CALCULATING THE STRENGTH OF PRESSURE VESSELS IN THE PRESENCE OF CRACKS

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Tanks, containers, and reservoirs designed for various purposes and operating under the action of internal pressure constitute some of the commonest constructional elements in engineering. Their working conditions sometimes mean that the development of plastic deforming proves to be difficult. This can be due to various causes among which we may mention the large absolute dimensions of the construction, radiation work hardening, the embrittling influence of the atmosphere, and in particular a reduction in temperature, and hydrogen pickup.

As a result of the suppression of the capacity in the material for being plastically deformed, we eliminate the possibility of the favorable redistribution of the stresses and deformations over the volume of the body, and over its individual structural constituents. Therefore, local overstressing develops together with initial microcracks, and there is a tendency toward their further development which in the final account is terminated by macroscopic brittle failure. As is known, the danger of brittle failure consists not only in its apparent suddenness, but also in the fact that it may occur under conditions of stress below the calculated levels. This means that the actual store of strength proves to be lower than that which is established according to ordinary calculation methods for strength, without taking into account cracks.

The method proposed in [1] for calculation is useful for determining the degree of underutilization of the strength of the tank, that is, to establish the actual (final) store of strength in the case of brittle failure occurring due to the presence of cracks. Simultaneously, the threshold size of the cracks which will not lead to the sudden breakdown of the component is established. Thus, the use of the calculation taking into account the presence of cracks determined in the appropriate experiments, lends support to the idea of protecting the construction against brittle failure [2]. Let us now examine certain examples for calculating pressure vessels, the results of testing of which are given in [3].

Example 1. A welded cylindrical container (made by the Budd Company) of diameter 508 mm, was subjected to the action of internal pressure. The thickness of the wall h = 1.02 mm. The material used in constructing the container is steel containing 20% nickel, tempered into martensite. The yield point \(\sigma_{0.2} = 214.9 \text{ kg/mm}^2\), the strength \(\sigma_B = 215.6 \text{ kg/mm}^2\). With a single hydraulic loading the vessel fails under a pressure of 53.9 atm, which corresponds to a peripheral stress of \(\sigma_t = 134.4 \text{ kg/mm}^2\). The ratio of this stress to the maximum strength of the steel is underused almost by a factor of two.

From the broken vessel we cut two specimens in the longitudinal and transverse directions which showed the following critical intensity coefficients: in the longitudinal direction \(K_C = 337 \text{ and } 364 \text{ kg/mm}^{3/2}\), \(K_I = 253 \text{ and } 248 \text{ kg/mm}^{3/2}\); in the transverse direction \(K_C = 196 \text{ and } 145 \text{ kg/mm}^{3/2}\), and \(K_I = 178 \text{ and } 132 \text{ kg/mm}^{3/2}\).

The evaluation characteristics given in [3-5] will be subsequently used. The type of fracture can be predicted from the ratio of the length of the plastic zone \(d\) in front of the crack edge to the thickness \(h\) of the flat specimens or the flat construction element. According to Irvin, with a planar stressed state \(d = \frac{K_C^2}{\pi \sigma_t^2}\). If \(\beta = d/h < 1\), then the fracture is mainly straight (breakdown occurs by rupture), if \(\beta > 1\), then the fracture is mainly oblique (breakdown occurs by shear). If the coefficient \(\alpha = K_C^2/K_I < 2\), then the characteristic of the material \(K_C\) is inserted in the calculation; if \(\alpha > 2\), then the calculation is done with respect to the magnitude \(K_I\), typical of the stated thickness of the flat component.
In the stated case the parameter $\beta$, evaluating the conditions of breakdown from the type of straight or oblique fracture, will be as follows: for the longitudinal direction $\beta = 0.8$, for the transverse $\beta = 0.2$ (with respect to average values of $K_c$). Since this ratio is less than 1, then the breakdown occurs in conditions close to the flat deformation for the volume stressed states,* according to the type of rupture. In these conditions the construction is sensitive to cracks. The coefficient $\alpha$, showing an increase in the coefficient of stress intensity, with the planar stressed state over its value, with a volume stressed state in the case of the planar deformation, for the longitudinal direction, equals 1.33, and for the transverse 1.1. Since $\alpha < 2$, the calculation should be done with respect to the maximum coefficient $K_{IC}$, and not with respect to $K_c$.

The investigation of the vessel after breakdown showed the presence of the original defect in the form of a crack on the outer surface, approximately perpendicular to the direction of rolling of the sheet. This crack was the cause of the reduction in the strength of the container. Since the extent of the crack on the surface of the tank was more than ten times greater than its depth $l$, in order to calculate the coefficient of intensity we used the type of plate with a lateral shear [2]

$$K = 1.1a_1 \sqrt{\frac{1}{\pi l}}.$$  \hspace{1cm} (1)

In this equation the peripheral stress is used since the tank is welded across a helical line at an angle of $79^\circ$ to the resultant, and the transverse direction of the crack on the sheet is the axial for the tank. The detected crack depth $l = 0.76 \text{ mm}$.

We find the destructive depth of the crack by calculation. The limit of crack formation is written in the form [1]

$$l = K_{IC} \sqrt{1 - \left(\frac{\sigma}{\sigma_0}\right)^2},$$  \hspace{1cm} (2)

in which the average value $K_{IC} = 251 \text{ kg/mm}^{3/2}$ is inserted for the longitudinal direction. From the equality

$$K = l$$  \hspace{1cm} (3)

with a destructive stress of $\sigma = 134.4 \text{ kg/mm}^2$, we find the critical depth of the crack $l = 0.58 \text{ mm}$. In Fig. 1, the value of the crack depth can be obtained graphically. By comparing the resulting depth of the crack with the experimental value of 0.76 mm, we may conclude that the calculation gives supporting (in the strength reserve) values for the critical size of the crack.

* See the preconditions of Ya. B. Fridman and B. A. Drozdovskii in the book [4].