PRIMJENA SINTAP ANALIZE U SLUČAJU DEBELOSTIJENE POSUDE POD TLAKOM S PUKOTINAMA U NOSIVOJ ZONI

APPLICATION OF THE SINTAP ANALYSIS IN THE CASE OF A THICK-WALLED PRESSURE VESSEL WITH CRACKS IN THE SUPPORT ZONE

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Keywords:
SINTAP, basic level, CDF, Ansys, thick-walled pressure vessel, cracks

Paper received:
09.11.2023.
Paper accepted:
25.12.2023.

Originalni naučni rad

REZIME

Mehanika loma je područje koje se sve više proučava i primjenjuje u modernoj industriji. Jedna od najprihvaćenijih metoda za ocjenu strukturalnog integriteta u ovom području je SINTAP metoda. Iako postoje brojni izvori koji govore o ovoj metodi, vrlo malo njih opisuje njezinu konkretnu primjenu. U ovom radu prikazana je primjena navedene metode, uz odgovarajuće jednadžbe, na osnovnoj razini analize. Relevantni parametri mehanike loma određeni su numerički pomoću softvera Ansys na primjeru tlačne posude debelih stijenki s pukotinama u potpornoj zoni. Analiza uzima u obzir učinke pogonskih opterećenja, kao i zaostalih naprezanja koja proizlaze iz zavarivanja.

Original scientific paper

SUMMARY

Fracture mechanics is a field that is increasingly studied and applied in modern industry. One of the most widely accepted methods for assessing structural integrity in this field is the SINTAP method. Although there are many literary sources available that discuss this method, very few of them present its concrete application. This paper presents the application of the mentioned method, along with appropriate equations, at a basic level of analysis. The relevant fracture mechanics parameters are determined numerically using Ansys software, with the example of a thick-walled pressure vessel with cracks in the support zone. The analysis takes into account the effects of operational loads, as well as residual stresses resulting from welding.

1. INTRODUCTION

From the very beginning, the field of mechanical engineering has inevitably encountered certain operational issues, including cracks in machinery and their components. Since machinery and its components are quite expensive, it is not cost-effective to procure and put entirely new machinery into operation, except in cases of absolute necessity. This has raised the question of the possibility of continued operation despite the presence of structural discontinuities, such as cracks. For this reason, a new branch of mechanics called fracture mechanics began to develop in the mid-20th century, specifically addressing this issue. One of the most recognized and widely used methods for assessing the structural integrity of various structures with structural discontinuities is the Structural Integrity Assessment Procedure method (SINTAP). While many published papers and books discuss this issue, most of them focus on the theoretical aspect and the history of the procedure without concrete application. At the same time, a large number of Computer-Aided Engineering (CAE) software programs have been developed in the past few decades, enabling the reliable assessment of relevant fracture mechanics parameters. The aim of this paper is to demonstrate the specific application of the SINTAP procedure at a basic level, using the example of a thick-walled pressure vessel with cracks in the support zone. The analysis takes into account both the effects of operational loads (due to pressure) and residual stresses (due to welding). First, the appropriate formulas for the SINTAP procedure are presented, followed by the less favorable vessel support method (the case of securing it with bolts to the supports). Afterwards, the cases of complete and partial attachment, using bolted connections, are examined. The largest existing cracks, which geometric parameters were experimentally measured to determine the appropriate stress intensity factors for crack propagation, are introduced. Finally, a Crack Driving Force (CDF) diagram is presented as the ultimate representation of the results of the structural integrity assessment of the vessel. Pressure vessels have been the subject of many studies, some of which are mentioned below.

James Newman and Ivatori Raju presented a method for determining stress intensity factors for cracks on the inner side of cylindrical pressure vessels using the finite element method in their work [1].

Researcher Kenneth Karanja Kiragu applied an energy-based method, the modified closure technique, to pressure vessels with multiple longitudinal cracks in his master's thesis [2]. The Ansys 10 software was used to determine forces at the nodes at the crack tip and displacements near the crack tip.

Petr Brož's work [3] addresses both internal and external semi-elliptical cracks and thick-walled pressure vessels. Hybrid finite elements are used in a three-dimensional stress analysis to determine stress intensity factors, and comparative calculations for pipes are provided using weight functions.

2. TECHNICAL DESCRIPTION

During earlier research as presented in [4], which pertains to thick-walled pressure vessels, a higher number of cracks on the external surfaces were observed. These vessels are made from DIN 40Mn6 material using the plastic deformation process, with a tensile strength of 592 MPa and a yield strength of 319 MPa. The fracture toughness of this material ranges from 74 to 80 MPa√m [4]. For the purpose of numerical analysis, a thick-walled pressure vessel is modeled, as shown in Figure 1. The locations and approximate positions of the cracks are depicted in Figure 3, where the zones of the cracks are labeled as P1, P2, P3, P4, and P5, respectively.

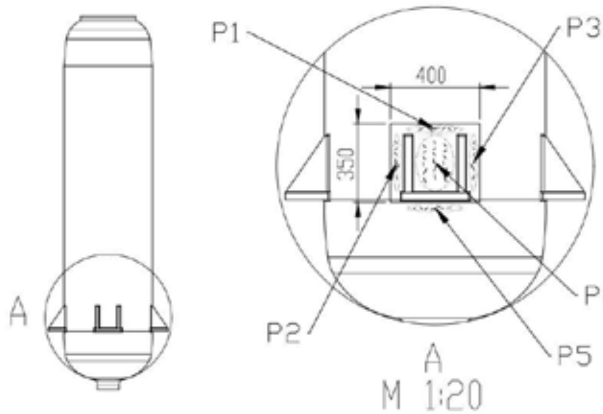


Figure 1. *Crack locations and positions relative to the bracket*

3. SINTAP – APPLIED EQUATIONS

According to the CDF methodology, the calculation of the applied parameter, such as J-integral, is performed to define the stress and strain fields around the crack tip in the observed structure. If a basic level of analysis is being applied (level 1), the J-integral is calculated using the equation [5]:

$$J = \frac{K_I^2}{E'} f\left(\frac{F}{F_Y}\right), \qquad \ldots(1)$$

where:

K_I – is the stress intensity factor at the first loading case [MPa√mm],

F – is the applied load (for pressure vessels, it's the operating pressure) [MPa],

F_Y – is the allowable load determined based on the material's yield strength [MPa],

$f\left(\frac{F}{F_Y}\right)$ – is the dimensionless function representing the ratio of applied load to allowable load [-] and

E' – is the material's modulus of elasticity E (for plane stress) or $E/(1-\nu^2)$, where ν is the Poisson's coefficient of the material [MPa].

In the literature, the ratio of applied to allowable load is often denoted as L_r, and the same notation is used in this paper. The value of the dimensionless function representing this ratio, for materials that harden continuously during deformation, is determined according to the expression [5]:

$$f(L_r) = (1 + 0.5L_r^2)^{-1/2}[0.3 + 0.7exp(-\mu L_r^6)], \qquad \ldots(2)$$

where:

$$\mu = Min[0.001(E/\sigma_Y); 0.6], \qquad \ldots(3)$$

where σ_Y is the material yield strength [MPa]. On the other hand, if $L_r > 1$, for materials with plastic behavior that can be described by a power-law, $f(L_r)$ is determined using the relation [5]:

$$f(L_r) = f(L_r = 1)L_r^{(N-1)/2N}, \qquad \ldots(4)$$

where:

$N(< 1)$ – strain hardening curve exponent, and
$f(L_r = 1)$ – value derived by applying eqaution (2) in the case of $L_r = 1$.

The criterion for assessing whether further crack propagation will occur can be represented by the expression [5]:

$$J < J_{mat}, \qquad \ldots(5)$$

where J_{mat} – is the critical value of the J-integral for a given material (determined based on the material's fracture toughness) [N/mm].

It's important to note that the analysis presented above is valid when there are no secondary stresses, such as thermal or residual stresses. The stress intensity factor in equation (1) results from the effect of only the operational stresses. In the presence of residual stresses, a new parameter, K_r, must be introduced. This factor is defined by the relation [6]:

$$K_r = \frac{VK_I^s + K_I^p}{K_{mat}}, \quad \ldots(6)$$

where V – is a multiplicative factor that takes into account the interaction between primary and secondary stresses.

After determining $f(L_r)$ and K_r, it can be concluded that further crack propagation will not occur if the following condition is met [6]:

$$K_r < f(L_r). \quad \ldots(7)$$

Furthermore, it can be concluded that plastic collapse of the structure will not occur if the following inequality holds [6]:

$$L_r < L_r^{max}, \quad \ldots(8)$$

where L_r^{max} – is the ratio of the arithmetic mean of the tensile strength and yield strength of the material to the material's yield strength [-].

In order to apply equation (6), it is necessary to be able to determine the factor that takes into account the interaction between primary and secondary stresses. The multiplicative factor V can be approximately determined using the relation [8]:

$$V = \frac{\sqrt{E'J^s}}{K_I^s}\{f(L_r) + 0.42L_r(0.72 + L_r)[f(L_r)]^2\}, \quad \ldots(9)$$

where J^s – is the value of the J parameter resulting from the effect of only secondary stresses [N/mm].

The value of the J-integral resulting from the effect of secondary stresses can be determined iteratively using numerical simulations. In this case, a finite element model was created, and its loading was equated to the direction and intensity of the principal residual stresses determined experimentally. Under such conditions, the numerical calculation of the value of J^s was performed.

As for the allowable load, the allowable pressure can be determined using the relation [7]:

$$p_{allow} = p_0\left(\frac{a/t}{\sqrt{1 + 0.34\rho\frac{a}{t} + 1.34\rho^2\frac{a}{t}}} + 1 - \frac{a}{t}\right), \quad \ldots(10)$$

where:

$$p_0 = \frac{2}{\sqrt{3}}\sigma_Y ln\frac{r_e}{r_i}, \quad \ldots(11)$$

$$\rho = \frac{c}{\sqrt{rt}}. \quad \ldots(12)$$

The following notations are used in expressions (10-12):

p_0 – the pressure with what the pressure vessel can be loaded without cracks [MPa],
a – crack depth [mm],
c – crack half length [mm],
r_e – external radius [mm],
r_i – internal radius [mm],
r – mean radius [mm],
t – wall thickness [mm],
ρ – dimensionless parameter [-].

4. STRESSES FOR DIFFERENT SUPPORT CONDITIONS

Stresses under different support conditions have been determined numerically due to the complex geometry of the toroidal part of the pressure vessel. In order to simulate the conditions present in the case of partially fastened bolts, the following boundary conditions have been introduced: displacement boundary conditions at the openings of the cantilever supports, with movement prevented along the longitudinal direction (for the model: the y-axis direction), clamping at one point at the bottom of the model, and symmetry conditions with respect to the cross-sectional plane. A test pressure of 52.5 MPa, acting on the inner surface of the vessel, was adopted as the load. These specified boundary conditions, as well as the load, are depicted in Figure 2. The simulation utilized a tetrahedral finite element mesh with element sizes of 50 mm.

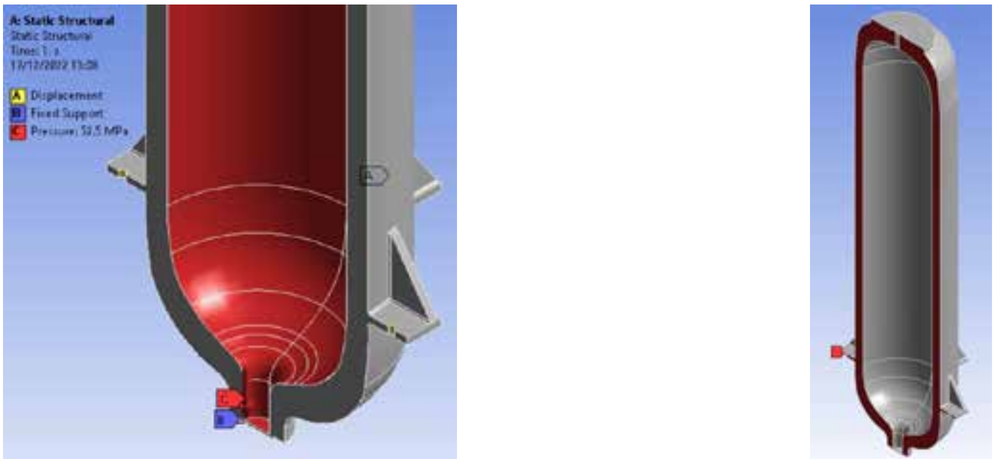


Figure 2. *Boundary conditions and loads in the case of partially fastened bolts*

Maximum principal stress in the bracket vicinity is shown in Figure 3.

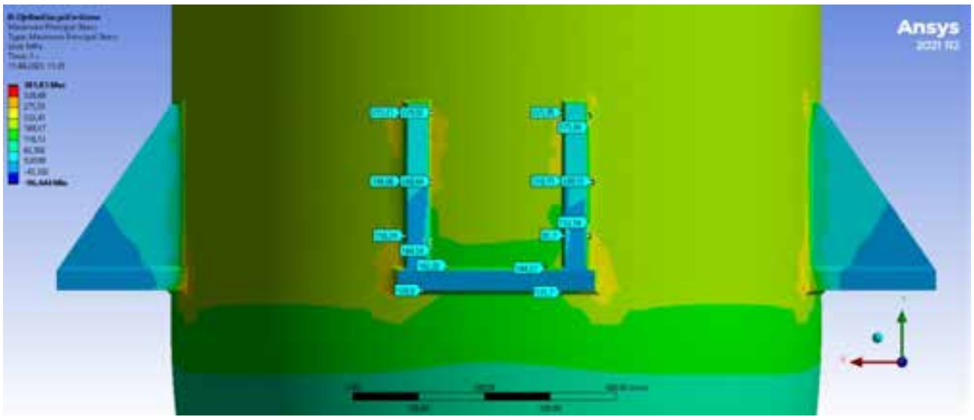


Figure 3. *Maximum principal stresses in the bracket vicinity (partially fastened bolts)*

In the case of fully fastened bolts, different boundary conditions are required compared to the case of partially fastened bolts. Specifically, it is necessary to introduce boundary conditions clamping the lower surfaces of the bracket supports (Figure 4). This is justified by the fact that in the case of fully fastened bolts, there will be frictional forces between the lower surfaces of the brackets and the upper surfaces of the supports with which they come into contact. These forces are mainly due to the bolt preload and, to a lesser extent, the weight of the vessel. The same symmetry conditions and loading are applied in this case as well (Figure 3).

In the case of solid supports, it is important to consider the stiffness of the bracket supports. The supports should be designed or reinforced as needed to have sufficient stiffness to prevent the transfer of deformations from the vessel to the bolts.

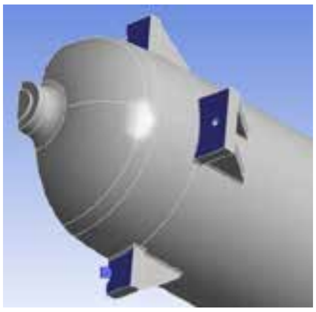


Figure 4. *Lower bracket surfaces fixed support condition*

Maximum principal stress in the bracket vicinity is shown in Figure 5.

Figure 5. *Maximum principal stresses in the bracket vicinity (fully fastened bolts)*

It is important to note that in this case, the maximum principal normal stresses are significantly lower compared to the previous case, and they exhibit compressive character in the vicinity of the lower surface of the cantilever support. The lowest value of the maximum principal normal stress (compressive) is -275 MPa, and it is observed in the area around the lower surface of the bracket. Using known formulas from elasticity theory, the corresponding principal normal stresses in the cylindrical part of the vessel have been determined. The results of numerical simulations differ significantly from analytical results for both support conditions, what was expected. A comparison of the values of maximum principal normal stresses obtained analytically and numerically is provided in Table 1.

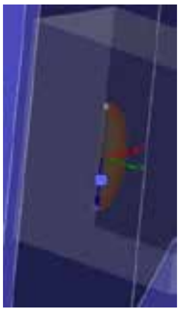
Table 1. *Results comparison (in the area around the lower surface of the bracket)*

Stress	Analytical result $[MPa]$	Numerical result $[MPa]$	Deviation [%]
Partially fastened bolts			
$\sigma_1$min	199.9	233.2	14.3
$\sigma_3$max	0	12.9	-
Fully fastened bolts			
$\sigma_1$min	199.9	-178	212.3
$\sigma_3$max	0	-570	-

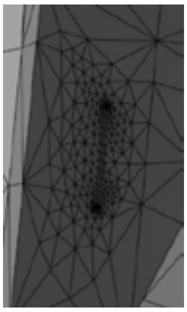
Considering the compressive effect of the principal normal stress in the case of fully fastened bolts, it can be concluded that the case of partially fastened bolts is the less favorable method of support.

5. CRACK PLACEMENT

Cracks are introduced for both support cases. Based on the orientation of the principal normal stresses, it has been determined that the most unfavorable orientation of the cracks is in the direction of the axial axis of the pressurized vessel. Before introducing the cracks themselves, it is necessary to set boundary conditions and loading on the model, as shown in the previous chapter. The option of a semi-elliptical crack has been adopted, where the small and large semi-axes of the ellipse are defined, with two large semi-axes together representing the length of the crack, and the small semi-axis its depth. To define the thickness of the crack, the option of the largest contour radius is used. The coordinate system is set up so that the x-axis is oriented towards the body and perpendicular to the body at the given point, and the z-axis is parallel to the body, as is the y-axis. The crack is located in the x-z plane. The representation of the mentioned coordinate system, as well as the defined cracks and the corresponding finite element mesh, is shown in Figure 6.



a)



b)

Figure 6. *a) Local coordinate system and semiellyptical crack and b) crack finite element mesh*

6. SIMULATIONS AND SINTAP

The CDF (Crack Driving Force) approach was used for the assessment of structural integrity as part of the SINTAP procedure. Values of experimentally determined residual stresses were considered, being both before and after the construction subjected to annealing in order to relax the residual stresses. Before annealing, the maximum residual stress was 332 MPa, while after annealing, the maximum residual stress was reduced to 182 MPa [4]. In this case, cracks were tested at the working pressure, which amounted to 35 MPa [4]. Four cracks were observed in cases of fully and partially fastened bolts, both before and after the annealing of the construction. Their geometrical parameters are shown in Table 2.

Table 2. *Assessed crack geometry*

Crack	Depth a [mm]	Half length c [mm]
I	9.4	18.8
II	18.8	37.6
III	27	50
IV	28.2	56.4

Cracks I, II, and IV were chosen, because it was determined that the majority of cracks in the construction have an a/c ratio of 0.5, whereas crack III was selected for analysis, because it is the largest crack present in the construction. By applying the expressions from Chapter 3 and the boundary conditions from Chapters 4 and 5, the corresponding results were obtained and presented in Table 3.

Table 3. *Obtained the SINTAP analysis results*

Crack	Fully fastened bolts		Partially fastened bolts		$f(L_r)[-]$
	K_r $[-]$		K_r $[-]$		
	Before thermal treatment	After thermal treatment	Before thermal treatment	After thermal treatment	
I	0.522	0.294	1.179	0.784	0.95
II	0.916	0.527	1.605	1.065	0.949
III	1.052	0.623	1.809	1.22	0.949
IV	1.077	0.647	1.867	1.269	0.949

Figure 7 shows the values of the stress intensity factors for crack I for the first loading condition, in cases of fully and partially fastened bolts.

(a) (b)

Figure 7. *Crack I SIF in the case of a) fully and b) partially fastened bolts*

The structural integrity of the vessel, considering the appropriate conditions and the presence of specific cracks, is determined based on inequality (7). For easier interpretation of the results from Table 3, they are also presented graphically in Figure 8, along with the theoretical curve from equation (2).

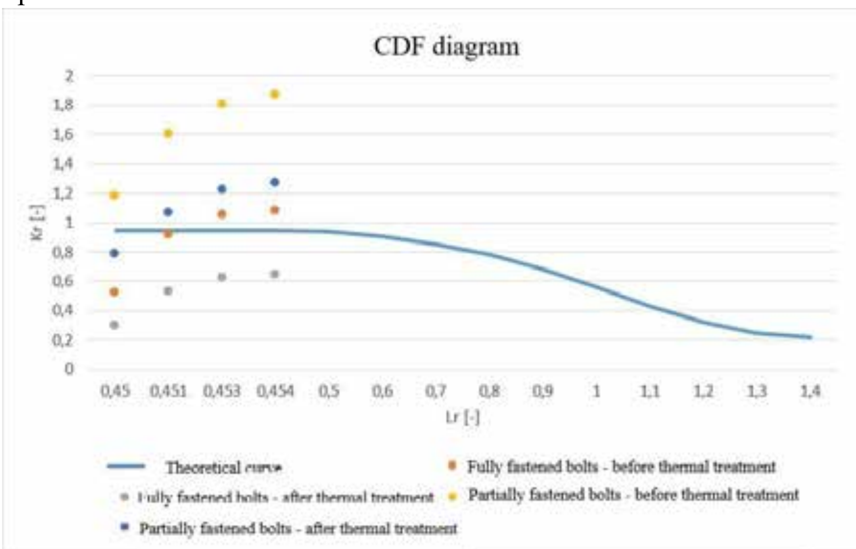


Figure 8. *Assessed cracks CDF diagram*

7. RESULT DISCUSSION

Based on equation (7), it is concluded that cracks which coordinates are within the area bounded by the theoretical curve and the coordinate axes on the graph shown above are safe in terms of structural integrity. The reverse statement is also true. Based on the graph, it can be inferred that all cracks are safe for further operation if the pressure vessel undergoes the annealing process and is fully attached to its support. If the vessel is fully attached, but does not undergo the necessary heat treatment to relax the residual stresses, conditions are created for the propagation of crack III (and crack IV, which in this case is only theoretical, since the largest crack measured in the tested vessels is crack III). Conditions become significantly unfavorable in the case of partially fastened bolts. Specifically, even if the annealing process is carried out, only crack I will not compromise the structural integrity of the construction. If residual stress relaxation is not performed in the case of partially fastened bolts, conditions are created for the further propagation of all the examined cracks, leading to the conclusion that the most unfavorable case is partially fastened bolts without stress relaxation.

These results are expected because the measured values of residual stresses before annealing were higher than the yield strength of the pressure vessel material. The superposition of residual stresses on working stresses under these conditions inevitably leads to structural failure. It is worth noting that this study applied a level 1 SINTAP analysis, which is one of the most conservative approaches. It is potentially possible to arrive at more accurate conclusions by using higher levels of analysis, which were not utilized in this study because the necessary input data for a higher-level analysis were not available.

8. CONCLUSION

The paper presents the application of SINTAP analysis in determining the structural integrity of pressure vessels with observed discontinuities in the form of cracks. A combination of analytical and numerical methods, as well as experimental methods, was used. Through appropriate numerical simulations, it was found that the less favorable way of supporting a thick-walled pressure vessel with compromised integrity is in the case of partially fastened bolts (free radial deformation). Firmly fastened bolts, with bracket supports of sufficient rigidity, can have a favorable impact on the operational properties of the vessel in the case of compromised integrity. This method of support with deformation limitation can temporarily prevent uncontrolled crack growth and create enough space to undertake activities to restore the vessel's integrity, such as adequate repair or replacement.

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