INFLUENCE OF CRACK-DEPTH RATIO IN A THICK-WALLED PRESSURE VESSEL ON STRESS INTENSITY FACTOR FOR DIFFERENT SUPPORT CONDITIONS

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ABSTRACT
Thick-walled pressure vessels present very demanding constructions in which cracks often occur during exploitation, the rehabilitation of which demands considerable finances. A large number of numerical simulations using the commercial software ANSYS have been carried out for this paper, with the goal of determining the influence of the crack-depth ratio on the stress intensity factor of the observed crack. The aforementioned ratio has been varied, while the crack aspect ratio has been kept constant (a/c=0.5) in all of the simulations. The cracks have been placed into the heat affected zone, i.e. in the vicinity of welded flanges, wherein two support conditions have been taken into account: complete and partial flange fixture. The results obtained through the performed analysis have been presented using diagrams.

Keywords: thick-walled pressure vessel, stress intensity factor, heat affected zone, support conditions, crack-depth ratio

1. INTRODUCTION
Thick-walled pressure vessels represent very responsible constructions in engineering practice. In many of these constructions, discontinuities in the form of cracks occur during operation, especially in the heat-affected zone near the welded console supports used to attach the structure to the base. Repairing these cracks requires significant financial resources, which is why it is worth examining whether these pressure vessels are safe for further operation despite the presence of these cracks. There are several procedures to determine this, but each of them requires determining the stress intensity factor of the corresponding crack. The investigated cracks are distributed in five zones and are present on the outer side of the thick-walled pressure vessel made of 40Mn6 steel, as schematically shown in Figure 1.

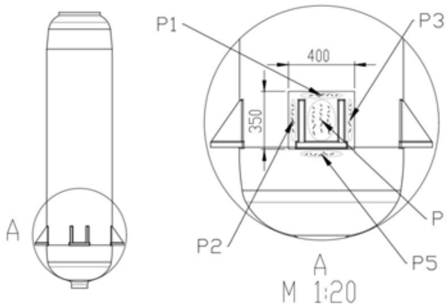


Figure 1. Crack locations and orientations

To determine the value of the stress intensity factor, the commercial software Ansys 2021 R2 was used. Numerical simulations were performed at an internal pressure of 525 bar using a semi-elliptical crack model with a constant crack aspect ratio (a/c = 0.5). The crack-depth ratio was varied, wherein the wall thickness was set at 94 mm.

Furthermore, simulations were performed for two different support conditions, namely partially and fully fixed flange, to determine the more unfavorable case. The corresponding boundary conditions for both cases are shown below.

2. BOUNDARY CONDITIONS AND NUMERICAL SIMULATIONS

2.1. Determining the less favorable support condition

To determine the more unfavorable support condition, numerical simulations were first performed without the presence of any cracks. To simulate the case of partially fixeded support, the displacement boundary condition was applied at the openings of the flange supports, with longitudinal displacements prevented while displacements in other directions were allowed, as well as fixed support at one point of the vessel at the bottom. Since simulations were performed using half of the model, symmetry with respect to the cross-sectional plane needed to be defined. A pressure of 525 bar was applied as the load. The aforementioned boundary conditions and load are shown in Figure 2.

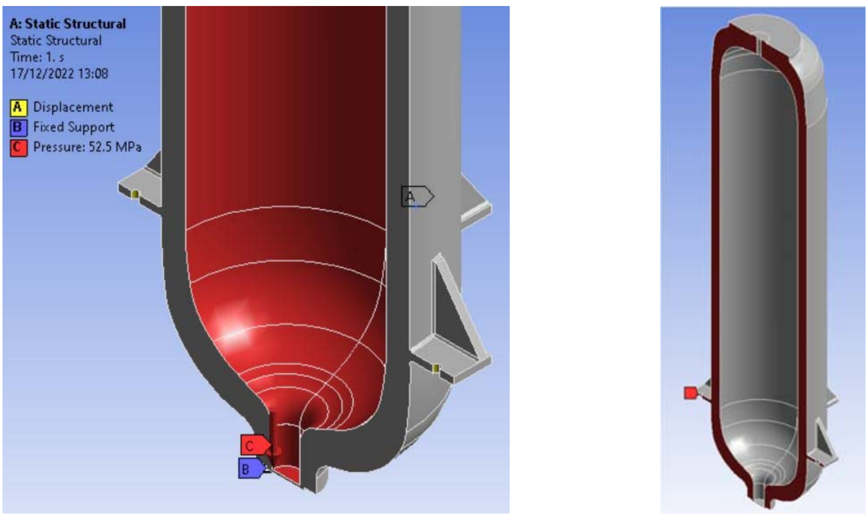


Figure 2. Boundary conditions and loading for the case of partially fixed supports

In the case of fully fixed flange, it is necessary to apply the fixed support boundary condition on all surfaces of the flange supports, and to again define symmetry with respect to the cross-sectional plane, as shown in Figure 3.

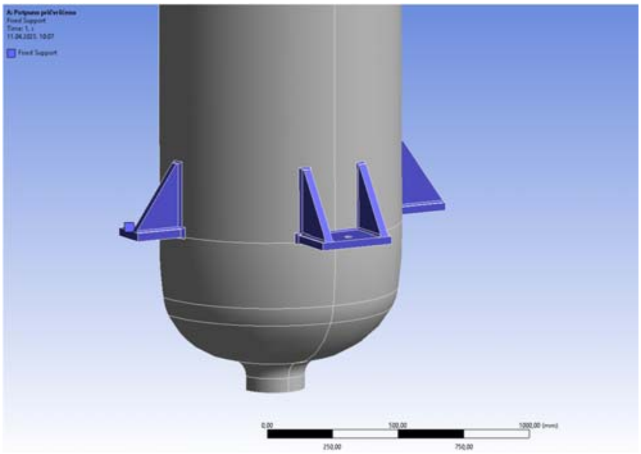
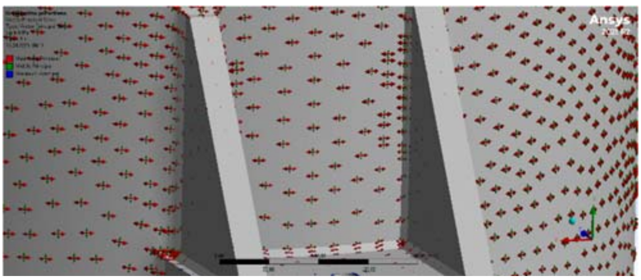
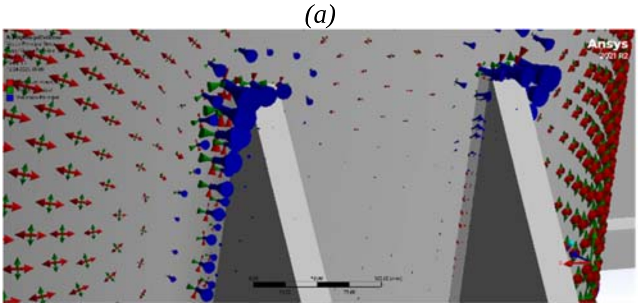


Figure 3. Boundary condition for the case of complete fixed supports

After conducting the simulations, the stress states were determined for both cases. The relevant criterion adopted is the values and orientations of the principal normal stresses, which directly lead to the formation and propagation of cracks. The directions of the principal normal stresses are graphically shown in Figure 4 for both cases.



(a)



(b)

Figure 4. Principal normal stress directions for a) partially and b) fully fixed supports

The values of principal normal stresses for both cases are shown in Table 1.

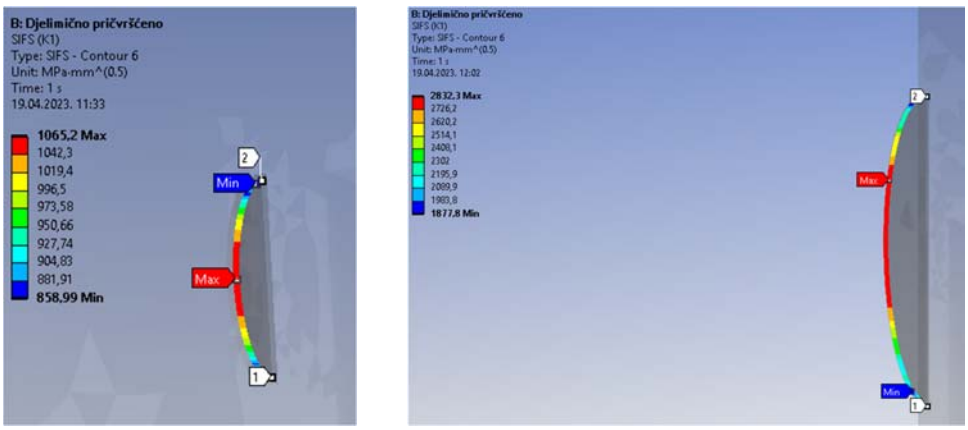
Table 1. Principal normal stress values in the critical zone

Stress	Numerical result [MPa]
Partially fixed case	
σ_1	233.21
σ_2	126.81
σ_3	12.983
Fully fixed case	
σ_1	-178.05
σ_2	-216.03
σ_3	-570.07

Where σ_1, σ_2 and σ_3 are the maximum, middle and minimum principal normal stresses, respectively. Based on Figure 4 and Table 1, it can be concluded that the case of partially fixed support is more unfavorable. Namely, in the case of fully fixed supports, there is a compressive action of the principal normal stresses, which tends to close the existing crack.

2.2. Crack introduction and result presentation

The simulations included a series of semi-elliptical cracks. The crack-depth ratio was varied and simulations were performed until the value of the stress intensity factor was obtained, which was equal to the fracture toughness of the tested material, which is 2308 $MPamm^{0.5}$. Figure 5 shows the values of the calculated stress intensity factors (hereafter referred to as SIF), at the values of a/t = 0.1 and a/t = 0.5, for the case of partially fixed supports.



(a) *(b)*

Figure 5. Display of the stress intensity factor (SIF) at a/c=0.5 for the case of partially fixed supports: a) at a/t=0.1 and b) at a/t=0.5

The simulations for the case of partially fixed supports were not carried out at values of a/t>0.5, because at a/t=0.5, the resulting value of SIF is higher than the fracture toughness of the material. In this case, a linear dependence of SIF on the ratio of a/t was established, as shown in Figure 6.

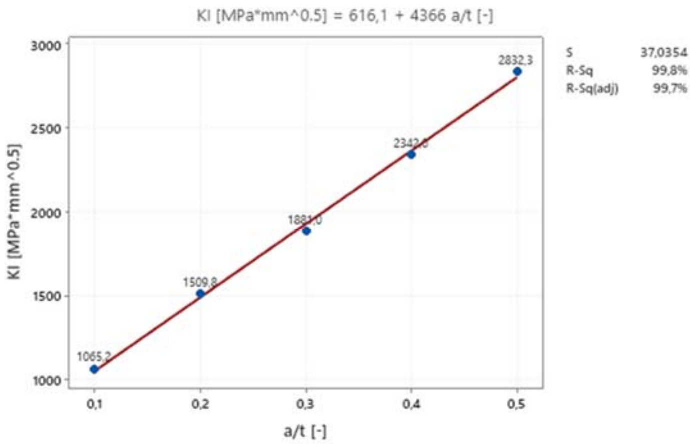


Figure 6. The dependence of the SIF on the a/t ratio for the case of partially fixed supports

For easier interpretation, a linear regression procedure was performed for this case, and the equation of the regression line was obtained:

$$K_I = 616.1 + 4366\frac{a}{t}, \quad \text{... (1)}$$

where K_I is the SIF for the first loading case [$MPamm^{0.5}$].

The obtained regression model is obviously adequate, based on the statistical parameters shown in Figure 6.

The same procedure was performed for the case of fully fixed supports. In this case, the value of a/t was varied in the range of a/t=0.1 to a/t=0.7, and for no simulation was the value of the stress intensity factor obtained at the level of the fracture toughness of the material. Further simulations for this case were not possible due to software limitations. For the case of fully fixed supports, a parabolic dependence of SIF on the a/t ratio was established, as shown in Figure 7.

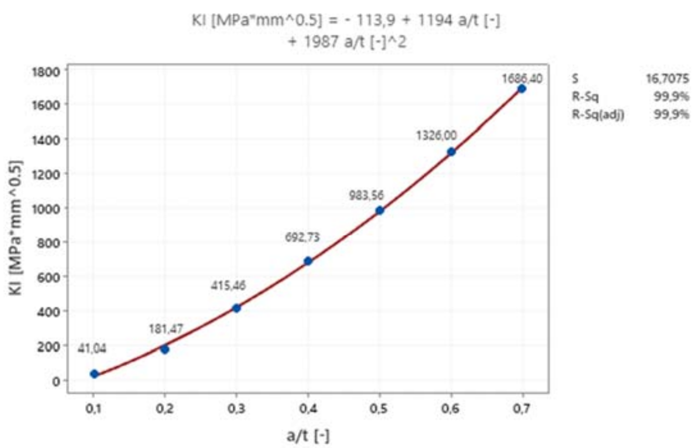


Figure 7. Dependency of SIF on the ratio of a/t for the case of fully fixed supports

As in the previous case, high adequacy of the model was established. The model equation is given by

$$K_I = -113.9 + 1194\frac{a}{t} + 1987\left(\frac{a}{t}\right)^2. \quad \text{... (2)}$$

3. CONCLUSION

The stress intensity factor is one of the key parameters in linear-elastic fracture mechanics and is essential to determine for any reliable analysis of the structural integrity of constructions with cracks. The paper has shown several important findings, primarily that:

- the value of stress intensity factor on the outer surface of thick-walled pressure vessels is highly dependent on the degree of anchorage - the case of fully anchored supports is much more favorable,
- for the case of partially anchored supports, there is a linear dependence of the stress intensity factor on the crack-depth ratio (a/t),
- for the case of fully anchored supports, there is a parabolic dependence of the stress intensity factor on the crack-depth ratio (a/t),
- it is possible to determine the value of stress intensity factor with a very high degree of accuracy in both cases by applying equations (1) and (2).

4. REFERENCES

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