LIFETIME OF PRESSURE VESSELS WITH CONSTRUCTION ERRORS

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Abstract. In the present paper is presented a theoretical research about the lifetime determination of cylindrical pressured vessels with errors of construction. It's a matter of the eccentricity error between the cylinders from which is formed the body of vessel. In the same time is taking into account the crack presence in the thermal influenced zone of welding joint and of the fatigue conditions work of vessel, which is stressed with a pulsating cycle.

Keywords: Lifetime, fatigue, pressure vessel, materials fracture mechanic, crack

1. INTRODUCTION

The pressure vessels represent the basic components of installations from most diverse domains: chemical and petrochemical industry, food industry, metallurgical industry, building materials industry etc. Also, have not to miss by sight their utilization in the frame of thermoelectric power station installations, nuclear installations, as well as for the construction of cosmic ships or submarines (pressure hull). As regards the developmental tendencies from this area, must be point out the preoccupations of researchers for the realization of vessels with bigger diameters and for very high work pressures. These superior characteristics are requested for the increase of industrial installations productivity. In this context appear the problem of the optimum size determination of the pressure vessels, from technical and economical viewpoint. The solution of this problem is necessary for decrease of weight, for economize of precious materials, for decrease of manufacture price; that is, finally, for reduce the cost of equipment [1]. For this objective touch the designer is due to have the necessary calculus methods and the mathematical relations. Only in this conditions can be determinate the effective state of stress settled in either point of vessels surface, depending on used construction materials, exploitation conditions and equipment construction form. Thus, such is known, the vessels are divided from viewpoint of the state of stress calculus, in revolution shells with thin wall (for which the report among the outer and inner rays $\beta \leq 1.1$), and bodies of revolutions with thick wall ($\beta > 1.2$). Indifferent which is the constructive form (cylindrical, spherical, ellipsoidal, conical etc.), the revolution shells with thin wall is manufactured through welding joint technological process of some components (cylinders, lids, etc.).

Preliminarily, these elements are obtained through different technological processes of plastic deformations at cold or warm, which is followed of thermal treatment for obtain an unstressed structure. Because of these technological processes, the components of pressure vessel can result with important dimensional differences towards the right dimensions. For instance, two cylinders with same thickness or different thickness can result with different diameters. From this reason, the median surfaces of cylinders shall present a discontinuity in the zone of contact between cylinders, where will be jointed through circular welding seam. One thing is can noticed and in the case in which the two cylinders are wrong location in the sight of the welding seam execution or in the case of local deformations of cylinders. In the same time, there is the possibility of summarization of these errors, however they are produced from various reasons.

The lack of continuity median surface of the vessel body has as the effect the state of stress modification in the zone of welding joint. This modification depends of distance between the median surfaces of two cylinders which form the vessel body. In the same time, this neglected execution of the pressure vessel can drive and to the decrease of his lifetime, because of cracks appearance in the thermal influenced zone of welding joint or in welding seam. Also, the cracks can appear in the material metallic structure along of a technological process, owing to encroach of the right work conditions. Taking into account that the pressure vessels work under fatigue conditions (usually under a pulsating cycle of inner pressure), these cracks can be expanded, with seriously consequences.

2. THE LIFETIME DETERMINATION OF PRESSURE VESSELS WITH FISSURES

The influence of cracks about lifetime of metallic structures can be studied with the help of fracture mechanics concepts. Thus, based on these concepts is can passed from the fracture description as a global phenomenon (as in material resistance), to the fracture interpretation as a local phenomenon of appearance and propagate of cracks or other flaw of materials. Apply of fracture mechanics concepts to the metallic structures calculus can be done if the following hypotheses are accepted: the existence of flaws in used material; the fracture of material is initiated in the zone with flaws, through some mechanisms such as the fatigue of material; from macroscopically point of view, fracture of material is described as a flaws expansion phenomenon, that is, the expansion of material's cracks; thus, the expansion of cracks begin in the moment in which, locales, in the zone with discontinuities is exceeded a critically size, what can be specifically energy, tension or deformation.

The crack is most dangerous flaw studied of the fracture mechanics. The conclusions and the results obtained through the crack behavior research are valid for other types of flaws. The crack expansion can be gradually or quickly, unstable, with catastrophic character. The influence factors of fracture materials with cracks are the following: the type of loading, the size of tensions, the temperature, the form and the sizes of the structure, the form and the sizes of the crack, the environment conditions (corrosion, radiations etc.), the characteristics of the construction materials (chemical composition, structure, elaboration way, size of grains, tenacity etc.).

Depending on the type of the deformation at the peak of crack, which preface the crack expanding, were establish the following basic mathematical models of fracture mechanics [2,3]: in the case of a linear - elastic deformation at the peak of crack is applied the fracture mechanics of linear - elastic materials; in the case of a elastic - plastic deformation at the peak of crack is applied the fracture mechanics of elastic - plastic materials; if the material deformation at the peak of crack has a plastic unstable character (plastic instability), the domain is better covered through the calculation procedures of classic materials resistance; the conditions which determine the plastic instability can be better correlated with the characteristics of resistance σ_r, than with the rupture tenacity, K_C.

The basic concept in the fracture mechanics of linier-elastic materials is the stress intensity factor, K_I, which describes exhaustively the state of stress and deformations in the zone adjacency of the crack peak, if this zone remain in the elastic domain of static solicitation. The crack unstable expand if is attained the critical value of stress intensity factor, K_{IC} or K_C, which is called the rupture tenacity. This characteristic is established from experimental determination on samples, being specifically for every type of material.

Usually, in the common materials, always appear plastic deformations at the peak of crack. In this case is necessary to apply the fracture mechanics of elastic-plastic materials and the stress intensity factor must be modified. For this reasons in the domain of fracture mechanics of elastic-plastic materials are used other concepts, for instance: Crack Opening Displacement, δ, and Contour Integral, J, with their critical values δ_C, and respective J_C. The concepts and the analytically methods, conjunct with the experimental characteristics of tenacity, K_{IC}, K_C, δ_C, J_C etc., offer the possibility to design or verify the technically constructions taking into account the inherent flaws of materials.

The verification of a metallic construction can be achieved through the determination of the crack critical length, a_{cr}, that is, the settlement of maximum size of flaw; if is reach this critical length, the structure is destroyed. For critical length determination, is used the definition relation of stress intensity factor:

$$K = \sigma\sqrt{\pi \cdot a \cdot f} = K_{IC}\,; \tag{1}$$

in this relation σ is the tension from the material with cracks; a – the length of crack; f – shape factor of crack, which depend of ratio between the length of crack and the dimension of object with crack; K_{IC} - rupture tenacity of material. So, the critical length of crack is determinate with relation:

$$a_{cr} = \frac{1}{\pi \cdot f}\left(\frac{K_{IC}}{\sigma_{cr}}\right)^2 \tag{2}$$

This method is valid merely in the linear-elastic domain, and for her application is necessary to known the maximum tension in the reached zone and the tenacity characteristics K_{IC} or K_C.. In the state of stress analysis from construction element, the size of defect is considered negligible towards the size of construction element.

The interplay among the size of flaws and the element geometry is considered through the shape factor of crack, f, which has been determinate for different forms of cracks. Must mentioned that the stress state analyze is complete only are considered (beside of the tensions caused of pressure and temperature) as well the tensions caused of temperature variation (the transitory regime) and the residual tensions. Also, the resistance verification of a metallic construction with cracks can be achieved through maximum tension determination which can load the construction element. This aim is realizable using the definition relation of stress intensity factor, if are known the tenacity characteristic K_{IC}, the geometry of construction element and the distribution of flaws.

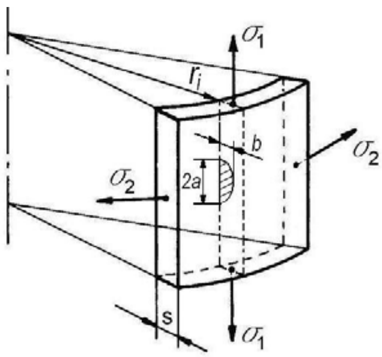

Fig. 1. Surface semi-elliptical crack at the inner surface of a cylindrical vessel.

The knowing of the cracks form, orientation, localization and distribution is very important for a correct calculus. In the same time, must known the evolution of crack expansion speed under variable solicitations [4,5]. If the neighboring flaws are sufficiently near each other (for instance agglomerations of pores, inclusions or micro-cracks) appear the possibility of interaction between flaws. In this case, the agglomeration of flaws must be considered that an alone flaw with a size equal with the size which result through the summarization of individual sizes of flaws. The most dangerous type of flaw is the surface semi-elliptical crack (fig. 1), for which the shape factor is determined with relation [6]:

$$f = \frac{1{,}2}{\Phi^2}, \tag{3}$$

where Φ is the elliptical integral of second order,

$$\Phi = \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{a^2 - b^2}{a^2}\sin^2\varphi \cdot \mathrm{d}\varphi}\,. \tag{4}$$

For a/b = 4 and $\varphi = \pi/2$, result $\Phi = 1.15$.

The number of cycles until rupture is determined with relation obtained through the integration of Paris equation:

$$N_r = \frac{a_c^{1-\frac{m}{2}} - a_i^{1-\frac{m}{2}}}{C\left(1-\frac{m}{2}\right)\cdot(\Delta\sigma)^m \cdot \pi^{m/2}}, \quad (5)$$

in which a_i and a_c are respectively, the lengths initially and finally of cracks; C, m – coefficients depending of material (m = 3; $C = 3{,}492\cdot10^{-12}$); $\Delta\sigma = \sigma_{max} - \sigma_{min}$ .The admissible cycles of work is determined by means of durability safety coefficient C_N = 10 [5,7,8]. The residual lifetime of work is established tacking into account of the effective time of work. For the settlement the residual durability of mechanical structures must be know a few important dates: the history of solicitations; the temporally variation of tensions; the mechanic characteristics of materials in the calculus moment.

3. STATE OF STRESS DETERMINATION IN THE ZONE WITH ERRORS OF CONSTRUCTION

For the broach of this problem is considered the general case of welding joint between two cylindrical shells with different thickness (fig. 2). The joint have an error towards the correct position which consists in the existence of distance *"e"* between the median surfaces of cylindrical shells, because of different diameters or wrong location.

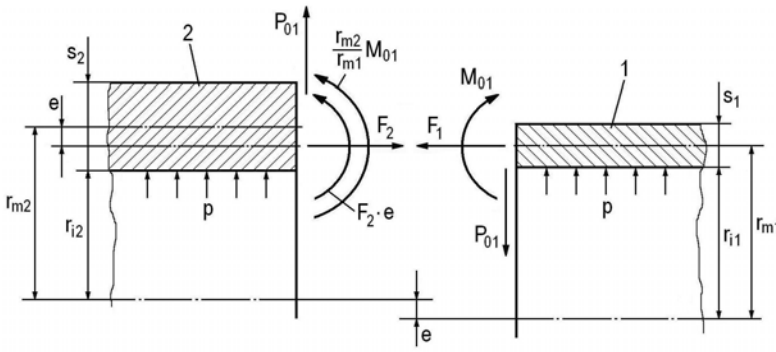

Fig. 2. Geometric parameters and loads in the case of two cylindrical shells with errors of construction.

The state of stress in the join zone of shells can be determinate through revolution shells theory application, with acceptance of following simplifying hypothesis: the effect of the welding seam is negligible; the temperature is considered constant on the length of shells; the difference between axially forces F_1 and F_2 is negligible.
Such is known, for the settlement of calculus relations of axial, tangential and equivalent tensions is necessary to write firstly the continuity equations of deformations (displacements and rotations), taking into account of error *"e"*. Finally, the values of tensions in the two shells results from the following relations [9,10]:

$$\sigma_1(x) = \frac{p\cdot r_m}{2\cdot s} \pm \frac{6\cdot m_{01}}{s^2}, \quad (6)$$

$$\sigma_2(x) = \frac{p\cdot r_m}{2\cdot s} \pm \frac{6\cdot\mu\cdot m_{01}}{s^2} + \frac{T}{s}, \quad (7)$$

in which: p is the inner pressure; r_m – ray of shell median surface; μ – transverse contraction coefficient; m_{01} – unitary bending moment; T - unitary tangential effort.

The equivalent tensions are calculated in accordance with the theory of deformation energy:

$$\sigma_{ech} = \left(\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2\right)^{0,5} . \tag{8}$$

4. CASE STUDY

The body of a pressure vessel is constructing from two cylindrical shells which are jointed through a circular welding seam. In the frame of preventive maintenance activity have been discovered surface semi-elliptical cracks at the inner surface, in the thermal influenced zone of welding joint. The length of cracks are between one and three millimeters and ratio a/b = 4 (fig. 1). Also, in the zone of contact between the two cylindrical shells (places 1 and 2 from figure 2) has been observed a discontinuity of exterior surfaces, e = 2 mm. Knowing as the pressure vessel work from eight years under fatigue conditions is necessary to determine the residual lifetime of this vessel. Is known too that the inner pressure is variable conform a pulsating cycle (between 0 and 0.8 MPa) with the period P = 1 hour.

The construction material for the two shells is steel R 510, STAS 1097/2-91, with following characteristics: σ_r = 350 MPa; E= $2{\cdot}10^5$ MPa; μ = 0.3; K_C = 100 MPa·m$^{0.5}$. The equipment has following constructive and working parameters: inner rays of shells r_{i1}= r_{i2} = 1 m; thickness of shells s_1=s_2 = 0.01 m; environmental temperature T_0 = 20^{o}C; temperature median surfaces in the work time T_{m1} = T_{m2} = 100^{o}C; work maximum pressure p = 0.8 MPa.

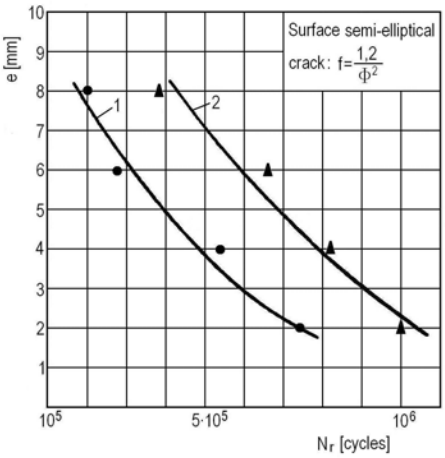

Fig. 3. Number of cycles until rupture vs. error of construction, for a vessel with cracks:
1 – crack at the inner surface of shell 1; 2 – crack at the external surface of shell 1 (fig. 2).

For the residual lifetime of vessel determination needs to take into account the crack existence and in the same time, must consider the construction error influence. In accordance with the results presented in the work [9], the maximum equivalent tensions from the joining zone increase along with the value of error *"e"*, but remain however below the flow limit of material (σ_c = 295 MPa), at the work temperature (100^{o}C). The biggest values of tension are developed at the inner surface of the shell 1, respectively at the external surface of the shell 2 (fig. 2). Thus, for e = 2, 4, 6 and 8 mm have been obtained, the following values of equivalent tensions: 158, 180, 210 and 245 MPa. Also, is can noticed as the value of tension concentrate coefficient towards membrane tension (σ_m = 160 MPa) increase from 1.156 (for e = 2 mm), to 1.53 (for e = 8 mm). At the external surface of shell 1 and internal surface of shell 2, the values of equivalent tensions are lower, for the same values of error *"e"*: 135, 142, 158 and 183 MPa.
Further on, is determined the number of cycles until rupture, N_r, tacking count of stress state for different values of *"e"*; as well as is considered the presence of semi-elliptical crack at the vessel inner surface (fig. 3). For this objective touch is used the relation (5) in which Δσ represent the maximum values of equivalent tensions in the zone of circular welding seam ($\Delta\sigma$ = σ_{max} - σ_{min} and σ_{min}=0 for a pulsating cycle); a_i – initially dimension of crack; a_c – critically dimension of crack, determined with relation (2).

Thus, in accordance with the results presented in the figure 3, is can noticed a decreased number of cycles until rupture along with the increase of error *"e"* values. In the same time is showed the influence of crack about the number of cycles until rupture. So, in the case of shell 1, the presence of crack at the inner surface is much more dangerous than the presence of crack at the external surface. In the case of shell 2, the situation is inverted.

Certainly, the vessel can't be loaded until rupture and is necessary to determine the admissible cycles of work, tacking into account a safety coefficient C_N =10. In accordance with the results presented in the figure 3, for the examined case (e = 2 mm), the number of cycles until rupture $N_r = 7.53 \cdot 10^5$ cycles; therefore the number of admissible cycles is [11,12]: $N_a = N_r$ / 10 = 75300 cycles. Afterwards, knowing the history of this equipment, which show that it work from eight years under fatigue conditions (a pulsating cycle with the period one hour), can be calculated the effective number of cycle (cycles realized in this time), N_{ef} = (8 years$\times$12 months$\times$30 days$\times$24 hours) /1 hour = 69120 cycles, the residual number of work cycles, N_R = 75300 – 69120 = 6180 cycles, and the residual lifetime of vessel T_R = 6180/24 = 257.5 days.

5. CONCLUSIONS

Because of manufacturing technological processes, the pressure vessel can result with some errors of construction. For instance, can appear differences between the diameters of cylinders where will be jointed through circular welding seams, or between the diameters of cylinders and diameters of lids. Also, the errors of construction can appear and in the case in which the two cylinders are wrong location in the sight of the welding seam execution, in the case of thickness differences, or in the case of local deformations of cylinders or lids. On the other hand, during of technological processes (welding, plastically deformations, press etc.), in the structure of metallic materials can appear cracks, pores, slag inclusion or other flaws.

The pressure vessels must to work in perfectly safety conditions because damages of this type of equipment can have seriously consequences. Thus, tacking count of this thing, in this paper is studied the problem of the life time determination of cylindrical pressured vessels with errors of construction. In the same time is take account of the cracks presence in the thermal influenced zone of welding joint and of the fatigue conditions work of vessel. In these conditions the resistance of construction material and the lifetime of vessel are reduced. The results presented, shows the increase of tensions in the joining zone along with the value of construction error. As well, in accordance with the results presented is can noticed a lifetime decrease which is caused of a surface semi-elliptical crack, in the fatigue conditions work of vessel, stressed from a pulsating cycle. In the same time is showed that the presence of cracks at the inner surface of shell 1 and at the external surface of shell 2 is most dangerous for the studied case. In accordance with the results presented, must underline the necessity to observe indications of standards with regard to pressure vessel execution and to construction admissible errors [13].

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