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DETERMINATION OF THE CRITICAL PRESSURE FOR A HOT-WATER PIPE WITH A CORROSION DEFECT

DOLOČITEV KRITIČNEGA PRITISKA V VROČEVODNI CEVI S KOROZIJSKO POŠKODBO

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This paper deals with a determination of the critical pressure, i.e., the allowable operating pressure, of a corroded pipeline. This allowable pressure, as well as the safe-working pressure, are determined by using the analytic expressions given in the DNV-RP-F101 procedure for corroded pipelines. The failure pressure was calculated numerically using the finite-element method (FEM) with assumption of linear-elastic and ideal-plastic behaviour of the pipe material.

Key words: corroded hot-water pipe, defect, DNV-RP-F101 procedure, allowable pressure, FEM analysis

V delu obravnavamo določitev kritičnega dovoljenega delovnega pritiska v korodirani cevi. Dovoljeni pritisk in varen obratovalni pritisk sta bila določena z uporabo analitičnih izrazov v DNV-RP-F101-proceduri za korodirane cevovode. Raztržni pritisk je bil izračunan numerično po metodi končnih elementov (FEM) s predpostavko o linearnem elastičnem in idealnem plastičnem vedenju materiala cevi.

Ključne besede: korodirana vročevodna cev, poškodba, DNV-RP-F101-procedura, dovoljeni pritisk, FEM-analiza

1 INTRODUCTION

Cylindrical shells under pressure are extensively used in various industrial structures including pipelines for oil, gas and hot-water transport. Since such usage usually requires underground exploitation for a longer period of time, such pipelines are subjected to damage [1] under external environmental conditions (primarily corrosion) as well as under mechanical factors (including loadings of structure). Such damage can lead to initiation and growth of the surface crack and finally lead to failure of structure [2]. Therefor, a need for investigation of influence of structural damage of cylindrical shells is present. Various studies have been done dealing with this problematic, including recent ones [3-6], using analytical and numerical approach to investigate effect of wall thinning, crack initiation and growth in pipes under internal pressure. Because of the importance of described problematic, this paper also deals with investigation of corrosion effects on pressurized cylindrical shell which is part of one pipeline of the hot water system.

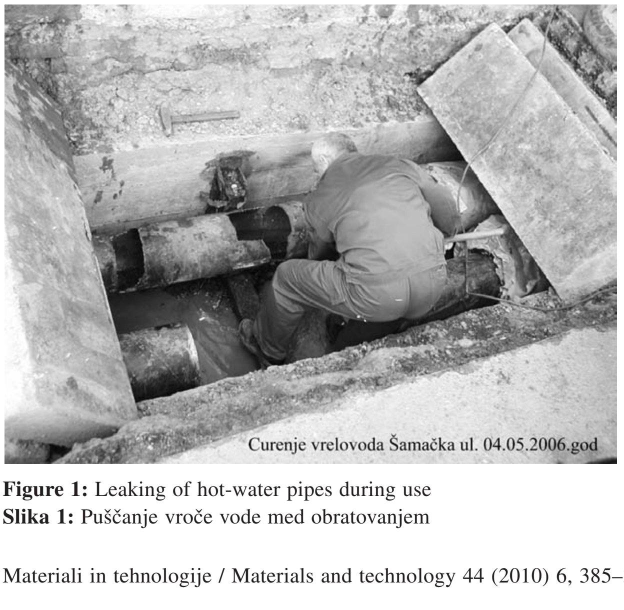

Figure 1: Leaking of hot-water pipes during use
Slika 1: Puščanje vroče vode med obratovanjem

2 CORROSION DEFECT OF HOT-WATER PIPES

The corrosion defects in hot-water pipes of the city system for hot-water distribution in Osijek, Croatia were analysed. Since the material of pipes in system is usually a high-quality unalloyed steel, which is not suitable for heat treatment, it can be affected by corrosion during exploitation. The corrosion mass-loss decreases the cross-section of the pipe at the point of damage. To quantify the effect of wall thinning due to high corrosion effect and to avoid eventual pipe failure (leaking of the pipe shown on **Figure 1**), a maximum allowable operating pressure of the pipe had to be determined.

The pressures in the hot-water pipes of the hot-water system in the city of Osijek are from 0.8 bar to 13 bar (in normal exploitation), and in the temperature range is 70–140 °C. All the fittings and pipes are made for normal pressure NP 16 (16 bar).

In this investigation, a control calculation for the pipeline (with NO 250 opening) with wall thickness 5 mm and with the measured geometry of corrosion

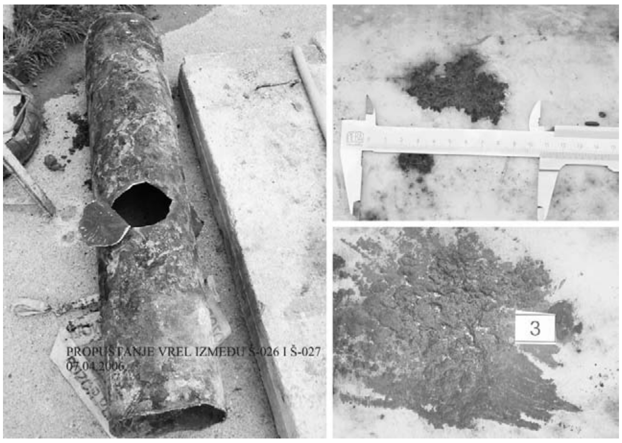

Figure 2: Determining the geometry of hot-water-pipe defects
Slika 2: Določitev geometrije poškodb vročevodne cevi

defects found during exploitation of the hot water system of Osijek is done. The Det Norske Veritas DNV-RP-F101 procedure (for corroded pipes [7]) was used for making analytic calculations and the defects were modelled numerically with the finite element method (FEM) [8]. The values of allowable pressure according to both procedures were determined and compared for different defect geometries.

Several kilometres of pipelines (of different dimensions from NO40 to NO350) were repaired this year and it was possible to determine and measure in-situ the real damage of pipes. The pipe with a characteristic defect, as well as the detail of defect size determination, is shown in **Figure 2**.

3 ANALYTICAL DETERMINATION OF THE ALLOWABLE PRESSURE OF A CORRODED PIPELINE ACCORDING TO THE DNV-RP-F101 PROCEDURE

Det Norske Veritas recommended the procedure for calculating the critical value of the pipeline pressure with determined defects in the document DNV-RP-F101 [7,9]. There are also some limitations during the application:

- carbon steel has to be used for making pipes,
- cyclic loadings and defects (e.g., cracks) are not considered,
- corrosion and mechanical defects are not combined,
- it is presumed that there are no defects in the pipe welds,
- it can be applied only up to the depth of the defect, and not greater than 85 % of the wall thickness.

It is also assumed that modern steels for pipes have an adequate toughness and it can be expected that the so-called **plastic collapse** of the pipes will occur. This collapse occurs when the equivalent stresses exceed the yield point through the whole remaining ligament in front of the defect (when looking through the thickness of the pipe).

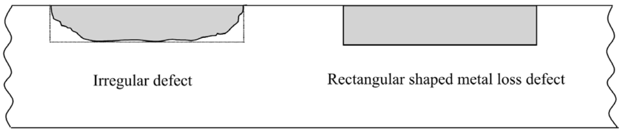

Figure 3: Illustration of irregular and rectangular defects
Slika 3: Oblika neenakomerne in pravokotne poškodbe

The analysis in this paper is limited to the assumption of a single defect and interacting defects are not considered. The calculation was performed for the presence of an outer, longitudinal corrosion defect and the pipe was loaded with an internal pressure. The superimposing of the effects of more close defects, the axial forces and the bending or temperature were not considered. The influence of an error in the radial direction was also not considered. It is assumed that the dimension of the defect in the radial direction is smaller than in the axial one. For calculation purposes, the irregular shape of the corrosion defect is idealised to rectangular (**Figure 3**).

Two approaches are possible for assessing the integrity of the corroded pipes and the main difference is based on a different safety philosophy. The first approach is probabilistic and it includes the safety factors that consider possible deviations of mechanical properties of the material and changes in wall thickness, i.e., the internal pressure. In this way, the measurement uncertainty of the defect dimensions and the material property specification are included in the determination of the allowable operating pressure. The second approach is based on the ASD (allowable stress design) format. The allowable pressure (capacity) of the pipeline with the corrosion defect is calculated, and this failure pressure is divided by a safety factor based on the original design factor. When assessing the corrosion defects, due consideration should be given to the measurement uncertainty of the defect dimensions and the pipeline geometry. These uncertainties are not included in the second approach, and are left to the user to consider and account for in the assessment.

3.1 Determination of the allowable operating pressure of a corroded pipeline

The maximum allowable operating pressure for a pipeline with a corrosion defect (metal loss) with an internal pressure is given by the acceptance equation:

$$p_{\mathrm{corr}} = \gamma_{\mathrm{m}} \cdot \frac{2 \cdot t \cdot f_u}{(D-t)} \cdot \frac{\left(1-\gamma_{\mathrm{d}} \cdot \left(\frac{d}{t}\right)^{*}\right)}{\left(1-\frac{\gamma_{\mathrm{d}} \cdot \left(\frac{d}{t}\right)^{*}}{Q}\right)} \tag{1}$$

where:

γ_m Partial safety factor for the longitudinal corrosion-model prediction,
t Uncorroded, measured, pipe-wall thickness, in mm,
f_u Tensile strength to be used in the design, in N/mm^2,
D Nominal outside diameter, in mm,
γ_d Partial safety factor for the corrosion depth,
Q Length correction factor, in mm.

It is important to point out that the partial safety factors γ_m and γ_d, as well as the ratio $(d/t)^*$ depend on the applied method of inspection, i.e., the accuracy of the measured defect depth. In this case, the safety factor γ_m was determined for the low class of measuring safety as γ_m = 0,79. Furthermore, the measured $(d/t)^*$ ratio is defined as:

$$\left(\frac{d}{t}\right)^{*}=\left(\frac{d}{t}\right)_{\text{meas}}+\varepsilon_{\text{d}}\cdot \mathrm{StD}\left[\frac{d}{t}\right] \tag{2}$$

where:
$(d/t)_{\text{meas}}$ Measured (relative) defect depth,
ε_d Factor for defining a fractile value for the corrosion depth
StD$[d/t]$ Standard deviation of the measured (d/t) ratio.

In this paper, it is assumed (with the permission of [7]), that $\varepsilon_d = 2$, i.e., StD$[d/t] = 0.16$ with $\gamma_d = 1.2$. The length-correction factor is defined as:

$$Q=\sqrt{1+0.31\cdot\left(\frac{1}{\sqrt{D\cdot t}}\right)^{2}} \tag{3}$$

The pipe material was unalloyed carbon steel St. 37.0 (according to DIN 1629) with less than 0.16 % C, with a yield point R_e^H = 235 MPa, i.e., tensile strength R_m = 360–440 MPa and elongation A_5 = 25 %. The lower value of tensile strength, i.e., f_u = 360 MPa, was considered in the calculation.

The outside diameter of the pipe is D = 273 mm and the pipe-wall thickness is t = 5 mm. The ratio of the corrosion defect depth d and the pipe-wall thickness t is as follows: d/t = (0.1, 0.2, 0.3, 0.4 and 0.5). The defect length l was also changed by the introduction of the geometry factor k:

$$k=\frac{1}{\sqrt{D\cdot t}} \tag{4}$$

where k = (0.2, 0.4, 1.0, 1.84 and 2), which corresponds to a defect length l = (7.4, 14.8, 36.9, 68 and 73.9) mm. The allowable pressure, which considers the measurement uncertainty, was calculated and the results are given in **Figure 4**.

The allowable operating pressure p_{corr} = 5.66 MPa for the measured defect geometry on the pipes (t = 1.5 mm and l = 68 mm) is shown in **Figure 4**. It is obvious from these results that the allowable pressure is almost constant for the smaller defect lengths ($l \le 10$ mm) and the defect depths up to 1/3 of the pipe-wall thickness ($d \le 1/3\ t$).

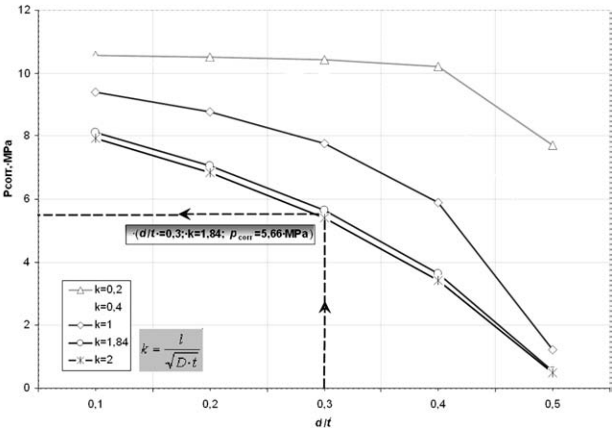

Figure 4: The allowable operating pressure of the corroded pipeline
Slika 4: Dovoljen delovni pritisk korodiranega cevovoda

As a comparison, the allowable operating pressure for the same geometry is determined acording ASME code [10] for vessels under internal pressure with expression (5) giving maximum allowable pressure of 6.03 bar.

$$P=\frac{SEt}{R+0.6t} \tag{5}$$

where:
R Inner radius of pipe, in mm,
S Allowable stress, in MPa,
E Material and pipe construction quality factor.

3.2 Determination of the failure pressure of the corroded pipeline

The failure pressure of the corroded pipe with a single defect can be calculated from:

$$P_{\text{f}}=\frac{2\cdot t\cdot f_{\text{u}}}{(D-t)}\cdot\frac{\left(1-\dfrac{d}{t}\right)}{\left(1-\dfrac{d}{t\cdot Q}\right)} \tag{6}$$

with the equation elements the same as for equations (1) and (3). The pressure where the failure of pipeline occurs are shown as a diagram (**Figure 5**). By comparing the pressure of the leaking for the measured defect (d = 1.5 mm and l = 68 mm) with the results for the allowable pressure acquired by the probabilistic approach, it should be noted that these pressure values are two times higher.

Since we are dealing with the pressures where the failure occurs, we must multiply them by certain safety factors in order to have a safe working pressure. The value acquired from (6) must be multiplied by the modelling factor F_1 and the operational usage factor F_2:

$$P_{\text{sw}}=F_1\cdot F_2\cdot P_{\text{f}} \tag{7}$$

According to [7], the following safety factors were taken:

$F_1 = 0.9$

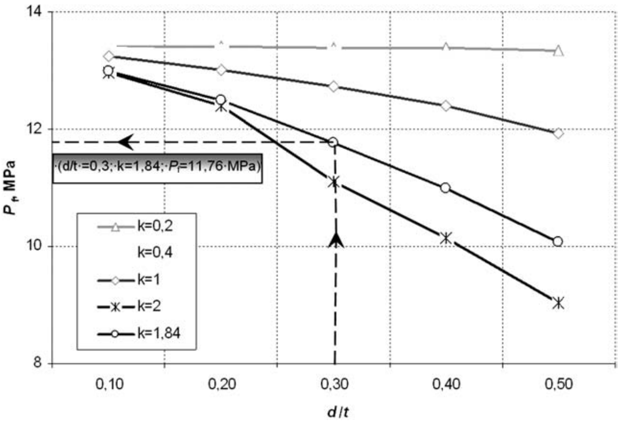

Figure 5: The failure pressure of the corroded pipeline
Slika 5: Raztržni pritisk korodiranega cevovoda

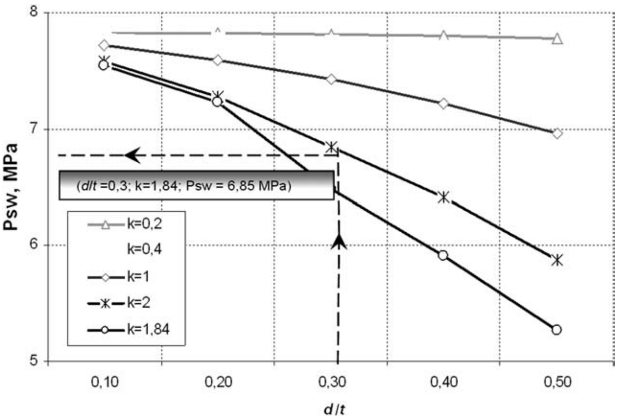

Figure 6: The safe working pressure of the corroded pipeline
Slika 6: Varen obratovalni pritisk korodiranega cevovoda

$F_2 = 0.72$
so that $P_{sw} = 0.9 \cdot 0.72 \cdot P_f = 0.648 \cdot P_f$, i.e., approximately 65 %, i.e., the same as when the failure pressure is divided by the safety factor of 1.54. **Figure 6** shows the pressure that allows safe operation of the pipeline, even with corrosion damage present.

The safe working pressure of the pipeline, calculated in this way, is higher than the one acquired with the probabilistic approach. Therefore, the calculation using the finite-element method was also made.

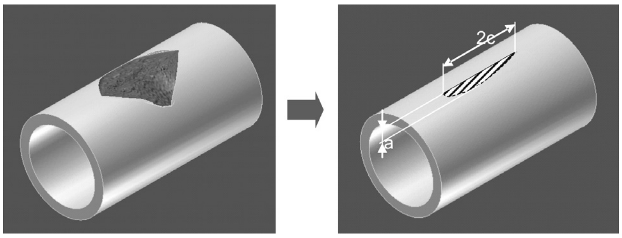

Figure 7: Idealization of irregular corrosion defect with a semi-elliptic crack
Slika 7: FEM model cevi s semieliptično razpoko kot korozijsko poškodbo

4 NUMERICAL DETERMINATION OF THE FAILURE PRESSURE OF THE CORRODED PIPELINE

The measured geometry of the pipe (defect length = 68 mm, defect depth = 1.5 mm) was used for numeric modelling of the corrosion defect. Corrosion defect are irregular, therefore to investigate such defects using finite element method a crack shape idealization is required. It is important that crack idealization is done in such a manner that it yields to conservative results e.g., idealized crack has to be more dangerous than the real one. Since longitudinal cracks in cylindrical shells are more dangerous than circumferential cracks, the corrosion defect is idealized as a longitudinal semi-elliptic crack (**Figure 7**). Length of semi-elliptic crack is determined from maximum longitudinal length of corrosion damage and depth of crack corresponded to measured depth of damage. Due to the present symmetry, only ¼ of the pipe was modelled with the finite elements (**Figure 8**).

The FEA Crack programme [11] was used for the crack modelling. It allows more control over the finite element mesh, especially in the crack region. For the finite element analysis the model is meshed with isoparametric finite elements (**Figure 9**). Finite element mesh consisted of approximately 25.000 nodes. The magnified

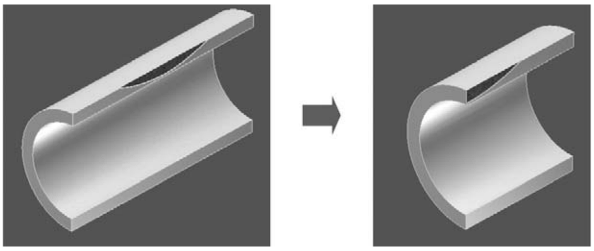

Figure 8: 3D model of the 1/4 of the pipe
Slika 8: Povečan detajl FEM modela

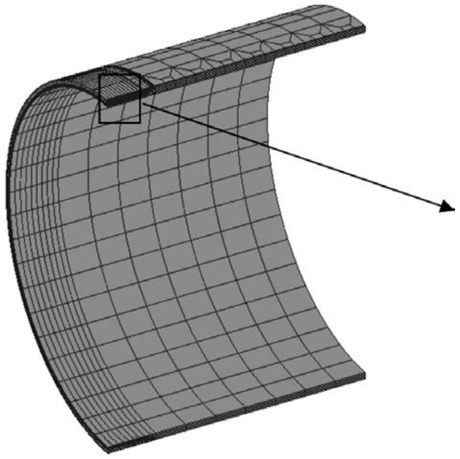

Figure 9: FEM model of the pipe with a semi-elliptic crack as the corrosion defect
Slika 9: FEM model cevi s semieliptično razpoko kot korozijsko poškodbo

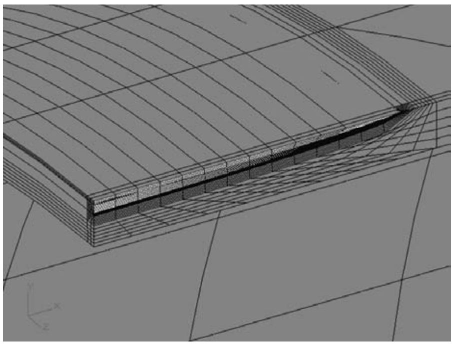

Figure 10: Magnified detail of the FEM model
Slika 10: Povečan detail FEM modela

detail of the finite element mesh is shown in **Figure 10**. The real stress-strain diagram is idealized, and the material is defined as linear-elastic and ideal-plastic.

The final element mesh was imported to the programme for finite element analysis – ANSYS 10.0. The model is loaded with internal pressure in order to determine failure pressure, which causes plastic collapse of the pipe. The pressure was gradually increased to allow precise critical load determination. The criterion for pipe failure was the internal pressure, which causes equivalent stress through the remaining ligament of the pipe, higher than the yield point of the material. In this case, this value was 8.2 MPa for the defined geometry of the pipe and the crack. **Figures 11 and 12** show the distribution of the equivalent stresses at the point of plastic collapse of the pipe. The red area with equivalent stress higher than 235 MPa spreads through the remaining pipe-wall thickness in front of the crack.

5 CONCLUSION

The aim of this paper was to determine critical, i.e., the allowable, operating pressure of the pipeline (Ø 273 × 5) mm with the measured geometry of the corrosion defect (for the hot water supply system of Osijek). The Det Norske Veritas DNV-RP-F101 procedure was used for analytic calculations of the corroded pipes, while the defects were modelled numerically using the finite element method. The values of the allowable pressure, i.e., the safe working pressure, were determined and compared according to both procedures for different defect geometry. The failure pressure, which causes plastic collapse of the pipe, was also determined using the FEM. The probabilistic approach is the most conservative for the corrosion defects with depth of 1.5 mm and length of 68 mm, because it gives the smallest allowable pressure (5.66 MPa), while the safe working pressure is 6.85 MPa (6.05 MPa according to ASME code), if the possible measurement uncertainty of the defect dimensions are not considered. The numerical calculation models the defects as a semi-elliptic crack and gives the failure pressure, which is 8.2 MPa. This failure pressure is of great practical value when assessing the hot-water system's integrity by using e.g., a FAD diagram.

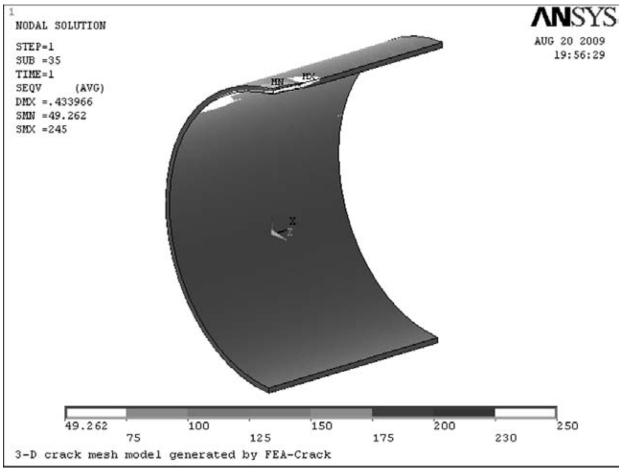

Figure 11: Field of equivalent stresses in front of the crack for a failure pressure of 8.2 MPa
Slika 11: Polje ekvivalentnih napetosti pred razpoko pri raztržnem pritisku 8,2 MPa

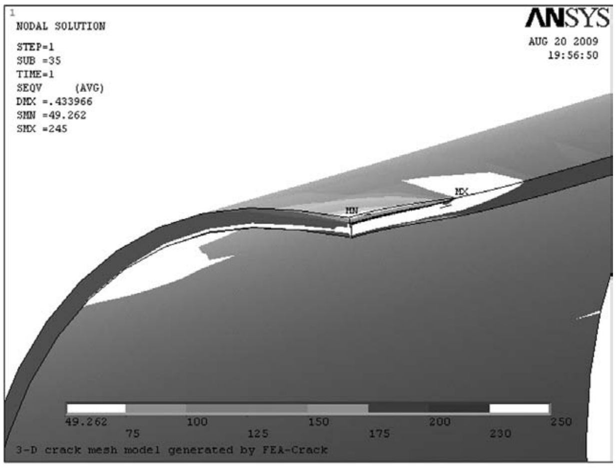

Figure 12: Enlarged detail of the field of equivalent stresses in front of the crack
Slika 12: Povečan detajl polja ekvivalentnih napetosti na čelu razpoke

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[11] FEA Crack, 3D Finite element software for cracks, Version 3.1

Note

The responsible translator for the English language is B. A. Željka Rosandić (Lecturer), J. J. Strossmayer University of Osijek, Mechanical Engineering Faculty in Slavonski Brod, Trg Ivane Brlić-Mažuranić 2, HR-35000 Slavonski Brod, Croatia.