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FEM-based verification of the PN-EN standard-based stress concentration factor for the drum-pipe joint of a boiler

R. Dwornicka*
Department of Mechanical Engineering, Cracow University of Technology,
Al. Jana Pawła II 37, 31-864 Kraków, Poland
* Corresponding author: E-mail address: dwornick@mech.pk.edu.pl

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Methodology of research

ABSTRACT

Purpose: The aim of this paper is to present the results of the comparative test between the PN-EN 12952-3:204/Ap1:2005 standard and FEM analysis as procedural tools for determining the stress concentration factor for the drum-pipe joint of a steam boiler.

Design/methodology/approach: Geometrical properties of the drum and the pipe are defined. In the first step the stress concentration factor is calculated using the formulas presented in the PN-EN 12952-3:204/Ap1:2005 standard. Then two grid models are defined for unweakened (the drum alone) and weakened (the drum with the pipe) elements. Next, the maximum stresses are computed by FEM analysis conducted in the ANSYS system. A quotient of the maximum stresses gives the FEM-based stress concentration factor. A whole family of factors is created with a stable quotient between element wall thicknesses. Comparative plots of the families are created for both cases: standard-based and FEM-based approaches.

Findings: There is rather a good conformity between plots derived from the PN-EN standard and from FEM analysis, with some slight differences due to the approximating character of the semi-empirical formulas presented in the PN-EN standard.

Research limitations/implications: The plot presented for the PN-EN standard has limited precision for the geometry of the individual element. The standard presents as an alternative some semi-empirical formulas which are described as 'approximating'. Ultimately, the numerical methods are more precise tools for determining the stress concentration factor.

Practical implications: The results obtained allow the maximum stresses in the cycle to be determined precisely, due to the dependency of the final value on the preceding values in the computation procedure of the stress concentration factor.

Originality/value: The calculated formulas may be significantly useful for determining the allowable cooling/heating rates of power plant devices.

Keywords: Numerical techniques; FEM analysis; Stress concentration factor

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1. Introduction

For identification of the maximum allowable cycle stress [1-6] for a pressurized container made from 15NiCuMoBn5 steel, it is necessary to determine the stress components derived from temperature and from pressure. The formula defining the stress component derived from pressure contains a stress concentration factor which is dependent on pressure α_m. The value of this factor may be read from a plot or calculated from the semi-empirical formula – both approaches are contained in the PN-EN 12952-3:204/Ap1:2005 standard [7]. In this paper, a comparison of stress concentration factor values vs. values obtained from Finite Element Method (FEM) analysis conducted in the ANSYS [8] system is presented.

2. Description of the approach

2.1. The object of investigation

A drum-pipe joint of a boiler made from 15NiCuMoNb5 steel is the object of investigation (Fig. 1).

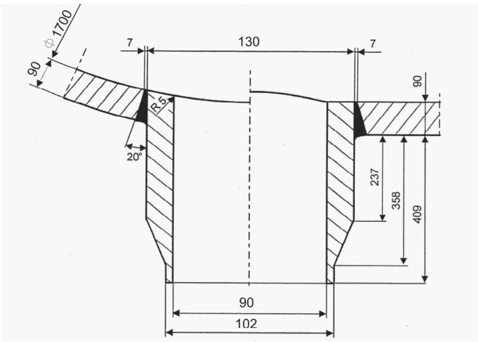

Fig. 1. The drum-pipe joint of the boiler

The geometry of this element is described as follows: external diameter of the drum d_o = 1880 [mm], internal diameter of the drum d_i = 1700 [mm], external diameter of the pipe d_{ob} = 102 [mm], internal diameter of the pipe d_{ib} = 90 [mm]. The quotient of drum wall thickness vs. pipe wall thickness is of the value:

$$\frac{e_{mb}}{e_{ms}} = 0{,}067 \tag{1}$$

where: e_{mb} – average pipe wall thickness and e_{ms} – average drum wall thickness. The maximum pressure inside the drum is of the value p_o = 4.61 [MPa]. At the start moment, the whole joint has a homogeneous temperature of the value T_o = 20 [°C].

The material of the element is 15NiCuMoNb5 steel. Its temperature-dependent properties may be read from the plot (Fig. 2) which is available in Duda [9]. For temperature of 100 [°C], they are as follows: thermal conductivity λ = 41.1 [W/m·K], thermal capacity c = 480 [J/kg·K], material density ρ = 7830 [kg/m^3], elastic modulus $E = 2.08 \cdot 10^{11}$ [Pa], Poisson's ratio ν = 0.29.

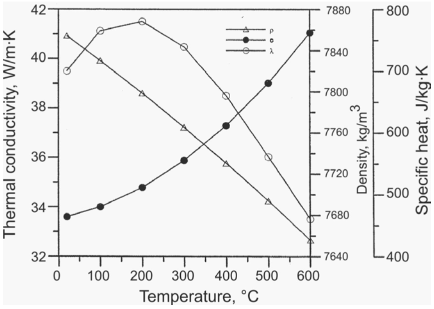

Fig. 2. Plot for determining properties of 15NiCuMoNb5 steel

2.2. Determination of standard-based stress concentration factor

For identification of the maximum allowable cycle stress [10, 11], it is necessary to determine the stress component derived from pressure. The stress $f_{tang,\,p}$ in the cylinder element derived from a pressure p is calculated [12, 13] from the formula (2) [7]:

$$f_{\mathrm{tang},p} = \alpha_m \cdot p \cdot \frac{d_{ms}}{2 \cdot e_{ms}} \quad \text{[MPa]} \tag{2}$$

where: $f_{tang,\,p}$ – stress derived from pressure, p – pressure, d_{ms} – average diameter of the element, e_{ms} – wall thickness of the element, α_m – concentration factor for stress induced by pressure in a cylinder shell with holes.

The value for the stress concentration factor α_m may be read from the plot presented in the standard [7] or calculated from the semi-empirical formulas (3, 4) also presented in the PN-EN standard [7]:

$$\alpha_m = 2{,}2 + e^A \cdot \zeta^B \tag{3}$$

where A, B, ζ – coefficients calculated from the element's geometrical properties:

$$A = -1{,}14 \cdot \left(\frac{e_{mb}}{e_{ms}}\right)^2 - 0{,}89 \cdot \left(\frac{e_{mb}}{e_{ms}}\right) + 1{,}43$$

$$B = 0{,}326 \cdot \left(\frac{e_{mb}}{e_{ms}}\right)^2 - 0{,}59 \cdot \left(\frac{e_{mb}}{e_{ms}}\right) + 1{,}08 \tag{4}$$

$$\zeta = \frac{d_{mb}}{d_{ms}} \cdot \sqrt{\frac{d_{ms}}{2 \cdot e_{ms}}}$$

where: d_{ms} – average diameter of the drum, d_{mb} – average diameter of the pipe, e_{ms} – average wall thickness of the drum, e_{mb} – average wall thickness of the pipe.

The plot (Fig. 3) of the stress concentration factor α_m for cylindrical shells, presented in the standard [7], takes only 10 curves for particular values of the drum and pipe wall thickness quotient into consideration. Values may be read from the plot with only limited precision.

The values of the α_m factor presented in Fig. 3 are related to joints welded by the TIG method, in which the weld should be mechanically processed or ground to avoid any gaps. There is no curve for the particular quotient 0.067 of drum wall thickness vs.

pipe wall thickness related to the example presented in this paper. It is necessary to calculate the stress concentration factor from the formula (3). The obtained value is $\alpha_m = 2.815$. The related maximum stress in the drum derived from pressure is calculated from the formula (2) as $f_{tang,\,p} = 45.8$ [MPa].

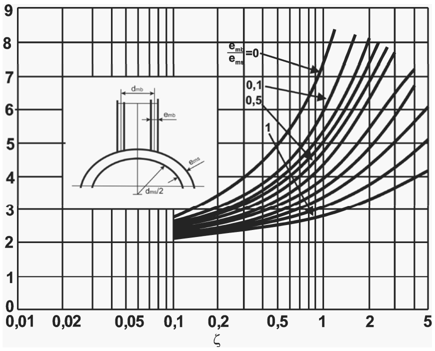

Fig. 3. Stress concentration factor for cylindrical shells [7]

2.3. Determination of FEM-based stress concentration factor

A numerical simulation [14, 15] of the thermal-pressure stress load was conducted utilizing the finite element method system ANSYS. Two FEM models were carried out: a single drum and a drum with a pipe. Due to the symmetry, a quarter of an element was modelled. In the next step, models were divided into elements describing a body (Fig. 4.)

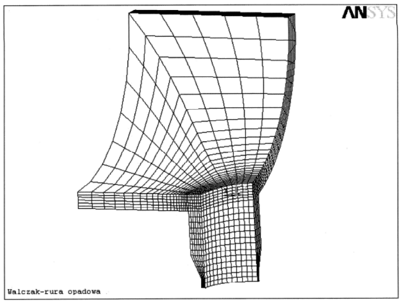

Fig. 4. A decomposition of the drum-pipe joint into elements

The FEM grid is denser in those places where maximum stresses are expected. In the remaining areas the grid may be sparser to avoid useless time consumption during processing. The immediate problem is solved with all known boundary conditions. That is, pressure on the inner surface is equal to 4.61 MPa, established pressure on the connecting pipes is calculated from the equilibrium of forces on the cross section. The element is mounted so as to prevent fixed movement of the body.

For the unweakened element (the drum), maximum stress derived from pressure was calculated at a value of $f_{tang,\,p} = 45.9$ [MPa]. These are circumferential stresses in the direction of the OX axis.

Analogically, the maximum stress derived from pressure was calculated for the weakened element (the drum with the pipe), the value of which was found to be $f_{tang,\,p} = 121.2$ [MPa]. These are circumferential stresses in the direction of the OZ axis. The stress distribution is presented in Fig. 5. It is possibility to determine the value of the stress concentration factor α_m using these two stress values obtained with ANSYS FEM models.

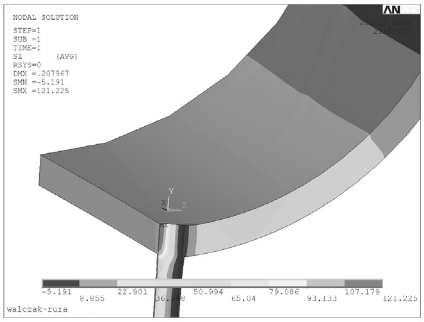

Fig. 5. Stress distribution in the weakened element

Maximum stress derived from pressure for the unweakened element (the drum) one should divide by maximum stress derived from pressure for the weakened element (the drum with the pipe). The value of the stress concentration factor derived from pressure equals: $\alpha_m = 2.64$.

3. A comparison of the stress concentration factors obtained from PN-EN standard and from FEM analysis

The stress concentration factor [16] obtained from PN-EN 12952-3:204/Ap1:2005 differs from the same factor obtained from FEM analysis conducted in the ANSYS system:

- the stress concentration factor obtained from the standard has a value of $\alpha_m = 2.81$;
- the stress concentration factor obtained from FEM analysis has a value of $\alpha_m = 2.64$.

The EU standard [1] anticipates that results obtained might be imprecise due to the simplicity of the formulas, and to achieve more precise results one must apply more complex numerical methods, e.g. FEM analysis, which gives better results due to the total discretization of the area. According to this recommendation, a comparative analysis was made for the stress concentration factors obtained: from the PN-EN standard and from FEM analysis.

The stress concentration factor was calculated from the standard-based formula (3) for three wall thickness quotients e_{mb}/e_{ms}: 0.1; 0.5; 1.0 where e_{mb} – the pipe wall thickness, e_{ms} – the drum wall thickness. For each of these, the geometrical parameters (internal and external diameters) of the drum and the pipe were varied whilst the quotient was kept constant. This allowed a dependency of the stress concentration factor to be plotted from the ζ parameter (see eq. 4).

Analogically, the ANSYS system was used to determine the stress concentration factor by FEM analysis. Computations were made for the same geometrical parameters as in the standard-based computations. The maximum stress values were determined for weakened and unweakened elements. The stress concentration factor was calculated as a quotient from these values. This allowed a dependency of the stress concentration factor to be plotted fromζ.

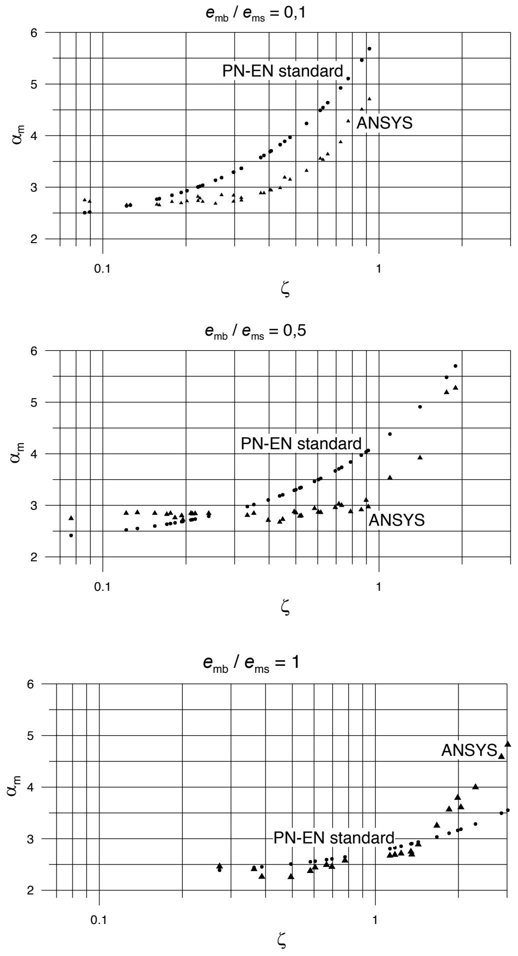

Fig. 6. Stress concentration factor obtained from the PN-EN 12952-3:204/Ap1:2005 standard and from FEM analysis

The plots obtained from the PN-EN standard and from FEM analysis are presented in Fig. 6. As it can be seen on these plots, the relations are very similar in both approaches. The small differences may be explained by the approximating character of the semi-empirical formulas included in the PN-EN standard.

FEM-based computations were performed for different grid densities and it was concluded that the results obtained were only slightly sensitive to grid density. The values obtained differed in the third digit.

4. Conclusions

This paper presents a comparison of two procedures for the determination of the stress concentration factor. The computation procedure based on the PN-EN 12952-3:204/Ap1:2005 standard was analysed. Analogically, the computation procedure based on FEM analysis conducted in the ANSYS system was also analysed. Comparative plots of the stress concentration factor were presented for different wall thickness quotients.

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