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COMPUTATIONAL DETERMINATION OF STRESS CONCENTRATION FACTORS FOR SPHERICAL AND CYLINDRICAL SHELLS WITH NOZZLES

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ABSTRACT

Calculation methods for the design or the determination of remaining service lifetime of components in conventional power plants within the European Union is based on the Pressure Equipment Directive 2014/68/EU and harmonized European standards such as EN 12952, EN 13445, EN 13480. Recent studies showed that these calculation methods contain simplifications and unnecessarily high or even no conservatisms. The results presented here refer to the geometric stress concentration factors according to EN 12952. With the help of parametrized FE models a vast amount of data points is generated which is then used to determine an improved mathematical description of geometric stress concentration factors.

INTRODUCTION

The German Federal Government has announced in its current coalition agreement that an exit from coal-fired power plants is targeted ideally for 2030 in order to achieve the climate protection goals. This requires a massive expansion of renewable energies and the construction of modern gas-fired power plants in order to cover the increasing demand for electricity and energy over the course of the next years. As a result, the demands on the existing conventional power plants in terms of their flexibility will change significantly again. In the past years, the demand on electricity could be served by a large park of power plants consisting of base, medium and peak-load power stations. These power plants are designed for a certain amount of, for instance, start-stop events or hours in full and partial load operation. With the increasing amount of solar and wind energy plants, thermal power plants, including also gas-fired plants, need to compensate for the fluctuating power input of renewables. As a result, the requirements have changed fundamentally. Each power plant should be designed for many load changes, allow fast load gradients and have a low minimum load.

Due to the changed operation conditions of conventional power plants in the course of the current energy supply concept of the German Federal Government the requirements to plant components changed considerably. Methods for design or the determination of remaining service life of components in conventional power plants are based on Pressure Equipment Directive 2014/68/EU and harmonized European standards such as EN 12952, EN 13445, EN 13480. Investigations on the design and service life assessment methods implemented in these regulations have shown that these methods are formally suitable, but have simplifications and conservatisms that unnecessarily restrict the flexible operation of critical components. Within this paper, geometrical stress concentration factors for spherical and cylindrical shells are determined by using finite element analyses and compared to formulations given in EN 12952-3.

GEOMETRIC STRESS CONCENTRATION FACTOR ACCORDING TO EN 12952

Within this section the two kinds of stress concentration factors α_{sp} for sphere-nozzle intersection and α_m for shell-nozzle intersection according to EN 12952-3 are described. In the corresponding subsections finite element modelling as well as post processing and a new mathematical formulation for the determination of geometric stress concentration factors are described respectively.

SPHERE-NOZZLE

EN 12952-3 gives four curves with wall thickness ratios from 0 to 1.0 for the determination of the stress concentration factor α_{sp} for sphere-nozzle intersections, see Figure 1. An equation for this family of curves is not given; therefore, a mathematical formulation for each curve is derived for $0.2 < \zeta < 6$ using the given diagram, see Equation (1), (2) and (3). The definition of variables is given in Figure 2. The equations obtained here are only used to compare the calculated stress concentration factors in the evaluation routine.

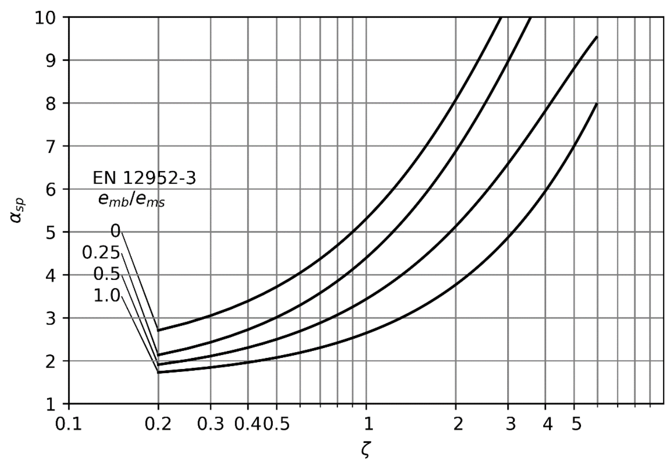

Figure 1. Family of curves for graphical determination of the stress concentration factor α_{sp} for sphere-nozzle intersection according to EN 12952-3, Figure 13.4-7a)

$$\zeta = \frac{d_{mb}}{d_{ms}} \sqrt{\frac{d_{ms}}{2e_{ms}}} \tag{1}$$

$$\varepsilon_{mr} = \frac{e_{mb}}{e_{ms}} \tag{2}$$

$$\alpha_{sp}(\zeta) = \begin{Bmatrix} -0.2639\,\zeta^2 + 3.5598\,\zeta + 2.0053 & \varepsilon_{mr} = 0 \\ -0.1924\,\zeta^2 + 3.0551\,\zeta + 1.5306 & \varepsilon_{mr} = 0.25 \\ -0.0122\,\zeta^2 + 1.1603\,\zeta + 1.4971 & \varepsilon_{mr} = 0.5 \\ -0.1171\,\zeta^2 + 2.0447\,\zeta + 1.5053 & \varepsilon_{mr} = 1.0 \end{Bmatrix} \tag{3}$$

FE Modelling

The sphere-nozzle configuration is implemented as parametrized 2D model by using the axisymmetric symmetry properties. Any chamfers or fillets are neglected in a first step, see Figure 2. Around 400 different parameter combinations for wall thickness and diameter of the sphere-nozzle intersection are calculated, see Equation (4), (5), (6) and (7). The geometry is designed as a closed model so that no further cutting force has to be taken into account apart from the internal pressure load. The models are generated with a global seed of 0.1 and a free meshing technique with quad elements of type CAX8R and evaluated using python scripts in Abaqus/CAE 2016.

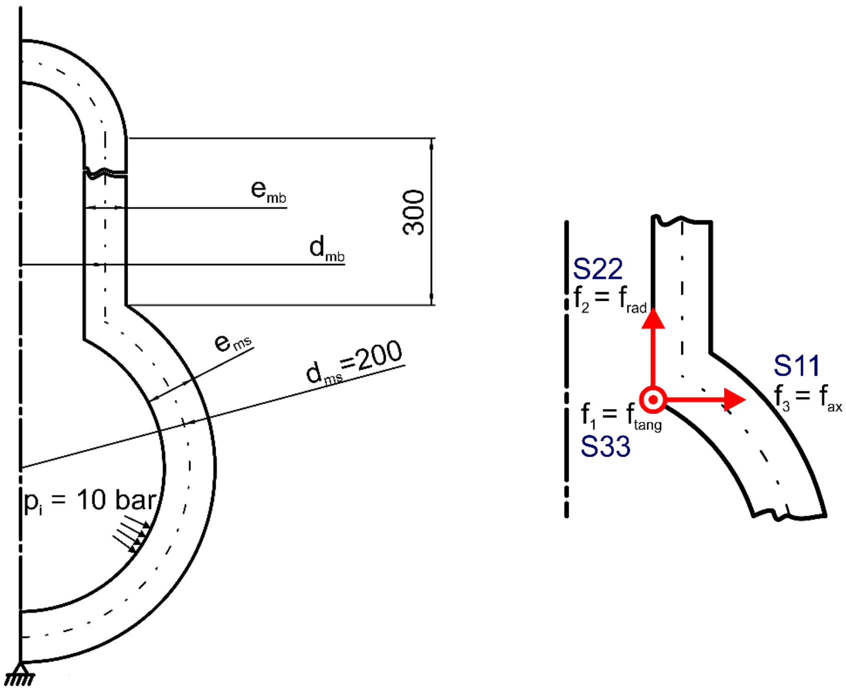

Figure 2. Schematic representation of the two-dimensional sphere-nozzle model with the geometric parameters as well as loading and the boundary conditions and definition of variables (left). Definition of the body-fixed principal stresses according to DIN EN 12952 (black) and designation of the stresses in the Abaqus/CAE coordinate system (right)

$$d_{ms} = 200\,mm \tag{4}$$
$$d_{mb} = d_{ms} \cdot \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\} \tag{5}$$
$$e_{ms} = \{2, 5, 10, 15, 20, 30, 50, 60, 70\} \tag{6}$$
$$e_{mb} = e_{ms} \cdot \{0.1, 0.25, 0.5, 0.75, 1.0\} \tag{7}$$

Post processing

The evaluation is carried out for the most stressed point on the inner edge of the intersection of the two solids. This approach is in accordance with DIN EN 12952-3. The definition of the principal stresses and their direction is shown in Figure 2. The radial stress f_{rad} and axial stress f_{ax} are assumed to be equal to the negative internal pressure whereas f_{tang} is determined by FE analysis. These assumptions are supported by the results of the finite element (FE) calculations. Each parameter combination gives a value for ζ as well as one value for the stress concentration factor α_{sp} which is calculated according to Equation (8) with p_i being the inner pressure and f_{tang} being the tangential stress at the evaluation point. The determination of ζ is based on the input parameters for each model, see Equation (1). In Figure 3, the tangential stress is plotted for parameter combination 0014. Figure 4 provides the evaluation of all stress concentration factors α_{sp} and the geometry parameter ζ as defined in EN 12952 for all calculated parameter combinations.

$$\alpha_{sp} = \frac{f_{tang}}{p_{\mathrm{i}} \frac{d_{ms}}{4\, e_{ms}}} \tag{8}$$

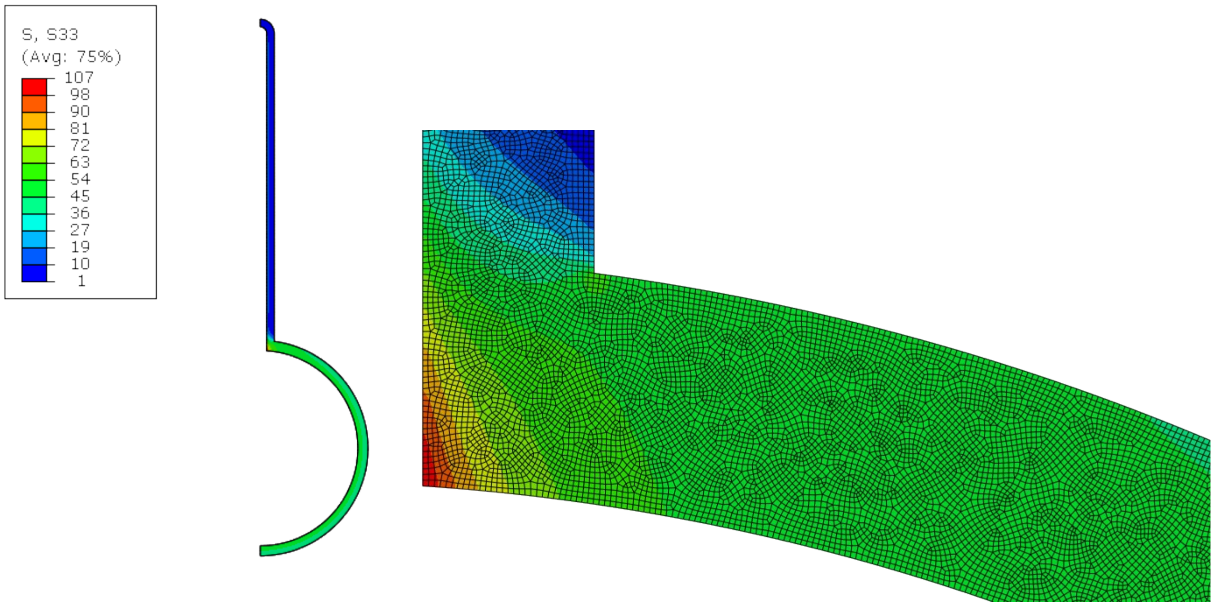

Figure 3. Representation of the tangential stress S33 or f_{tang} with mesh using for the parameter combination 0014.

Proposal of a mathematical formulation

The constant parameters in Equation (9) were calculated using a python script and a numerical optimizer. The polynomial function was expanded piece by piece by the respective parts that were required to describe the data points. The surface was shifted in order to achieve a conservative covering behavior for all data points $0{,}2 < \zeta < 6$ and $0{,}1 < \varepsilon_{mb} < 1$. A representation of all data points with the family of curves for five ratios of wall thicknesses is given in Figure 5. This figure also gives a comparison with the family of curves given by DIN EN 129520-3. It can be seen from this representation that parts of family of curves defined by EN 12952 are not conservative for the parameter combinations under consideration here. For higher values of ζ the proposed formulation of a new set of curves reduces conservativity significantly.

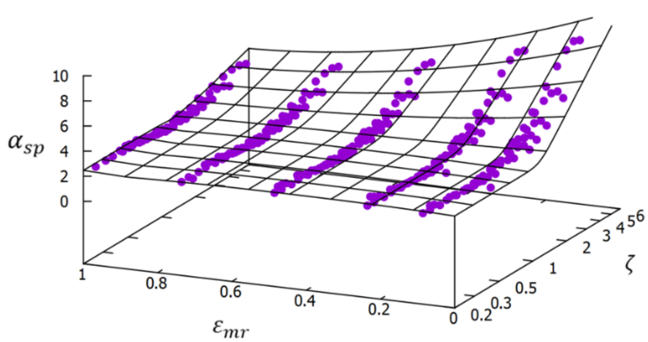

Figure 4. Data points of all parameter combinations in three-dimensional representation

$$\alpha_{sp}(\zeta, \varepsilon_{mr}) = 0.3 + \log_{10}\left(\left|261.26\,\varepsilon_{mr} - 296.86\varepsilon_{mr}{}^{2} + 19.58\,\zeta^{11.94-15.79\varepsilon_{mr}+7.31\varepsilon_{mr}{}^{2}} + 108.7\right|\right) \tag{9}$$

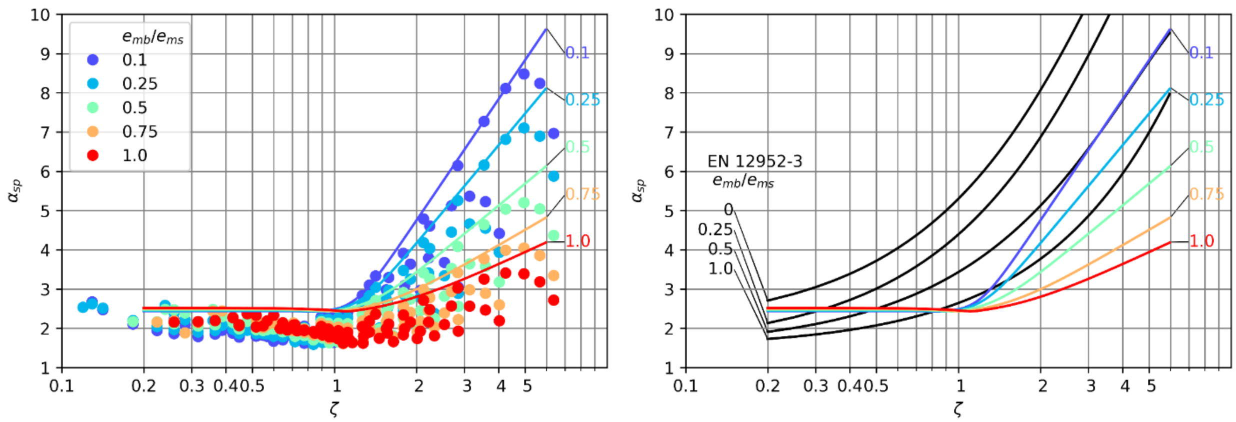

Figure 5. Data points with proposed and EN 12952 curves for the design of sphere-nozzle intersection

CYLINDRICAL SHELL-NOZZLE

DIN EN 12952-3 gives four curves for the stress concentration factor α_m for shell-nozzle intersections, see Figure 6. A mathematical formulation of this family of curves is also given, see Equation (10), (11) and (12). The definition of variables is given in Figure 7.

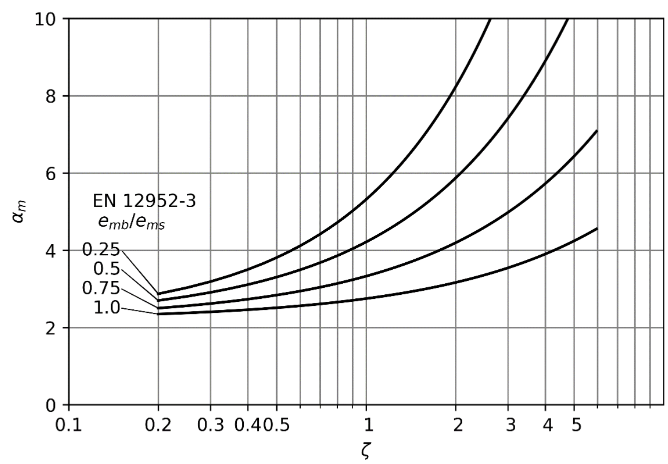

Figure 6. Family of curves for graphical determination of the stress concentration factor α_m for jacket-nozzle intersection according to EN 12952-3

$$\alpha_m(\zeta, \varepsilon_{mr}) = 2.2 + e^{A}\zeta^{B} \tag{10}$$

$$\zeta = \frac{d_{mb}}{d_{ms}}\sqrt{\frac{d_{ms}}{2e_{ms}}} \tag{11}$$

$$\begin{aligned} A &= -1.14\,(e_{mb}/2e_{ms})^2 - 0.89(e_{mb}/2e_{ms}) + 1.43 \\ B &= 0.326\,(e_{mb}/2e_{ms})^2 - 0.59(e_{mb}/2e_{ms}) + 1.08 \end{aligned} \tag{12}$$

FE Modelling

For the modelling of a pipe with a branch, a 3D model is build up and parametrized using the symmetry properties. Any chamfers or fillets are neglected in a first step, see Figure 7. Around 400 different parameter combinations for wall thickness and diameter of the sphere-nozzle intersection are calculated, see Equation (4), (5), (6) and (7). The geometry is designed as a closed model so that no further cutting forces have to be taken into account apart from the internal pressure load. The models are generated with a local seed of 0.1 close to the evaluation point and a free meshing technique with tetrahedral elements of type C3D10 and evaluated using python scripts in Abaqus/CAE 2016.

$$d_{ms} = 200\,mm \tag{13}$$

$$d_{mb} = d_{ms} \cdot \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\} \tag{14}$$

$$e_{ms} = \{2.1, 5.2, 10.5, 15.5, 20.5, 25.5, 40.5, 50.5, 60.5, 70.5\}\,mm \tag{15}$$

$$e_{mb} = e_{ms} \cdot \{0.1, 0.25, 0.5, 0.75, 1.0\} \tag{16}$$

This parameter field is restricted by some geometric and logic boundaries that have to be fulfilled. Such as the outside d_{mb}+e_{mb} and inside diameter d_{mb}-e_{mb} of the branch, that have to be smaller than the outside d_{ms}+e_{ms} and inside diameter d_{ms}-e_{ms} of the pipe or jacket. In addition, the wall thickness of the branch e_{mb} should not be bigger than that of the pipe or cylindrical shell e_{ms}. Parameter combinations that do not meet these conditions could not be examined so that these conditions are fulfilled for all models.

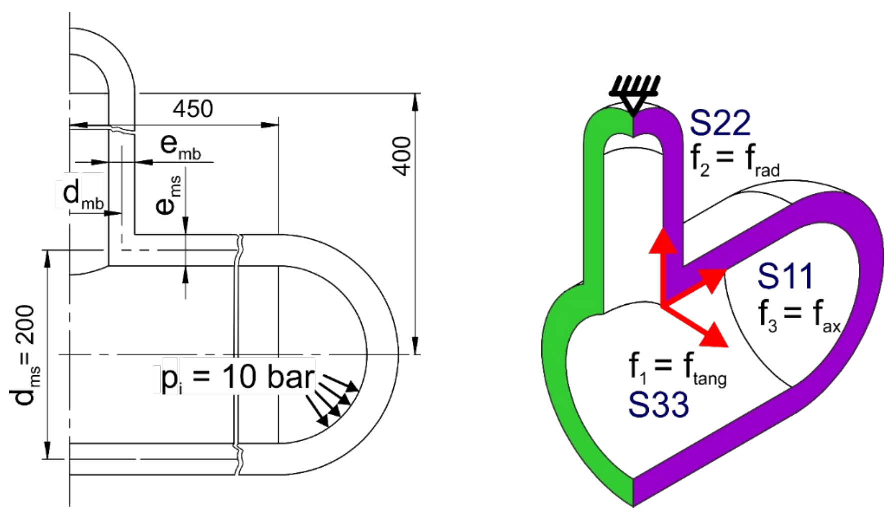

Figure 7. Schematic representation of the three-dimensional cylindrical shell-nozzle model with the geometric parameters as well as loading and the boundary conditions and definition of variables (left). Definition of the body-fixed principal stresses according to DIN EN 12952-3 (black) and designation of the stresses in the Abaqus/CAE coordinate system as well as symmetry planes (right)

Post processing

The evaluation process is equal to the evaluation process described for the sphere-nozzle intersection. In Figure 8, the tangential stress is plotted for parameter combination 0152. Figure 9 provides the evaluation of all stress concentration factors α_m, see Equation (17), and the geometry parameter ζ as defined in EN 12952-3 for all calculated parameter combinations. It appears that the wall thickness ratio ε_{mr} and the relative wall thickness δ_{mr}, see Equations (18) and (19), are helpful tools for the evaluation of this data.

$$\alpha_m = \frac{f_{tang}}{p_i \frac{d_{ms}}{2\, e_{ms}}} \tag{17}$$

$$\varepsilon_{mr} = \frac{e_{mb}}{e_{ms}} \tag{18}$$

$$\delta_{mr} = \frac{e_{ms}}{D_{ms}} \tag{19}$$

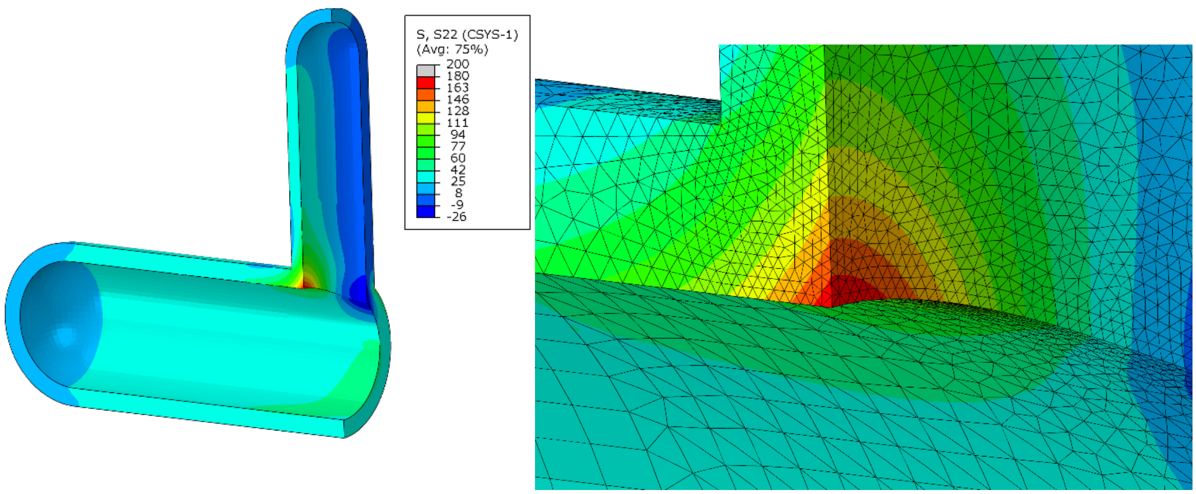

Figure 8. Representation of the tangential stress with mesh fort the parameter combination 0152 (V05).

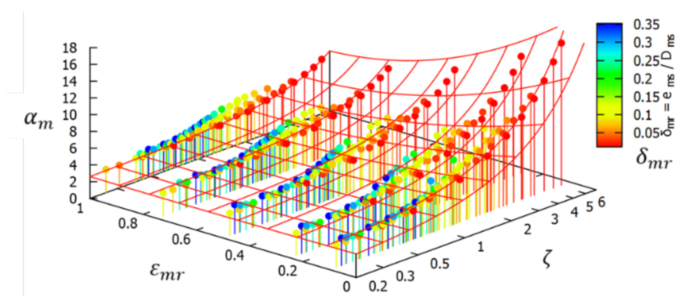

Figure 9. Evaluated data points grouped by to wall thickness ratio ε_{mr}= e_{mb}/e_{ms} and relative wall thickness δ_{mr}= e_{ms}/D_{ms}

Proposal of a mathematical formulation

A mathematical formulation is determined as described above but for this case a different polynomial function with mixed, constant, linear and quadratic components is used and 12 constants are fitted, see Equation (20). A graphical representation of the equation is shown in Figure 9 as family of surfaces and in Figure 10 as family of curves. It can be seen from these diagrams that parts of family of curves defined by EN 12952-3 are not conservative for the parameter combinations under consideration here. For a wall thickness ratio e_{mb}/e_{ms}=1 values of ζ the formulation of stress concentration factors according to EN 12952-3 seem to be not conservative. The proposed formulation of a new set of curves reduces conservativity in some areas of the parameter field.

$$\begin{aligned}\alpha_m(\zeta,\varepsilon_{mr},\delta_{mr}) \\ &= 2.42 + 2.197\,\zeta - 3.656\,\zeta\,\varepsilon_{mr} + 0.075\,\varepsilon_{mr} + 1.879\,\zeta\varepsilon_{mr}{}^2 \\ &- 3.119\,\zeta\,\delta_{mr} + 3.572\,\varepsilon_{mr}\,\delta_{mr} - 4.694\,\varepsilon_{mr}{}^2\,\delta_{mr} \\ &+ 8.276\,\zeta^2\,\delta_{mr} - 5.398\,\zeta^2\,\varepsilon_{mr}{}^2\,\delta_{mr}{}^2 - 5.544\,\zeta^2\,\varepsilon_{mr}\,\delta_{mr} \\ &+ 6.852\,\zeta\varepsilon_{mr}\,\delta_{mr}\end{aligned} \tag{20}$$

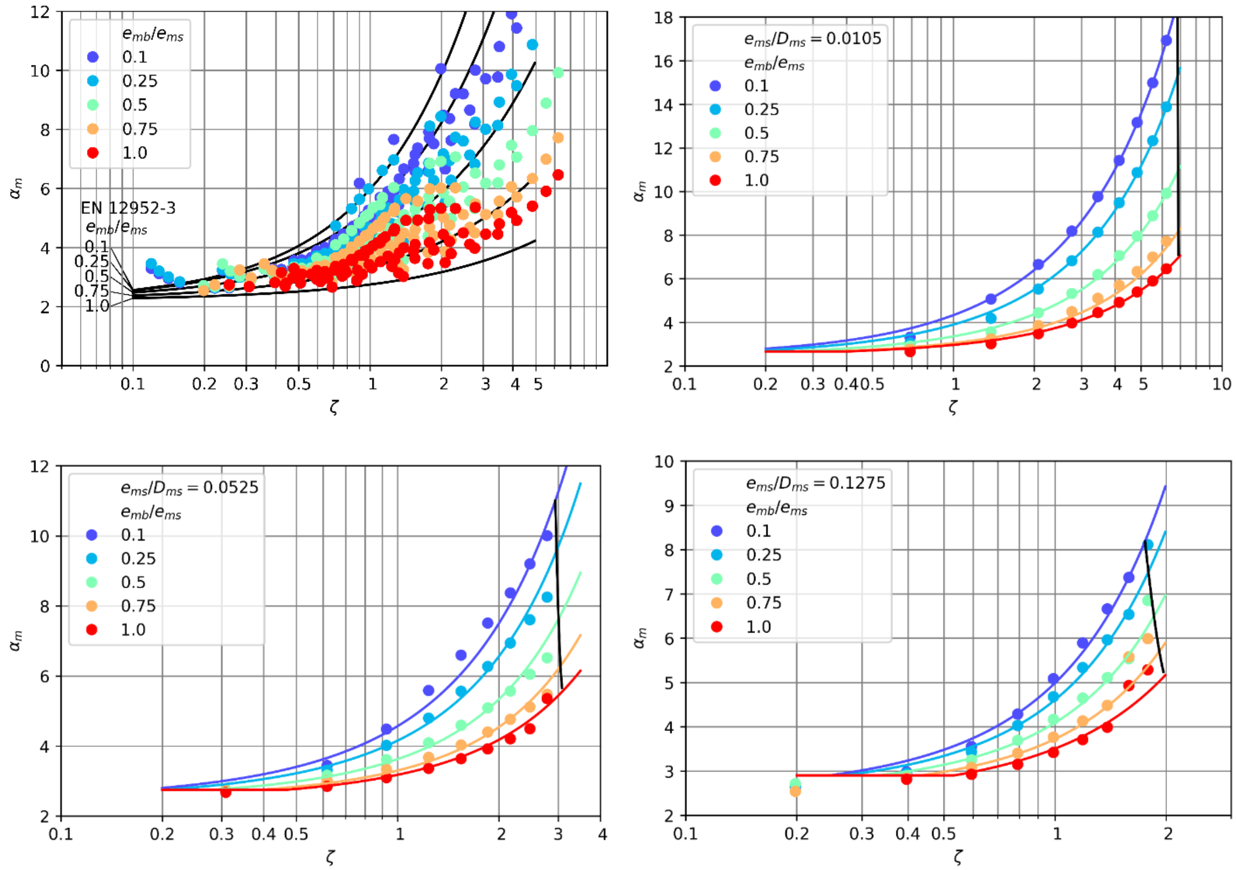

Figure 10. Evaluated data points in comparison with the old formulation according to DIN EN 12952-3 (upper left). Selection of evaluated data points grouped by wall thickness ratio and relative wall thickness with the proposed polynomial function and the geometric limit (shown in black – upper right and lower).

CONCLUSION

With the calculations carried out here, both conservative and non-conservative areas of the curves proposed in EN 12952-3 could be identified. Mathematical formulations for both, the sphere-nozzle intersection as well as the shell-nozzle were derived from the calculated parameter fields and a more precise mathematical description was developed using as little parameters as possible. Furthermore, the influence of fillets and rounds is investigated which does only show a subordinate impact on the stress concentration factors. Other influencing factors could not be identified during these investigations.

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