FABRICATION AND ASSEMBLING ERRORS INFLUENCE ON THE FATIGUE STRENGTH OF THE SPHERICAL TANKS SHELL - THEORETICAL APPROACH

JINESCU V. VALERIU[1], TEODORESCU NICOLETA[1*], SIMA TEODOR[1]

[1] Politehnica University of Bucharest, Faculty of Mechanical and Mechatronics Engineering Bucharest, 060042, Romania

Abstract: In the paper are summarized the major and most often encountered manufacturing errors influence on the stress concentration factor and on the state of stress of the spherical tanks shell, used for the storage of liquefied gases, discontinuous equatorial supported, complex loaded. There are presented stress concentration factor calculus formulas to be used to take into account the welds flaws.
The spherical tanks shell is subjected to low cycle fatigue stress, especially due to the extension of the working time period (often encountered in nowadays practice). So it is evaluated the low cycle fatigue strength/number of cycles of the spherical tanks shell both in the absence of fabrication and assembling errors and taking into account these kinds of errors. Here is presented the theoretical approach. Another part will deal with the calculus approach and the conclusions.

Keywords: spherical tank shell, stress concentration factor, manufacturing errors, assembling errors, fatigue

The allowable fabrication and assembling errors are usually given only by experience; it is not the result of a quantitative evaluation. The worst situation is when all the possible errors happen in the same time, leading to a superposition of consequences, in terms of the increase of the spherical shell stress concentration. In the everyday practice often one measures much higher values for the most common errors than the allowable ones; for these higher values the manufacturer ask the permission from the designer in order to “save” the parts fabricated with rather big errors. Here we have the intention to evaluate quantitatively the influence of those errors on the state of stress or on the concentration factor to see if it is all right for the designer to admit such derogations from the values stipulated in the project.

This first part of the work is only a theoretical approach. There are summarized the errors encountered in fabrication and assembling of the spherical tanks shells and their influence on the stress concentration coefficient. The spherical tanks shell can be subjected also to low cycle fatigue stress, especially due to the extension of the working time period (often encountered in nowadays practice). So it is evaluated the low cycle fatigue strength/number of cycles of the spherical tanks shell both in the absence of fabrication and assembling errors and taking into account these kinds of errors. In a second part of the work will provide a calculus approach. The calculus results are expected to form a correct basis even for the allowable errors/for bigger errors.

[*]Corresponding author, email: nicoleta_teodorescu@yahoo.com
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1. CONSTRUCTION ERRORS

The spherical tanks are used for gases/liquefied gases (under pressure) storage. These types of vessels present the advantage that at given pressure and volume, need the lowest metal consumption; there is also the disadvantage of a more difficult execution and assembling.

All technological operations of the spherical parts induce inner stresses with complex distributions, which finally can modify significantly their performances.

The general-classic causes which determine the stresses appearance (residual stresses) are available also in the case of the making processes (during material elaboration of the construction material – casting, rolling, forging etc.). The stresses amount can increase in the case of a wrong technological design, which generates additional stress concentration. Connecting the fabrication system with the general causes of the stresses appearance, one can say that:
1 – The non-uniform plastic deformations (strains) are mainly generated by: cold plastic deformations; form errors due to the fabrication (flattening, for example); construction local deformations or local material dimensional non-conformity (local thinning for example); assembling errors (eccentricity between the welded sheet plates; assembling eccentricity of the supporting pillars etc.);
2 – The non-uniform temperature distribution is generated by: thermal processes (welding, grinding, cutting etc.); local heating; non-uniform thermal distribution in the case of the thermal treatment;
3 – The structure modifications are generated by: welding processes which generate local volume, density and metallographic structure modifications.

The technological process undergoing in the spherical tanks imposes strict conditions regarding strength, sealing and reliability.

The main factors which influence the spherical tanks parts strength are:
a) Constructive factors: - parts form and dimensions;
b) Technological factors: material quality; surfaces roughness; surface thermal treatment; residual stresses;
c) Working conditions: the loading type (steady-state, dynamic/fatigue); over-loadings; corrosion; working temperature etc.

The form errors effect on constructive pressure vessels parts strength is presented in paper [1] and in paper [2] are presented the aspects regarding pressure vessels lifetime in the case of the geometric form errors presence. In [3, 4] are presented the general needs for materials, dimensions and geometric-constructive form errors in pressure equipment components fabrication.

2. WELDING SEAMS ERRORS

The causes of flaws appearance in welds (or nearby) can be: un-adequate construction form; wrong parts assembling; non-weld-able base material; filler metal wrong choice; un-adequate applying of the welding procedures; human errors.

The weld flaw can be an error from: the discontinuity of the welding seam; the welding seam exterior aspect, form and dimensions, the structure and chemical composition.

No matter the characteristics of the metallic structure, the multitude of the specific welding structure flaws can be:
a) Defects of preparation and assembling (the chamfer geometry un-adequate);
b) Joint geometry form and dimensions errors;
c) Exterior defects/discontinuities (cracks, pores, notches etc.);
d) Inner defects (voids/inclusions (pores, blow, gas inclusions etc.); lack of fusion and incomplete penetration; cracks and micro-cracks);
f) Chemical composition errors;
g) Poor mechanical and technological characteristics.

In the preparation phase, in order to proceed to the spherical tank welding, one has to verify the form and the dimensions of the weld joints, pursuing a design. So one have to verify all the elements of the weld joint to be in an allowable domain, as one can see, for a butane spherical tank, presented for example, in the Figure 1.

A detailed description of the possible flaws which can appear during the welding process is presented in papers [4, 5, 6, 7].

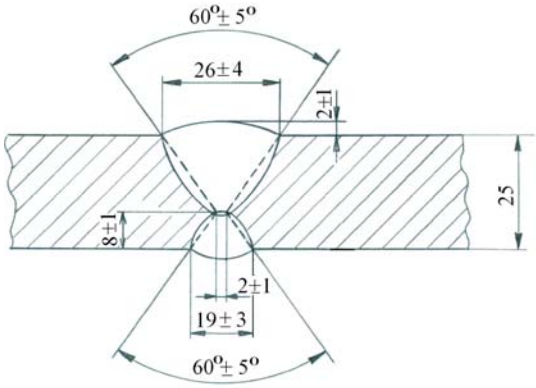


Fig. 1. The admissible errors for a butane spherical tanks butt weld.

At the assembling of the spherical tanks there are totalized all the flaws due to design, fabrication, transportation and depositing of their components, adding those to those of the erection/installing itself. In the paper [8] there are presented the flaws produced by different causes during the installation tests (design errors, execution/fabrication errors, transportation and depositing deficiencies, failures of the different structural elements, deficiencies in energy supply, fires, assembling deficiencies, operating errors, testing errors etc.).

3. STRESS CONCENTRATION FACTOR DUE TO WELDS. WELDS FATIGUE BEHAVIOR

The assessment of the real state of stress, mainly in the welding seam and in the nearby zones is a very complex problem because of the stress concentrators (due to flaws), which might reach dangerous values. So is very important to know the real stress distribution in the seam and in the nearby zone.

The butt welds represent, from the stress distribution point of view, the best type of joints. If the seam is of good quality and Δa (Figure 2.) is removed, the value of the stress concentration factor equals 1. Figure 3 presents the stress distribution draft in the different sections of the welding seam.

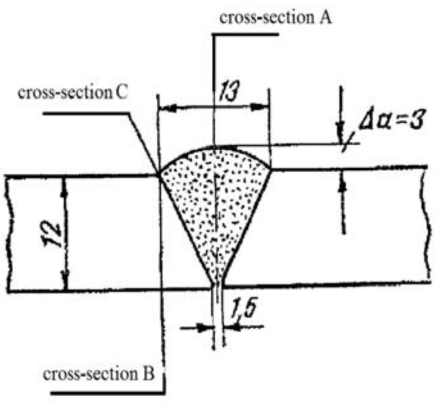


Fig. 2. Butt weld characteristics [9].

The smaller the knob seam and the smoother the connection between the weld seam and the base metal are, the lesser stress concentration coefficients values were noticed.

In the Figure 4 there are presented the normal stress concentration coefficient, α_k, in the case of a butt weld function of Δa, and of the connecting radius r, for thickness of the welded parts between 10 and 40 mm [9].

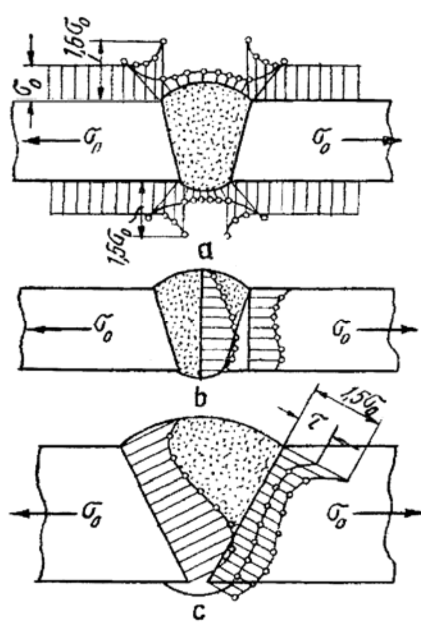


Fig. 3.

a) Stress distribution draft in normal direction; c) Tangential stress distribution draft (for C and B, C sections, respectively) A, B, C sections shown in Figure 2 [9].

The stress concentration coefficient can reach much higher values if the joint presents incomplete root penetration or if the root is not re-welded.

The influence of the stress state function of the positioning of the two parts, in the case of corner welding, is presented in Figure 5 [10].

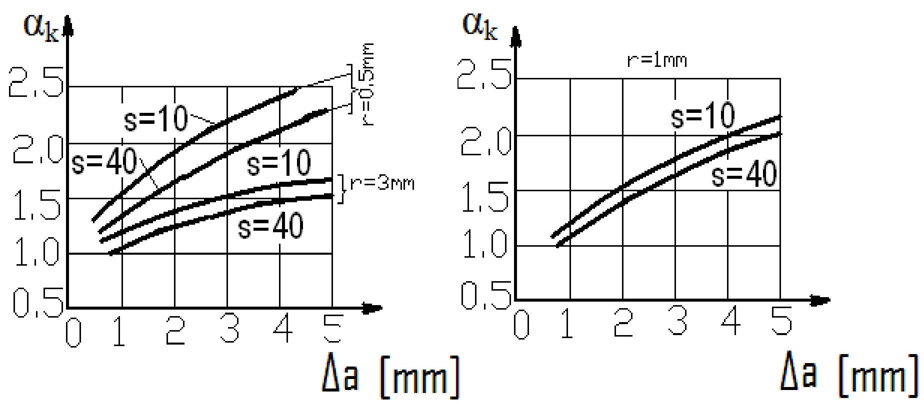


Fig. 4. Stress concentration coefficient function of the knob values.

Eccentricity between the welded sheet plates in the case of a spherical tank and also the pillars axis eccentricity with respect to the spherical shell medium radius, both influence the shell state of stress [5].

In Figure 6 can be seen the influence of the eccentricity between the welded sheet plates (aluminum made), for example, on the fatigue strength [11].

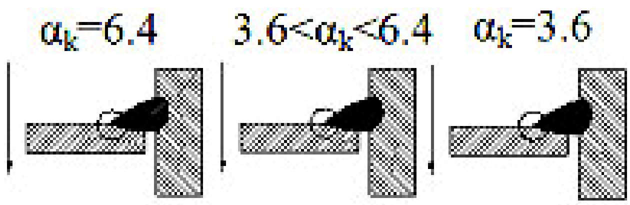


Fig. 5. The influence of the positioning of the pieces for corner welds [10].

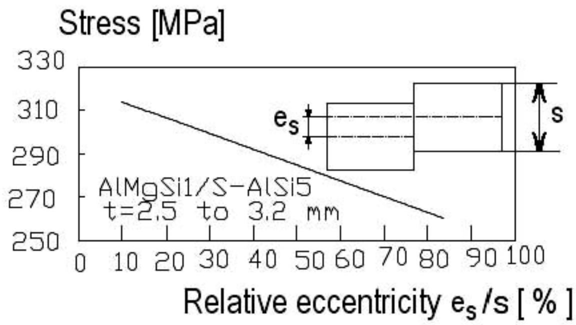


Fig. 6.The influence of the eccentricity between the welded sheet plates on the fatigue strength [11].

In the Figure 7 it is presented the influence of the weld knob angle on fatigue strength [11].

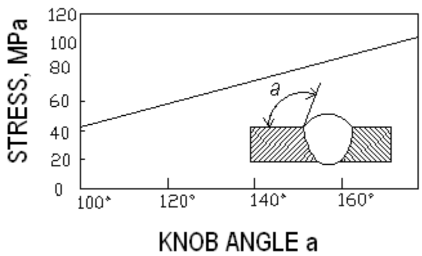


Fig. 7. The influence of the weld knob angle on fatigue strength [11].

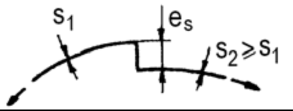
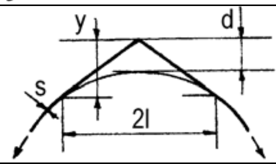
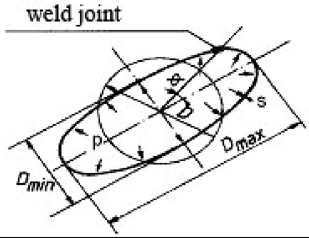
In Table 1 is presented the ASME code recommendations [4] regarding the values for the stress concentration coefficient for different types of weld joints.

Table 1. Stress concentration coefficient - recommended values [4].

The weld joint type	**Stress concentration coefficient**
Butt joint with complete penetration, with weld on both sides	1.2
Corner joint, without margins preparation, with loading perpendicular on the bed plate	1.5
Corner joint, without margins preparation, with axially loading along the seam	2.7
Corner joint, with complete penetration, with sharp edges	2.0

In Table 2 are presented the expressions for $\alpha_{k,w}$, for three types of butt weld joints geometrical errors (characteristic for the spherical shell tanks).

Table 2. Stress concentration coefficient calculus in the case of butt weld joints geometrical errors, for spherical tanks.

Error type	**Detail drawing**	**Stress concentration coefficient expression**
Axial miss-alignment		$\alpha_{k,w} = 1 + \frac{e_s}{s_1\left(1-\mu^2\right)}$
Angular miss-alignment (fixed ends)		$\alpha_{k,w} = 1 + \frac{3d}{s\left(1-\mu^2\right)}$
Ovalization		$\alpha_{k,w} = 1 + \frac{1{,}5a \cdot \cos 2\theta + s}{s\left[1 + \frac{p\left(1-\mu^2\right)}{2E} \cdot \left(\frac{D}{s}\right)^3\right]}$ p is the inner pressure; $a = D_{max} - D_{min}$.

In the case of spherical shell tanks, under membrane loading, the weld joint axial or angular miss-alignment (of the spherical plates), introduces supplementary bending stresses, which have the character of peak stress. These are cross-weld joint oriented, depending on the miss-alignment nature and the magnitude and also of the contour conditions [12]. The stress concentration coefficient values can be calculated with:

$$\alpha_{k,w} = \frac{\sigma_b + \sigma^m}{\sigma^m} \tag{1}$$

where: σ_b is the bending stress introduced by the weld's flaw; σ^m is the membrane stress.

The moderate severe imperfections or flaws, for example, the knob, excessive convexity or weld seam thinning, solid inclusions and edge notches can be assimilated with elliptical form concentrators [12].

4. SPHERICAL SHELL STRESS CONCENTRATION FACTORS-CONSTRUCTION GENERATED

The spherical shell stress concentration factor must take into account the influence of the geometrical local errors resulting during the spherical sheet plate's construction (flattening, thinning) and during the assembling (eccentricities at the assembling of the tubular supporting pillar on the spherical shell). At those local errors influences one adds the influence of the errors due to the welding.

One calculates (taking into account a complex loading (working/storage pressure/hydraulic test pressure, wind, hydrostatic pressure, own weight, deformation restraint (due to horizontal forces determined by the temperature difference between working conditions and assembling conditions and also by the seismic loadings) exerted by the supporting system on the spherical shell and loadings due to the supporting system discontinuities): - the membrane equivalent stress with and without errors, $\sigma^m_{ech,e};\sigma^m_{ech}$; - the equivalent total stress obtained from the superposition of the membrane and contour loadings (from the equatorial supporting zone), with and without errors, $\sigma^{m+c}_{ech,e};\sigma^{m+c}_{ech}$. The principles of the calculus were presented in papers [13, 14], and will be further discussed in the second part of the work. After that one takes into account the influence of the errors due to the welds.

Result a stress concentration factor due to the spherical sheet plate's construction and eccentricities caused by assembling,

$$\alpha_{k,e} = \frac{\sigma_{ech,e}^{m+c}}{\sigma_{ech}^{m+c}} \quad (2)$$

and then one obtains the total stress concentration factor superposing the influence of the welds errors:

$$\alpha_{k,t} = \alpha_{k,e} \cdot \alpha_{k,w,e} \quad (3)$$

The maximum stress concentration factor can be obtained comparing the total equivalent stress obtained taking into account both the local construction errors and those due to weld in the equatorial region (the highest loaded zone) and the total membrane stress without any errors:

$$\alpha_{k,t,\max} = \frac{\alpha_{k,w,e} \cdot \sigma_{ech,e}^{m+c}}{\sigma_{ech}^{m}} \quad (4)$$

5. FATIGUE LOADING CHARACTERISTICS. CALCULUS MODEL

The stress concentration, causing an increase of the maximum stresses, which in most of the cases have far bigger values than the nominal stresses, cause crack generation and in the end a decrease of the fatigue strength of the spherical tanks parts. The effective stress concentration factor depends on the loading type, un-symmetry loading cycles factor, the sheet plate's dimensions, the type and form of the flaw which causes the stress concentration, sheet plate's material behavior etc.

In the literature it is indicated, in tables or in diagrams, the values for the effective concentration, mostly for symmetric cycles, because it is easier to be experimentally obtained. The variation of this coefficient for different un-symmetry degrees does not exceed 10% from the value obtained for the symmetric cycles, of the same amplitude as the real cycle. So, one can use for the un-symmetric cycles the coefficients determined for the symmetric cycle, being affected only the cycle's amplitude. For the case of weld joints, there are presented in paper [9] experimental results for $\alpha_{k,\sigma,w}$, both for symmetric and un-symmetric cycles, for different values of the un-symmetry coefficients. The value of the fatigue strength is influenced by the dimensions of the parts (sheet plate's, in the case of spherical tanks), so one take it into account by means of the dimensional coefficients ε_σ or ε_τ, which is less than 1, because almost always the parts are bigger than the fatigue testing specimens. In some cases, the effective concentration factor can include dimensions coefficients ε_σ, ε_τ, being defined in this case as complex concentration coefficient [9].

$$\alpha_{k,\sigma,w,coplex} = \frac{\alpha_{k,\sigma,w}}{\varepsilon_\sigma}\text{, respectively } \alpha_{k,\tau,w,complex} = \frac{\alpha_{k,\tau,w}}{\varepsilon_\tau}. \quad (5)$$

The weld joints fatigue strength is smaller than that of the base material because of the stresses concentration effect caused by welding process. The existence of a weld lids to the decrease of the part fatigue strength even the weld is of a good quality and does not modify the force flux in the piece. In the case of variable loading, the butt joint presents the best strength comparing with other types of joints because the welded pieces are in the same plane, so the force lines flux remain un-deranged. In the paper [9] there are presented the values for the effective stress concentration coefficients for different types of joints, different loadings, both for the seam and for the connecting zone (Heating Affected Zone).

In the case of a spherical tank for liquefied gases storage, under pressure one can supposes that the pressure can vary function of the pressure connected with the liquid level fluctuations, which can be daily or weekly (depending on the fabrications the tank serves), so one can talk fatigue loading of limited duration when

$N \in \left[\left(10^3..10^4\right), N_0\right]$ or about low cycle fatigue loading when $N < \left(10^3..10^4\right)$cycles (see Wöhler schematized curve, Figure 8), in both cases can be used isothermal hypothesis [15-17].

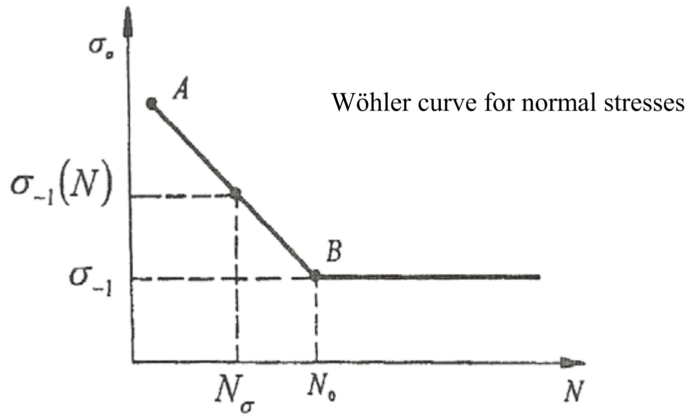


Fig. 8. Wöhler curve for normal stresses.

The loading cycles, in the case of the spherical tanks shell are un-symmetrical the un-symmetry coefficient is $R \in [0;1)$; for the pulsating cycle $R = 0$.

For the low cycle fatigue, when the maximum stress value is over the yield stress value, but under the rupture stress value, $\sigma_y < \sigma_{max} < \sigma_u$ and considering that the medium stress value $\sigma_m > 0$, one can calculate the total participation with the respect to the allowable state caused by fatigue loading with the expression [15]:

$$P_T^* = \left(\frac{N_\sigma}{N_{\sigma,al}}\right)^\chi + \left(\frac{\sigma_m}{\sigma_{m,al}}\right)^{\frac{1}{n}+1} \cdot \delta_{\sigma_m} \tag{6}$$

where $\delta_{\sigma_m} = 1$, for $\sigma_m > 0$; $N_{\sigma,al} = \frac{N_{\sigma,cr}}{c_N}$, where one can use; $c_N = 10$; for quasi static loading n=1; and

$\sigma_{m,al} = \frac{\sigma_{-1,p}}{c_\sigma}$ (for real structures with flaws); for the pulsating cycle $\sigma_a = \sigma_m = \frac{\sigma_{max}}{2}$. For a safe work, in this complex case of loading, it is necessary fulfilling the condition $P_T^* \le 1$. With $P_T^* = 1$ it is possible to calculate from (6) the safe number of cycles, N_σ.

In the case of $\sigma_{max} < \sigma_y$ it can be used the expression,

$$P_T^* = \left(\frac{\sigma_a}{\sigma_{a,al}}\right)^\alpha + \left(\frac{\sigma_m}{\sigma_{m,al}}\right)^{\frac{1}{n}+1} \cdot \delta_{\sigma_m} \tag{7}$$

or [18]

$$P_T^* = \left(\frac{\sigma_a}{\sigma_{a,al}}\right)^{\alpha+1} \cdot \left(\frac{N_\sigma}{N_0}\right)^{\frac{\alpha+1}{m}} + \left(\frac{\sigma_m}{\sigma_{m,al}}\right)^{\alpha+1} \cdot \delta_{\sigma_m}, \quad (8)$$

where $\alpha = 1/n$ depends on the rate of loading (static, rapid, shock); *m* – the exponent in the Basquin's equation; $\sigma_{m,al} = \sigma_u / c_u$ where σ_u - ultimate stress.

For $P_T^* = 1.0$, from (7) or (8) can be calculate the maximum allowable stress, the needed condition to have a safe working life for the spherical tank.

CONCLUSIONS

There were presented a sum of errors which can happen in spherical tanks fabrication and assembling and also their influence on the stress concentration factor and on the fatigue behavior. It was emphasized especially the welds errors influences, theoretically speaking, the values for the stress concentration factor were given manly from the literature. For the fatigue loading calculus here is recommended a new approach, based on critical energy concept. In the next paper will be presented the ones calculated based on the expressions here presented; it will be analyzed the influence of the construction and fabrication errors on a 1000 m^3 tank for propylene storage at 2.1 MPa.

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