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METHODS FOR DETERMINATION OF LOCAL STRESSES IN WELDED PIPE JOINTS (Review)

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For welded joints of pipelines and elements of welded structures, including tubular ones, changes of section in weld zone are typical. The local rise of stresses or their concentration appears in the places of shape change. The level of concentration often plays a decisive role in determination of stress-strain state of structure in whole, has an effect on life at cyclic loads as well as influences the process of nucleation and propagation of cracks. This paper provides a review of works dedicated to the procedures for determination of maximum local stresses acting in the zone of stress concentration caused by geometry of welded joints of pipelines and tubular structures. 49 Ref., 1 Table, 4 Figures.

Keywords: *pipeline welded joints, tubular structures, weld geometry, local stresses, stress concentration factor*

Stress concentration, caused by weld geometry, is one of the main factors determining the characteristics of fatigue resistance of welded joints [1].

The experience shows that the stress concentration shall be taken into account not only at effect of vibration load, but also at static load and impact, when there is a possibility of brittle fracture [2], that is particularly relevant for pipelines operated at low climatic temperatures, for example, under conditions of the Extreme North or transpolar regions [3, 4].

Traditionally, the maximum stresses in elastic deformation are obtained by multiplication of nominal stresses on value of theoretical stress concentration factor (SCF), which is a quantitative evaluation of stress concentration.

An approach according to which the theoretical stress concentration factor is presented as a product of two factors is very wide spread in the recent years in engineering practice. The first takes into account macrogeometry, i.e. welded assembly structure, therefore it was titled as structural SCF. The second considers presence of weld and its microgeometry. Such an approach provides sufficiently trustworthy result that was also proved by domestic researchers [5]. Presence of linear (pipes misalignment) or angular (pipe distortion) displacements of edges in the welded assembly promote additional external loads, which are considered by corresponding factors, to which first two are multiplied [6].

Stress concentration related with dimensions of reinforcement and geometry of transition zone from weld to base metal, first of all depends on relationship of a radius of this transition to thickness of base metal [7] and in our case to pipe wall thickness [8].

Investigation of SCF effect on fatigue strength is described in many works of domestic and foreign authors [9, 10] that indicates significant scientific interest in this issue, in particular, applicable to welded joints of pipelines and tubular structures [11].

Analytical, experimental and numerical methods are used as a rule for evaluation of stressed state of loaded parts and structure elements, and modern procedures are based on their combination with the maximum application of the advantages of each of them. Therefore, aim of the present review is tracing the modern tendencies and determination of priority directions of further development of procedures for calculation of the maximum local stresses in pipe welded joints.

Majority of the works, published in the recent decades, are based on application of a finite element method (FEM) for deriving the formulae a allowing determining hot spot stresses (HSS), which are the maximum local stresses. Use of the indicated approach allows determining structural SCF applying shell members at axial load as well as bending moments in various planes of investigated welded assembly. For example, in work [12] in a such a way there were determined the values of structural SCF along the whole weld length in the case of application of axial load along the branch pipe F_a, bending moment across the pipe section and branch pipe M_{IPB} and in pipe section plane M_{OPB} (Figure 1) for T-joints.

SCF values (Figure 1) satisfactorily match with the results of works provided in [12]. It should be noted that the authors [12] were limited by graphic interpretation of the results, and did not derive the equations allowing determining SCF depending on geometry parameters.

Formulae for determination of structural SCF in the joints of square and circular pipes of DT/X tubular structures were obtained in work [13] using FEM. Comparative evaluation of the SCF calculation val-

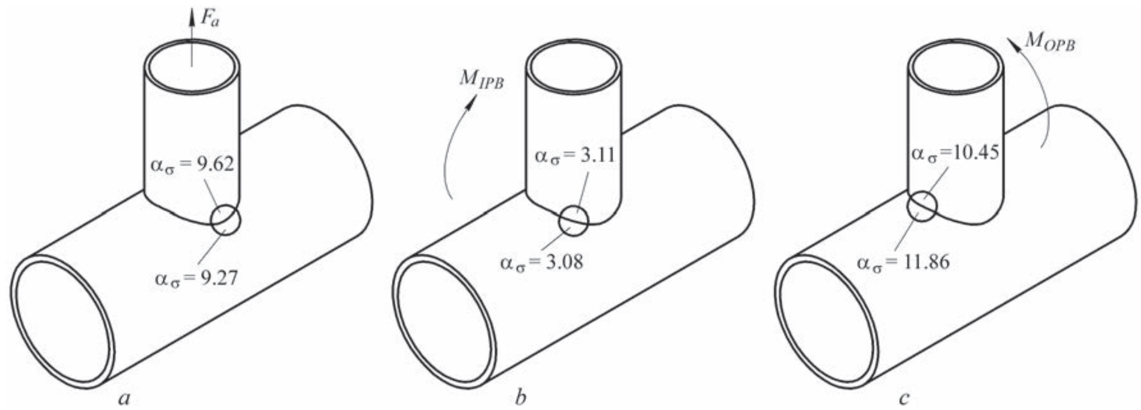

Figure 1. Maximum values of SCF on data of [12] under effect of axial force (*a*), moment across pipe section and connecting pipe (*b*) and moment in pipe section plane (*c*)

ues of indicated joints with corresponding value for similar joints of circular pipes, obtained by known at that moment formulae, was carried out. It was determined that «square–circle» joints at applied axial load and bending moment out of plane have SCF less than «circle-circle» joints. At bending moment the picture is opposite in the structure plane.

The authors of [14] analyzed using FEM around 2 thou variants of structures with different intersection angles and six schemes of loading (tension and bending in different directions and planes) for welded joints of X- and cruciform tubular structures. As a result, new parametric equations for determination of structural SCF were derived based on regression analysis. The results of calculation on obtained dependencies were compared by authors with the experimental results performed with steel and acrylic models. The coincidence was satisfactory, therefore, obtained formulae were recommended for calculation of tubular frames.

Work [15] in many respects is similar to work [14], but dedicated to K-tubular structures. They based on solution using FEM of 254 problems, corresponding to different variants of structures, and further regression analysis of obtained results, provided the dependencies for determination of structural SCF. Verification of obtained results was also carried out on steel and acrylic models.

A procedure for prediction of values of structural SCF and deflection angle of K-tubular structures was developed in work [16] by the same authors based on [15] and data base of other their works.

Authors of [17] for K-tubular structures based on a displacement method in the effective concentrator determined the local stresses considering weld geometry parameters. The authors of this work studied the stress concentration in the welded joints with fillet welds having corrected profile. Minimizing the SCF (here weld shape SCF) was reached by means of removal of defects in a transition zone from weld to base metal and providing the profile with necessary radius.

Data base of SCF was obtained in work [18] based on FEM for welded joint of XX-spatial tubular structures. Using it a simple and efficient procedure for prediction of SCF values at different types of loads was developed. The equations and diagrams recommended for engineering practice were obtained for SCF determination.

The approach used in works [12–15] is extended to T-, X- and Y-tubular structures for twelve schemes of load application in work [19].

Paper [20] specifies the values of structural SCF for welded joint of connecting pipe and spherical reservoir in a wide range of variation of their parameters (diameters and thicknesses of walls) and presented in form of tables and diagrams.

The authors used FEM and theory of thin shells under internal pressure. Both methods showed good reproducibility of the results even with consideration of reinforcement, present in the joint. Therefore, in authors' opinion, the results obtained in this work can be used for branch to cylinder shells welds.

The results of experimental investigations of fatigue life of DT-joints of pipes are presented in work [21]. The authors using TIG welding made two types of samples of steel S31803. The first type of the samples simulated tubular structure, i.e. welding of smaller diameter pipe to pipe of larger diameter. The second type of the samples presented itself the elements of pipelines, i.e. pipe with welded to it connecting pipes. In course of investigations the authors determined structural SCF for both types of the samples. Based on the results of in-situ measurements as well as by means of calculation using formulae recommended by IIW (IIW Doc. XV-E-98-236), it was determined that SCF of the samples of second type is 35 % lower than that in the first.

Paper [22] presents the method for determination of structural SCF of welded joints of pipelines based on FEM, where SCF is outlined as a main factor effecting life of girth welds. According to ASME Section II and B31 codes for pressure vessels and pipelines, respectively, their life is determined by such important index as fatigue strength degradation factor (ASME Section III) and stress intensity factor (ASME B31). Both are the analogues of efficient concentration factor and related with SCF, therefore, the problem of more accurate and reliable determination of SCF is relevant. The authors of this work outline that generally accepted approach to its determination using FEM is not effective enough for welds of pipelines due to sensitivity of the results to mesh size, and proposed method provides SCF values which do not depend on it. An important result of this work is determination of functional relationship between the fatigue strength degradation factor and SCF.

Developed and presented in work [22] approach was successfully realized by its authors in work [23] by the example of T-tubular structure working in bending in plane, the proposed method was used for HSS determination. Similar to work [21], [23] studies tubular structures as well as joints of pipelines. In order to obtain the latter the model eliminated part of the pipe corresponding to intersection. The results indicate the following, namely structural SCF acquires the highest value on the larger diameter pipe. The nature of SCF distribution along the weld is different for tubular structure and pipeline joining. In a zone of maximum SCF of pipeline joining its value is 33 % lower than that in the tubular structure. The latter result coincides with the results of work [21] obtained on full-scale specimens and using analytical dependencies.

Work [24] in many aspects is similar to [22], moreover, authors note the excessive conservatism of ASME codes, which provide oversetimated values. Authors of work [24] obtained using FEM the diagrams of dependence of structural SCF on relationship of pipe diameter D and welded to it branch of diameter d with alternating wall thickness. The data were obtained for wide range d/D = 0.05–1.0. The values of structural SCF in loading by inner pressure are within 1.8–3.5 limits.

A new method for determination of structural SCF [22] presented in 2003 was validated till 2007. In work [25] the authors successfully used their method in updating 2007 ASME Div 2 codes. Issue of new edition became possible also due to new, more accurate method of SCF determination.

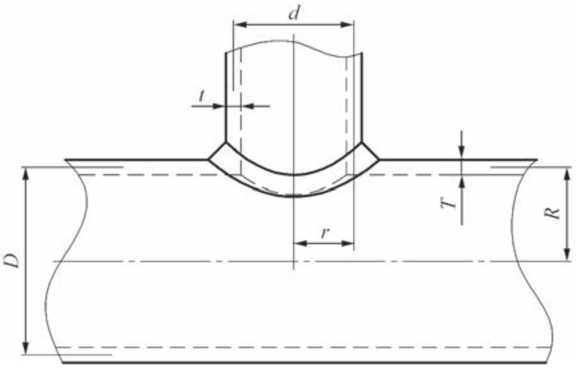

Figure 2. Parameters of T-joint of pipe and branch

Authors of [26] investigated the effect on structural SCF of local wall thinning in area of T-joint of pipe and branch (Figure 2).

The investigation was carried out in two stages. At the first stage the model was validated using known dependencies for structural SCF, which were obtained by such researchers as:

- Lind

$$\alpha_\sigma = \min\{K_1; K_2\},$$

where

$$K_1 = \frac{\left[1+1.77(d/D)\sqrt{D/T}+(d/D)^2\sqrt{s/S}\right]\left[1+(T/D)/\sqrt{s/S}\right]}{1+(d/D)^2\sqrt{s/S}/(s/S)},$$

$$K_2 = \frac{\left[1.67\sqrt{s/S}\sqrt{D/T}+0.565(d/D)\right]\left[1+(T/D)/\sqrt{s/S}\right]}{0.67\sqrt{s/S}\sqrt{D/T}+0.565(d/D)^2/(s/S)}, \quad (1)$$

$$S = d/(2t), \quad S = /(2T);$$

- Money

$$\alpha_\sigma = 2.5\left[(r/t)^2(T/R)\right]^{0.2042} \text{ for } r/R < 0.7;$$
$$\alpha_\sigma = 2.5\left[(r/t)^2(T/R)\right]^{0.24145} \text{ for } r/R > 0.7. \quad (2)$$

- Decock

$$\alpha_\sigma = \frac{\left[2+2(d/D)\sqrt{(d/D)(t/T)}+1.25(d/D)\sqrt{D/T}\right]}{1+(t/T)\sqrt{(d/D)(t/T)}}; \quad (3)$$

- Gurumurthy

$$\alpha_\sigma = 1.75(T/t)^{0.4}(d/D)^{-0.08}(\lambda)^{0.6}, \quad (4)$$

where $\lambda = d/(DT)^{0.5}$;

- Moffat

$$\begin{aligned}\alpha_\sigma = {} & [2.5 + 2.2.715(d/D) + 8.125(d/D)^2 - 6.877(d/D)^3] + \\ & + [-0.5 - 1.193(d/D) - 5.416(d/D)^2 + 5.2(d/D)^3](t/T) + \\ & + [0.078(d/D) - 0.195(d/D)^2 + 0.11(d/D)^3](D/T)^{1.2} + \\ & + [-0.043(d/D) + 0.152(d/D)^2 - 0.097(d/D)^3](t/T)(D/T)^{1.2}.\end{aligned} \quad (5)$$

The models in wide range of parameters of joint were constructed and effect of wall thinning on structural SCF was evaluated after validation. As a result it was determined that it rises with decrease of wall thickness. For relatively thin-walled pipes at $d/D < 0.2$ effect of thinning of SCF becomes not as significant up to opposite picture, when reduction of thickness can promote decrease of SCF. For relatively thick-walled pipes at $d/D > 0.3$ SCF considerably rises with thickness reduction. For joints with thinning as well as without it the maximum local stresses appear on a line of intersection of inner surfaces.

Distribution of SCF along the weld and zone of maximum SCF in the tubular welded structures have significant effect on structure life. Particularly, it is important to know the nature of SCF distribution for spatial tubular structures. Authors of [27] investigated the distribution of structural SCF for DKT-structures under effect of axial loads. Using parametric modelling and FEM the effect of structure geometry on SCF distribution along the welds was evaluated. The evaluation included also comparison of SCF values of flat structures (KT) with spatial (DKT). It is stated that structural SCF of DKT structure is 1.1–1.6 times higher than SCF of KT structure. The parametric equations were derived connecting the structural SCF with dimensions of tubular structure, correlation coefficient made 0.993–0.999. Data on distribution of SCF in T-shaped element of KT-structure are similar to the results in [12].

It should be noted that generation of reliable analytical dependencies is a relevant problem by now. An illustrative example of convenience of application of SCF formulae, similar to [27], in combination with other factors, is the papers [28, 29], which investigate the effect on structure life of residual stresses and impact treatment of welds. Very often in the literature SCF definition goes in combination with other factors determining life of welded joints.

Work [30] clearly demonstrated how a value of structural SCF effects the accumulation of fatigue damage of butt welded piles made by single weld at their piling in sea ground. Structural SCF in the considered case is related with bending due to eccentricity because of difference of thicknesses of joined pipes, and is introduced together with classification factor, depending on method of welding, i.e. presenting itself the theoretical SCF of weld shape. Increase of the latter from 1.34 to 1.52, i.e. by 13 %, results in rise of accumulated fatigue damage (that was determined on Palmgren-Miner hypothesis) by 46 %. It was determined by authors of mentioned above work in calculation way using GRLWEAP software.

In contrast to work [30], which considers only axial load in piling, the authors of [31] evaluated SCF under effect on the pile of axial load as well as bending moment (separately and together). Effect on accumulated fatigue damage was not estimated, however, a great work was carried out on determination of general SCF depending on diameter and thickness of pile wall t with the next weld parameters, namely convexity height makes 5 % of wall thickness plus 2 mm, and radius of transition from weld to base metal ρ is 1 mm. Width and height of reinforcement was determined constructively, radial displacement of pipes e was taken as fixed and made 2 mm. Obtained values were graphically presented and compared with known formulae for flat parts ($K_{dis} = 1 + 3e/t$) [32] and with specified formulae derived for pipes [33, 34]. It is determined that all results are in satisfactory agreement. Dependence of SCF on wall thickness obtained by the formulae and using FEM have similar nature. SCF has virtually no dependence on pipe diameter.

Separately it is necessary to outline the works of Inge Lotsberg. He made a great contribution in the development of methods of determination of local stresses in welded joints of pipelines and tubular structures. The peculiarity of his work is accurate analytical expressions for SCF based on classical shell theory. Thus, for example, Lotsberg formulae presented in work [35] allow determining the structural SCF depending on structure manufacturing errors. The formulae can be used for butt joints of pipes, strengthening and stiffening ribs, conical pipe crossings. His further works were directed on expansion of area of formulae application and evaluation of SCF effect on fatigue life of tubular structures [33, 36]; consideration of wider spectrum of loads, for example, under effect of internal pressure [34]; specification of empirical dependencies for SCF determination obtained by other authors [37]. The result of more than 40 years activity of the scientist became a book [38] accumulating virtually all aspects of fatigue life of tubular structures.

Expansion of field of application of the formulae for SCF determination is the typical feature for investigations of the recent years [39–43]. Works [39, 40] complement each other and are directed on investigation of the problem of SCF distribution in T-welded joints of square pipes (Figure 3).

In work [39] there were determined the zones of the largest SCF along the weld as well as its maximum values at bending moment loading in pipe plane (Figure 3, *a*). The evaluation was carried out experimentally on the pipe samples of different size (9 samples) by means of change of displacements taking into account nonlinear nature of their distribution along the hot line. It is known that the method of HSS determination allows the possibility of linear and quadratic extrapolation. The authors [39] determined that for the joints presented on Figure 3 it is necessary to use quadratic extrapolation. Particularly in this case SCF determination is more accurate, thus, it is possible to use fatigue curves, recommended by IIW. The authors note that application of formulae for SCF calculation is very convenient, therefore, derivation of such formulae they presented as the aim of their further investigations.

The same authors in work [40] have considered the similar joints under effect of axial loads where FEM was used for SCF determination. In other aspects the obtained set of data is similar to [39], the maximum SCF were obtained for the sample with the same relationship of dimensions that in [39]. It is determined that the largest SCF values are present in the joint at

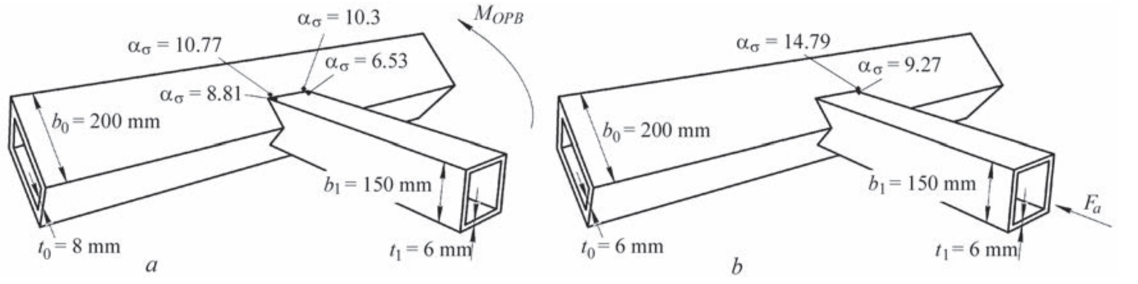

Figure 3. Maximum SCF on data of [39, 40] under effect of moment in pipe plane (*a*) and axial force along connecting pipe (*b*)

application of axial force to the smaller diameter pipe (Figure 3, *b*). Besides, the authors have compared the obtained results with SCF values of traditional T-joints (Figure 4) and circular pipes (Figure 2). The critical values of pipe size, at which the joints (Figure 3) have advantages over the rest, are provided.

The authors of [41] also researched T-joints of square pipes, in which smaller section pipe is turned to 45° relatively to position shown on Figure 3. FEM was used for the investigations, model was validated using full-scale measurements of displacements. In total four types of loads were considered, namely axial loads, applied to pipes of larger and smaller diameter, bending in the plane and out of it. The work proves the conclusion [39] that the quadratic extrapolation shall be used for of square pipe joints for HSS determination. Trustworthy formulae for determination of SFC at variants of loads mentioned above were derived based on determination of SCF using FEM on multiple models in the considered work.

Since formulae (1)–(5) for calculation of structural SCF of fillet T-welds of tubular structures (Figure 2) have comparatively low accuracy, the authors of [42] using FEM and based on solution of 1526 problems have derived simpler and more reliable formulae for determination of its value under effect of internal pressure.

The formulae for determination of SCF of K-tubular structures were derived in work [43] using FEM based on regression analysis of data obtained from multiple models. The structure considered by the authors was welded from larger pipe of circular and two smaller pipes of square sections. The formulae can be used for determination of SCF at each pipe under effect of axial loads.

Work [44] in methodological concept is related to work [26], but dedicated to estimation of effect of volumetric surface defects on life of tubing tees, including welded ones. At the first stage of investigation the author constructed the models of tees and using FEM determined the values of structural SCF. From all types of tees the maximum values were obtained for the tees with welded branch. They made $\alpha_\sigma = 4.5$ for tee with $D = 426$ mm, $T = 20$ mm, $d = 168$ mm, $t = 9$ mm. The zones of maximum concentration have become the place of further consideration of postulated defects. It should be noted that these zones matched with the zones marked by authors of [26]. A comparison of the results of SCF calculation on formulae (1)–(5) with the results obtained in [44] and experimental data is given in the Table. Numerical values of SCF agree with experimental data as well as calculation values. At that there is a difference in the results of calculations on formulae. Obviously, that formula (2) provides underestimated and formula (4) overestimated value for this dimension type of the tee.

Since most of the works considered above [6, 8, 11–31, 33–45] are limited by determination of only structural SCF using FEM, moreover, not all the researchers derive formulae for its determination, the experimental methods of SCF determination of weld shape is still relevant. Thus, authors of work [46] using polarization-optical method and models constructed by real dimensions of T- and Y-tubular structures, obtained the SCF value taking into account structural parameters and weld geometry. The constructed models consider weld shape instability and its effect on stressed state of tubular assemblies. HSS values de-

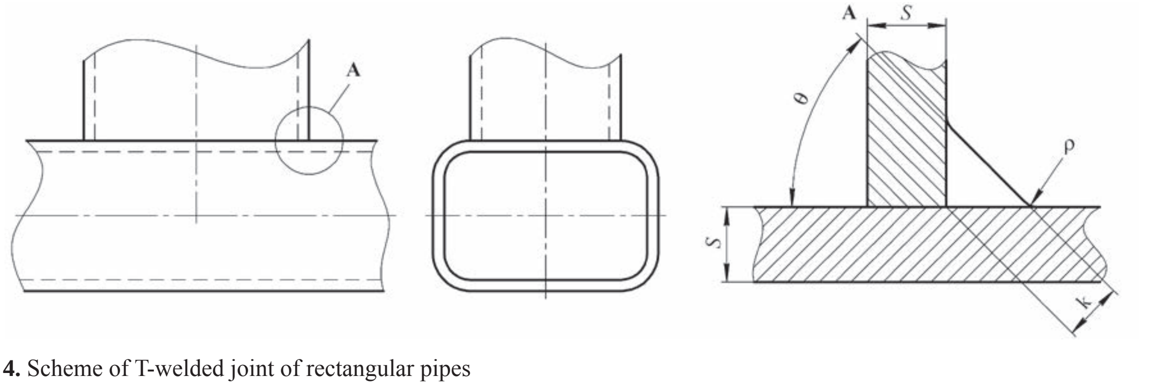

Figure 4. Scheme of T-welded joint of rectangular pipes

SCF of welded joints of tees under effect of internal pressure

Method of determination	Experimental [45]	FEM		Formula				
		[44]	[26]	(1)	(2)	(3)	(4)	(5)
Value	4.23	4.5	4.08*	4.47	3.57	4.11	6.14	4.18

*Value was obtained on data of [26] by method of interpolation of tee parameters, the closest to [44]; calculation on formulae (1)–(5) made for parameters obtained by interpolation. Experimental value corresponds to the same parameters.

termined taking into account actual geometry of weld by estimations of authors rise 2.5–3.0 times. Conclusions made in [46] indicate the need of consideration of weld geometry, otherwise it can result in formation of cracks in a weld to base metal transition zone in tubular assemblies. In work [47] the SCF values of butt welded joints of pipes were also obtained using polarization-optical method. The range of values depending on geometry parameters of weld made 1.1–1.7.

The authors of [48] in course of modeling of nonstationary processes in butt welded joint of pipeline using FEM obtained the value of theoretical SCF, which made 1.8. Thus result agrees with the results of [46] and SCF values of butt welded joints of flat parts given in reviews [9, 10].

The polarization-optical method was also used for determination of SCF of welded joints used in repair of main pipelines without interruption of product transporting [49]. SCF values depending on type of load made 1.6–3.0 for fillet and 1.2–2.0 for lap-butt welded joints.

Conclusions

1. During the last decades a significant progress was made in the problem of determination of SCF of pipelines and tubular structures. Today the procedures based on application of FEM are most wide spread for evaluation of stressed state. The procedures based on experimental methods of acquiring of local stresses and analytical methods have considerably lower amount.

2. The limitations of FEM application for calculation of SCF of pipelines and tubular structures in each separate case are related with high labor intensity in construction of accurate 3D model and its approximation by 3D finite elements. Therefore, most of the researchers tend to use parametric modeling based on shell elements and derive regression equations allowing calculation of SCF in wide range of parameters.

3. Formulae for SCF determination using FEM presented in the literature for indicated period are of private concernment. They can be used only for specific structure in a set range of parameters. The second peculiarity of existing dependencies is the fact that they allow determining only structural SCF, i.e. do not consider presence and geometry of weld. At that, the experimental investigations show that the stresses in the local zones of transition from weld to base metal noticeably rise, and elimination in calculations of weld presence can result in premature failure of welded tubular assembly.

4. In the modern engineering practice the local constituent of SCF, related with presence of weld, is recommended to calculate using the approximation formulae, however, such formulae for welded joints of pipes have not been yet derived today. Therefore, determination of a fatigue resistance characteristics of tubular welded structures is carried out using different methodological means, for example, a method of displacement in effective concentrator. It should be noted that application of fictional radius of weld to base metal transition does not allow determining the places with the maximum value of local SCF along girth or fillet weld in tubular structures and pipeline joints that plays an important role for reliable evaluation of their life.

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