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The Possibilities of Fracture Mechanics as Applied to Problems of Strength, Service Life, and Substantiation of Safe Operation of Heat-Generating and Mechanical Equipment

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Abstract—The fundamentals of fracture mechanics are briefly outlined, and its possibilities as a tool for estimating the longevity and bearing capacity of equipment components the metal of which contains cracklike flaws are pointed out. Experimentally obtained kinetic crack resistance diagrams lying at the heart of methods for determining the survivability of structures are given for some steels. Practical application of the methods of fracture mechanics is demonstrated on a particular example of substantiating temporary operability of a boiler drum having cracklike flaws near the holes for water downtake pipes.

Keywords: power equipment, strength, lifetime, cracklike flaw, crack growth resistance, fatigue, creep, longevity, survivability

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Fracture mechanics was established as a science in the mid 20th century. Its development was greatly prompted by catastrophic failures of bulky welded structures, in particular, marine oil tankers and gas-main pipelines in the United States [1]. An analysis showed that the stresses in these structures did not exceed their permissible levels, but the metal, which had high strength properties, featured increased brittleness [1, 2]. Technological flaws in the zone of welded connections, which grew into local cracks under fatigue effects, behaved as initiators of failure that originated from them as a result of spontaneous growth of the main crack. It should be noted that the initial (site) cracklike flaws would not necessarily have significant sizes. Similar incidents involving spontaneous failures of high-pressure boiler drums during hydraulic tests were observed at Russian thermal power stations: the first around 20 years ago and the second approximately 7 years ago (Fig. 1).

High potential hazard of such failures served at certain time in the past as a factor prompting development of a combined calculation and experimental approach using which one can estimate the bearing capacity of an article taking into account not only the level of stresses, but also the presence of cracklike flaws in the metal. Works on establishing and developing such technique created a basis of fracture mechanics as a self-contained section in the deformable body mechanics.

The field of stresses in the crack tip zone is described by the following expression [3]:

$$y_{ij} = \frac{K_n}{\sqrt{2pr}} f_{ij}(u), \quad (1)$$

where r is the radius-vector from the crack tip to the point, $f_{ij}(u)$ is the function of stress field, u is the angle between the radius-vector and crack plane, K_n is the stress intensity factor (SIF), which depend on the kind, geometrical characteristics, and size of the crack and on the field of stresses in the body without taking the crack into account.

Under elastic loading conditions, the SIF determines the field of stresses in the neighborhood of crack tip. Roughly speaking, the SIF in fracture mechanics is an analog of stresses in traditional strength analysis.

Efforts taken to extend the methods of fracture mechanics for the region of elastic-plastic deformation of bodies with cracks have brought about new parameters characterizing fracture, such as crack top opening, J integral, and some others [3, 4].

For making the fracture parameters of materials accessible for practical use, experimental methods for determining them had to be worked out and further developed as applied to assessing the loss of a structural element's bearing capacity. The conditions under which the parameter SIF (K_1) reaches its critical value serve as a criterion for determining whether a structural element having a cracklike flaw has reached its limiting state [3, 5]. This criterial characteristic is called static fracture toughness or the static growth resistance of material (yield strength or ultimate strength are the analogs of this characteristic in tradi-