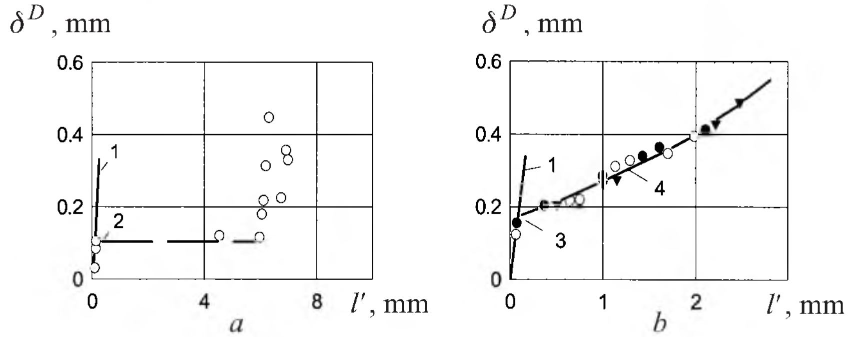

Fig. 1. Relationship between the initial crack tip opening δ' and increment of its length l' at quasi-brittle (a) and tough (b) states of the material: *1* – line of blunting of the crack tip ($l' = 0.5\delta^D$); *2* – critical crack tip opening at the stage of initiation of a quasi-brittle fracture δ_c^D; *3* – the same for the tough fracture δ_i^D and δ_i; *4* – δ_R-curve; ▼ – $\Lambda' = 10^{-5}$ m/s (static loading); ○ – $\Lambda' = 5$ m/s; ● – $\Lambda' = 9.7$ m/s.

For comparison of results of dynamic tests, and their application for the prediction of serviceability of structure elements, it is important to associate the loading conditions with the parameters controlling the rate of metal deforming in the region of a crack tip (pre-fracture). The rate of deformation has a decisive impact on the metal resistance to the fracture initiation and depends on the rate of loading, geometry and dimensions of the test specimens. In the given case, the rate of crack tip opening δ' is used as such parameter. It is calculated as a mean value of rate of the crack lips displacement in its tip for the time τ_{cr} from the beginning of the specimen deforming until the moment of fracture initiation $\delta' = \delta_{cr}^D / \tau_{cr}$, $\tau_{cr} = \Lambda_{cr} / \Lambda'$, where Λ_{cr} is the critical displacement of the specimen in the direction of the force action. Using characteristics δ' and δ_{cr}^D, it is possible to calculate directly the rate of deformation ε' in the contour of a blunted crack tip [5].

Results of Assessment of Fracture Toughness of Structural Steels and Their Welded Joints. Typical relationship between the fracture toughness δ_{cr}^D and the temperature T at different values of a rate parameter δ' ($\delta' = 2.2 \cdot 10^{-6}$–$26.4$ m/s) is given in Fig. 2. It is seen that in parallel with the level of δ_{cr}^D the temperature of transition from brittle (quasi-brittle) δ_c^D to the tough δ_i^D initiation of fracture T_i (determined as a temperature of beginning of the stable crack growth) is an important characteristic from the point of view of the fracture prevention. Above this temperature, the metal resistance to the initiation of the tough fracture δ_i^D is invariant as to the temperature itself and also to the rate of loading (straight line *5* in Fig. 2), i.e., $\delta_i^D = \delta_i$ (δ_i is the fracture toughness at static loading). In principle, the temperature curve of fracture toughness is shifted equidistantly (parallel transfer) to the side of positive temperatures with the increase in the rate of deforming δ'. Moreover, the transition temperature T_i depends linearly on the logarithm of a rate parameter δ'

$$T_i = k \ln \delta' + b. \tag{1}$$

These relationships for the examined materials of different systems of alloying and level of strength, and also their welded joints are presented in Fig. 3.

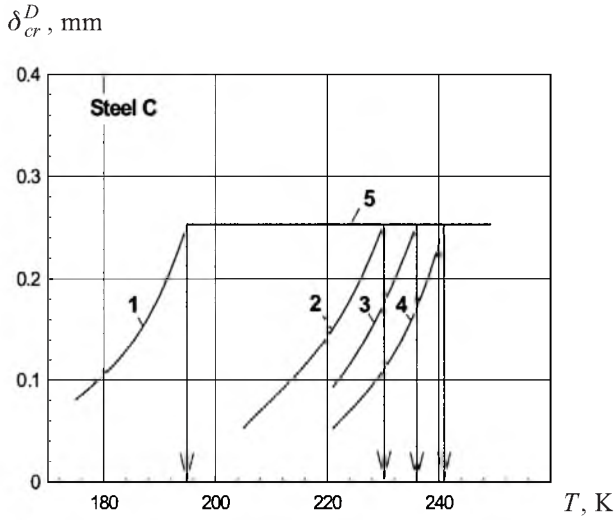

Fig. 2. Typical relationship between the resistance of structural steels and their welded joints to the initiation of fracture δ_{cr}^D and temperature at different rates of loading: *1* – $\delta' = 2.2 \cdot 10^{-6}$ m/s; *2* – $\delta' = 1.1$ m/s; *3* – $\delta' = 2.13$ m/s; *4* – $\delta' = 26.4$ m/s; *1–4* – δ'; *5* – δ_i^D and δ_i. Arrows denote the transition temperature T_i.

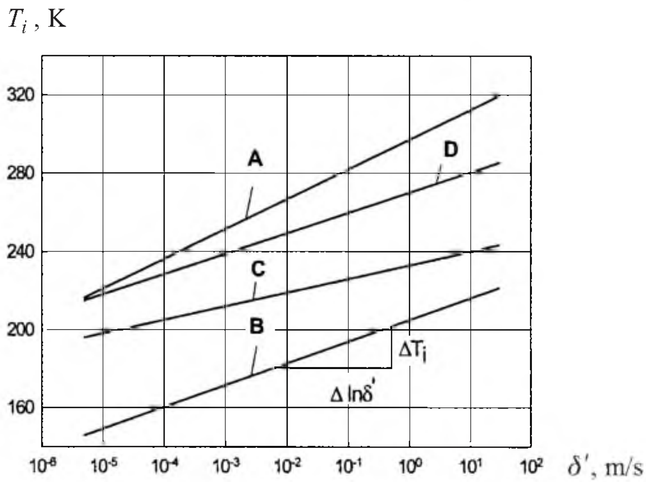

Fig. 3. Transition temperature T_i vs logarithm of the crack-tip opening parameter δ': *A* – steel X46 (Mn–Si), $k = 6.60$, $b = 297$; *B* – X70 (Mn–Ni–Mo–Nb), $k = 4.86$, $b = 205$; *C* – X70 (Mn–Ti), $k = 3.04$, $b = 233$; *D* – welded joint of steel C, $k = 4.50$, $b = 270$.

Resistance of Structural Materials to the Initiation of Fracture δ_i. It is known that the important condition in assessment of the fracture toughness on the basis of the nonlinear fracture mechanics criteria is an equality of the thickness t of a standard specimen and the material examined. This is due to the fact that the degree of restriction of the plastic deformation in the region of a pre-fracture and its effect on the value δ_i varies with thickness. The investigations showed that, when the condition of a plane deformation $t \geq \delta_i E/\lambda\sigma_{YS}$ (where E is the elastic modulus) is satisfied, δ_i reaches its minimum value for the given material which does not change with a thickness (Fig. 4). According to these data, the coefficient λ is equal to 4–5.

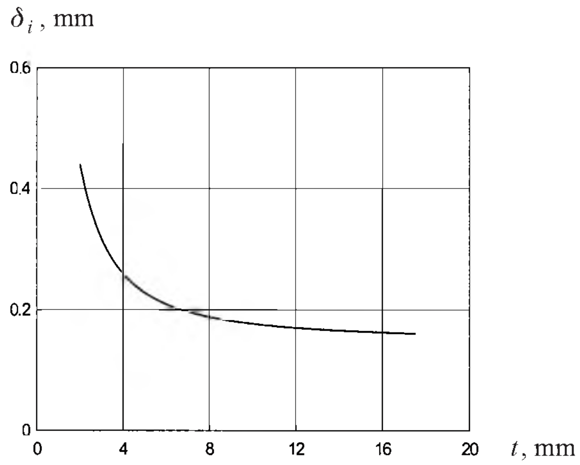

Fig. 4. Variation of steel X52 (Mn–V) resistance to the initiation of tough fracture δ_i with the specimen thickness t.

The established boundary conditions for the metal resistance to the initiation of the tough fracture δ_i to be independent of temperature, rate of loading and specimen thickness allow to consider the parameter δ_i as a material characteristic recommended to be applied in the assessment of "fitness-for-purpose" criterion of welded structural elements.

Methodology of Fracture Prevention. Based of the above investigations, the following approach to the assurance of serviceability of metal structural elements subjected to the dynamic loading is proposed. The required condition of selection of steels and welding technologies is $T_s > T_i$, where T_s is the minimum service (design) temperature. The transition temperature T_i depending on the service condition by the loading rate is determined by Eq. (1). Coefficients k and b of this relation are established using the experimental data.

The sufficient condition consists in the assurance of the fracture toughness δ_i^D of the parent material and metal of the welded joints at the level which guarantees the non-fracture of structural elements from the most probable crack-like defects $\delta_i^D > \delta_i^*$, where δ_i^* is the minimum required value of the fracture toughness which is established from the "fitness-for-purpose" concept with allowance for the coefficient K_D and the dynamic values of the mechanical properties.

It should be noted in conclusion that, in order to select the materials meeting the above-mentioned conditions, the widely used standard impact tests of the V-notched Charpy-type specimens can be used. Here, the required level of the impact strength C_{V*} is determined in accordance with the value δ_i^* on the basis of the $\delta_i^D - C_V$ correlation link. The test temperature $T_{C_{V*}}$, at which the preset level of C_{V*} should be provided, is set depending on the service conditions by the loading rate

$$T_{C_{V*}} = T_s - \Delta T_i ,$$

where ΔT_i is the shift in the transition temperature caused by the high-rate deformation. In accordance with Eq. (1), it is equal to

$$\Delta T_i = k \Delta \ln \delta' = k(\ln \delta'_1 - \ln \delta'_2).$$

Here, δ'_1 is the parameter of the service loading rate, while δ'_2 is the parameter of the static loading rate.

Conclusions

1. The method developed makes it possible to determine the critical crack-tip opening displacement (CTOD) at the stage of initiating of brittle (quasi-brittle) δ_c^D and tough δ_i^D fracture modes within the wide ranges of the temperature T and loading rate Λ' variations.

2. The metal resistance to the initiation of tough fracture δ_i is invariant to the temperature (T = 120–330 K), rate of loading ($\Lambda' = 10^{-5}$...120 m/s) and thickness ($t \geq \delta_i E / \lambda \sigma_{YS}$). The value δ_i can be considered as a critical characteristic of material and used for the assessment of the “fitness-for-purpose” criterion of the welded structural elements.

3. The temperature of transition from quasi-brittle to tough initiation of fracture T_i is important for assurance of the serviceability of metal structures under the conditions of the dynamic loading. Its shifting to the side of positive temperatures depending on the logarithm of the rate parameter δ' has a linear trend. This allows T_i to be determined for a wide range of rates δ' using a limited scope of the experimental data.

4. In order to prevent fracture of the welded structural elements under conditions of high-rate deformation, the metal should meet the requirements as to the transition temperature T_i ($T_s > T_i$, where T_s is the design or minimum service temperature) and to the resistance to initiation of tough fracture δ_i (set in accordance with the “fitness-for-purpose” concept) in parallel with the selection of the proper design of connections, type and shape of the welded joints aimed to reduce the stress concentration.

5. In case of establishing the correlation link $\delta_i - C_V$ (where C_V is the energy in the Charpy-type specimen V-notch) and shift in the transition temperature T_i caused by the high-rate deforming, the metal can be selected from the results of testing the standard impact Charpy-type V-notched specimens.

Р е з ю м е

На основі критерію нелінійної механіки руйнування δ_{cr}^{D} (CTOD) запропоновано методику оцінки в'язкості руйнування конструкційних матеріалів і їхніх зварних з'єднань в умовах одноразового динамічного навантаження. Установлено закономірності впливу швидкості навантаження, що визначається параметром δ' (швидкість розкриття вістря тріщини), на в'язкість руйнування. Рекомендовано методику попередження руйнування елементів зварних конструкцій за високошвидкісного деформування.

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Received 14. 11. 2001