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APPLICATION OF A CPSI BASED EXPERT SYSTEM FOR ASSESSMENT OF POWER PLANT COMPONENTS

The CPSI concept and its applicability for engineering components have been presented on different technical events, [1-3]. It proves to be an excellent tool in RSE (reliability of the structural element) having crack like defects. In technical literature can be found some compendiums, handbooks for calculating the stress intensity factors of engineering components under different loading conditions. The definition of crack propagation sensitivity index (CPSI) of the structural element is basically important because the NDE observations - loading conditions - crack growth resistance testing results are connected by applying fracture mechanics principles in reliability assessment of components. In the paper an overview will be given about the current state of the CPSI-Handbook which is under preparation.

Introduction

The basic words of the technical-economic life are the followings: safety, reliability and risk. The safety itself expresses the level of the actual safety of a system (structure, equipment, etc.) with a unit of %, i.e. it does not deal with investment and its cost items. Nowadays we are able to consider the risk level of the operating systems, i.e. the probability of failure of the system multiplies the consequences, which can be expressed in cost figure or in money.

Relating to structural integrity assessment of engineering components it is necessary to consider

- the damage process taking place in materials during a given operation conditions,
- the existing discontinuities, flaws in the structures and geometrical imperfections, and
- the fields (stress-strain, temperature, neutron, magnetic, etc,) raising in the structures during operation and simulated operation conditions.

The level of safety can be controlled by selected testing methods and in this case the following questions need to be answered:

- What kind of damage process can be realised in the supervised equipment?
- In which part of the equipment does the damage take place?
- What kind of testing procedure is able to detect it?
- What kind of qualification is required from the specialists?
- How often does it need to be controlled?, etc.

The reliability concept of the structures can be based on fracture mechanics principles and in this case the Material - NDE - Loading Condition issues should be considered at the same time. NDE and Loading Condition are expressed in the term of Crack Propagation Sensitivity Index (CPSI) of the quasi-static loaded structural element. This is a number without dimension which characterises the level of the danger of a detected flaw.

The reliability of engineering structures depends on the following main parameters:

- geometry, position and distribution of defects,
- loading condition (stress-strain field at different working conditions),
- crack propagation resistance of materials (at different stages of the life time).

Crack Propagation Sensitivity Index for quasi-static loaded elements

The Crack Propagation Sensitivity Index (CPSI) of quasi-statically loaded structural elements is the derivative of the $K-a$ function (see Figure 1.). Instead of the stress intensity factor (K) another invariant parameter of fracture mechanics can also be used (for instance the *J*-integral or the strain energy density, etc.). The CPSI concept and its applicability for engineering components have been presented in the literature 1-7.

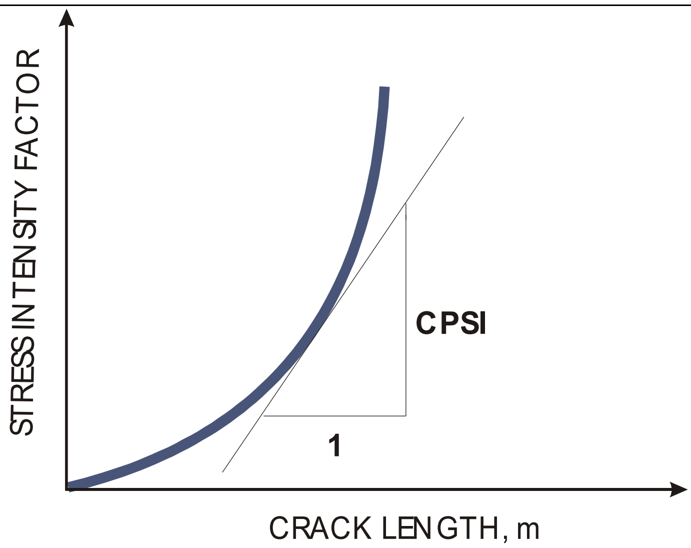


Figure 1. Definition of the crack propagation sensitivity index (CPSI) for quasi-static loaded structural element

The CPSI for a selected real structural element depends only on the crack geometry while the stress intensity factor (or other fracture mechanics parameter) depends on the type of the structural elements, on the loading conditions and on the type, position and geometrical parameters of the crack-like defects.

The simples case is a planar crack which geometry can be characterized by the crack length, by a. This is illustrated in Figure 2. which shows exactly that the requirements of crack sizing are quite different at the same reliability of the safety factors (i.e. at the same K_{Ic}/K_I values) of the element № 1 and № 2 2.

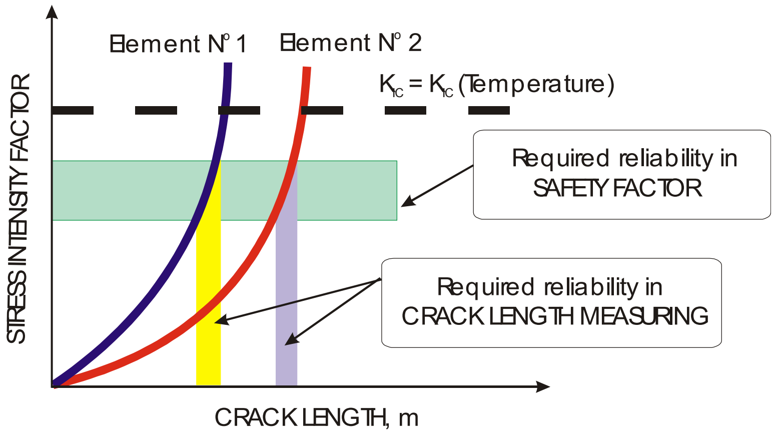


Figure 2. The practical use of CPSI for determination of the required reliability of crack sizing for different structural element

The solutions for the stress intensity factors are collected either in different handbooks 3-5 or in software 6 but the collection of their derivates do not exist yet in the literature. Therefore the collection of the derivate functions of the stress intensity factors for different structural elements, crack geometries and loading conditions are worked out and presented in a handbook 7. On the basis of this handbook a software is developed including plates, pipes, cylinders, spherical shells, spheres, round bars, bolts and components with hole. Within the framework of Ukrainian – Hungarian co-operation 100 different cases are implemented into the software. The software package at this moment is under control by the co-operated partners.

The CPSI value determines the requirement to the NDE reliability. If the CPSI value is high, the requirements should be also high 8. The application of the CPSI for the construction elements provides a possibility to link the reliability assessment calculation and the reproducibility of the NDE or crack growth resistance test results.

Case studies for the application of the CPSI concept

In this section two case studies are presented based on real structures for demonstrating the above-mentioned CPSI concept and its applicability for assessment of power plant components and pipelines. The first example is an axial, semi-elliptical surface crack (at inner surface – see Figure 3a, the second one is a circumferential, semi-elliptical surface crack (at inner surface – see Figure 3b). Based on the results provided by the developed software the critical crack lengths are also determined, which can be used for the residual lifetime assessment of the components.

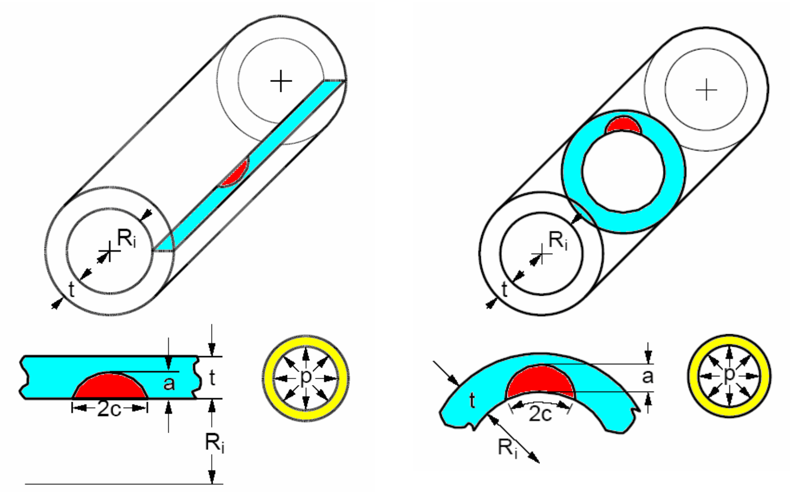
Axial, semi-elliptical surface crack (at inner surface):

Selecting the pipeline (see Figure 3a) having axial, semi-elliptical surface crack the stress intensity factors (K_a and K_c) can be calculated by the equations (1) and (1):

$$K_a = F\sigma\sqrt{\pi a}\,0.97\left(\frac{R_a^{\,2}+R_i^{\,2}}{R_a^{\,2}-R_i^{\,2}}+1-0.5\sqrt{\frac{a}{t}}\right)\frac{t}{R_i}, \quad \text{and} \quad K_c = K_a\left(1.1+0.35\left(\frac{a}{t}\right)^2\right)\sqrt{\frac{a}{c}} \tag{1}$$

where R_i – radius [mm], a – crack length [mm], $2c$ – crack width [mm], t – cylinder thickness ($R_a = R_i + a$), p – internal pressure [MPa] and

$$F = \frac{M_1 + M_2\left(\frac{a}{t}\right)^2 + M_3\left(\frac{a}{t}\right)^4}{\sqrt{Q}}. \quad \text{and} \quad \sigma = \frac{p\cdot Ri}{t} \tag{2}$$



a) b)

Figure 3. Case studies for the application of the CPSI concept
a) Axial, semi-elliptical inner surface crack, b) Circumferential, semi-elliptical inner surface crack

The derivate functions (dK_a/da and dK_c/da) have the following form (see (3) – (8)):

$$\frac{dK_a}{da}=\frac{dF}{da}\sigma\sqrt{\pi a}\,0.97\left(\frac{R_a^{\,2}+R_i^2}{R_a^{\,2}-R_i^2}+1-0.5\sqrt{\frac{a}{t}}\right)\frac{t}{R_i}+$$
$$+0.485F\sigma\sqrt{\frac{\pi}{a}}\left(\frac{R_a^{\,2}+R_i^2}{R_a^{\,2}-R_i^2}+1-0.5\sqrt{\frac{a}{t}}\right)\frac{t}{R_i}+ \quad , \tag{3}$$
$$+0.97F\sigma\sqrt{\pi a}\left(\frac{d}{da}\left(\frac{R_a^{\,2}+R_i^2}{R_a^{\,2}-R_i^2}\right)-0.25\sqrt{\frac{1}{at}}\right)\frac{t}{R_i}$$

$$\frac{dK_c}{da}=\frac{dK_a}{da}\left(1.1+0.35\left(\frac{a}{t}\right)^2\right)\sqrt{\frac{a}{c}}+0.7K_a\frac{a}{t^2}\sqrt{\frac{a}{c}}+$$
$$+\frac{1}{2}K_a\left(1.1+0.35\left(\frac{a}{t}\right)^2\right)\sqrt{\frac{1}{ac}} \quad , \tag{4}$$

where

$$\frac{dF}{da}=\frac{\left[\frac{dM_1}{da}+\frac{dM_2}{da}\left(\frac{a}{t}\right)^2+2M_2\frac{a}{t^2}+\frac{dM_3}{da}\left(\frac{a}{t}\right)^4+4M_3\frac{a^3}{t^4}\right]Q}{Q\sqrt{Q}}-$$
$$-\frac{\frac{1}{2}\left[M_1+M_2\left(\frac{a}{t}\right)^2+M_3\left(\frac{a}{t}\right)^4\right]\frac{dQ}{da}}{Q\sqrt{Q}} \quad , \tag{5}$$

$$\frac{d}{da}\left(\frac{R_a^{\,2}+R_i^2}{R_a^{\,2}-R_i^2}\right)=-\frac{4R_aR^2{}_i}{\left(R_a^{\,2}-R_i^2\right)^2}, \tag{6}$$

$$\frac{dM_1}{da}=-0.09\frac{1}{c}, \quad \frac{dM_2}{da}=-\frac{0.89}{c\left(0.2+\frac{a}{c}\right)^2}$$
$$\text{and} \quad \frac{dM_3}{da}=\frac{1}{c\left(0.65+\frac{a}{c}\right)^2}-336\frac{1}{c}\left(1-\frac{a}{c}\right)^{23}, \tag{7}$$

$$\frac{dQ}{da}=2.4156\frac{a^{0.65}}{c^{1.65}} \tag{8}$$

The calculated stress intensity factors (K_a and K_c) and crack propagation sensitivity indexes (dK_a/da and dK_c/da) for the pipeline with the following input data (Table 1.) can be seen in Figure 4.,5., 6. and 7.:

Table 1.

Input data for the calculation of CPSI

Geometrical parameters			*Loading parameter*		
R_i	radius	213 mm	p	internal pressure	12 MPa
a	crack length	5 mm			
$2c$	crack width	10 mm			
t	cylinder thickness	25 mm			

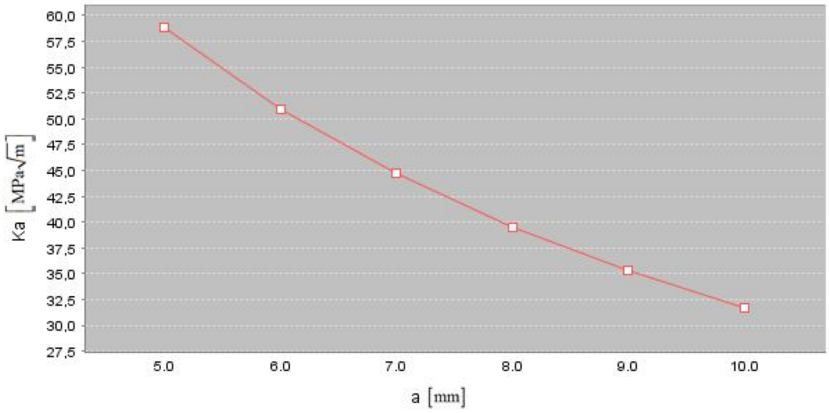


Figure 4. The K_a stress intensity factor changes as a function of the crack length

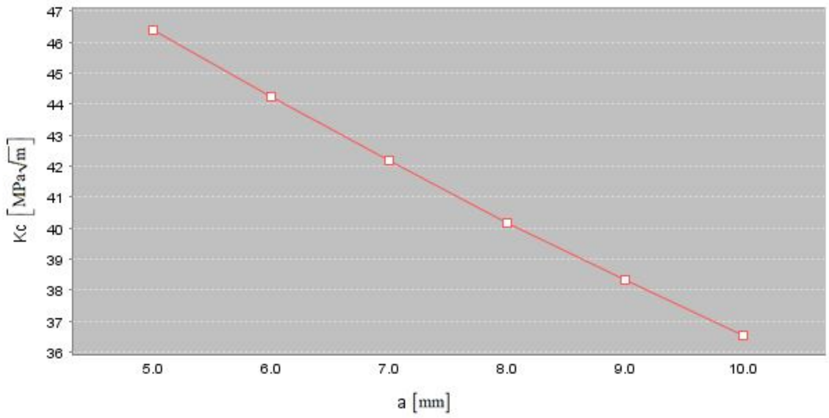


Figure 5. The K_c stress intensity factor changes as a function of the crack length

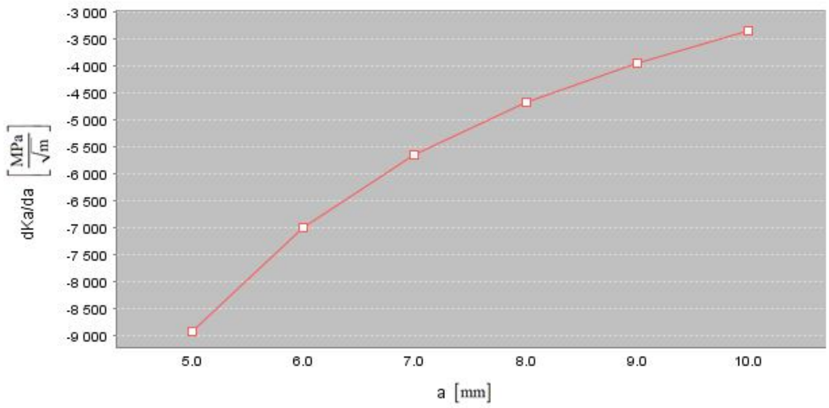


Figure 6. The changes of the dK_a/da crack propagation sensitivity index as a function of the crack length

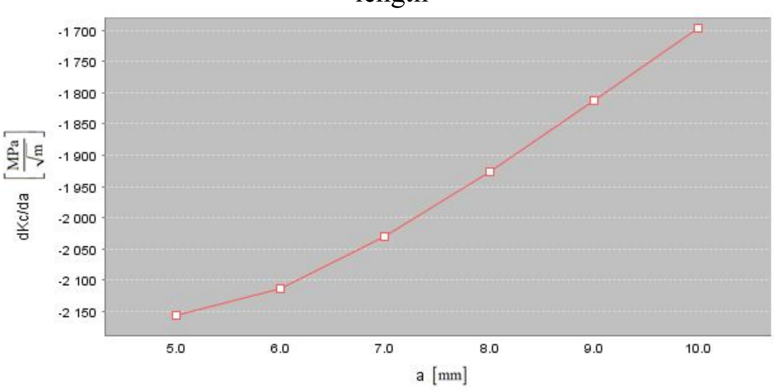


Figure 7. The changes of the dK_c/da crack propagation sensitivity index as a function of the crack length

Circumferential, semi-elliptical crack (at inner surface):

Selecting the same structure (pipeline), but (see Figure 3b) having circumferential, semi-elliptical crack, the stress intensity factors (K_a and K_c) can be calculated by the equations (9) – (17):

$$K_a = \sigma \left(1 + \left(\left(\frac{R_a}{R_i} \right)^2 - 1 \right) \right) Y_a \sqrt{a} \,, \tag{9}$$

$$K_c = \sigma \left(1 + \left(\left(\frac{R_a}{R_i} \right)^2 - 1 \right) \right) Y_c \sqrt{a} \,, \tag{10}$$

where $R_i = R$ – radius [mm], a – crack length [mm], $2c$ – crack width [mm], t – cylinder thickness ($R_a = R_i + a$), p – internal pressure [MPa] and

$$\sigma = \frac{p}{\left(\frac{R_a}{R_i} \right)^2 - 1} \,,\ R_a = R_i + a \,,\ Y_a = \frac{1}{\sqrt{1 - \frac{a}{t}}} (Y_1 + Y_2 + Y_3) \,, \quad Y_c = \frac{1}{\sqrt{1 - \frac{a}{t}}} (Y_4 + Y_5 + Y_6) \,, \tag{11}$$

$$Y_1 = 1.6561 - 0.3944 \left(\frac{a}{c} \right) - 0.46115 \left(\frac{a}{c} \right)^2 + 0.33664 \left(\frac{a}{c} \right)^3 + \frac{a}{t} \left[-0.78383 - 0.4868 \left(\frac{a}{c} \right) - 0.57149 \left(\frac{a}{c} \right)^2 + 1.1149 \left(\frac{a}{c} \right)^3 \right] , \tag{12}$$

$$Y_2 = \left(\frac{a}{t} \right)^2 \left[0.04206 + 13.568 \left(\frac{a}{c} \right) - 23.844 \left(\frac{a}{c} \right)^2 + 11.147 \left(\frac{a}{c} \right)^3 \right] , \tag{13}$$

$$Y_3 = \left(\frac{a}{t} \right)^3 \left[0.48946 - 18.201 \left(\frac{a}{c} \right) + 33.969 \left(\frac{a}{c} \right)^2 - 17.301 \left(\frac{a}{c} \right)^3 \right] , \tag{14}$$

$$Y_4 = 1.126 + 0.232 \left(\frac{a}{c} \right) - 0.28484 \left(\frac{a}{c} \right)^2 + 0.063055 \left(\frac{a}{c} \right)^3 + \frac{a}{t} \left[1.2214 - 7.6912 \left(\frac{a}{c} \right) + 10.601 \left(\frac{a}{c} \right)^2 - 4.9324 \left(\frac{a}{c} \right)^3 \right] , \tag{15}$$

$$Y_5 = \left(\frac{a}{t} \right)^2 \left[-3.1601 + 25.091 \left(\frac{a}{c} \right) - 41.651 \left(\frac{a}{c} \right)^2 + 21.397 \left(\frac{a}{c} \right)^3 \right] , \tag{16}$$

$$Y_6 = \left(\frac{a}{t} \right)^3 \left[1.6496 - 20.361 \left(\frac{a}{c} \right) + 35.868 \left(\frac{a}{c} \right)^2 - 18.949 \left(\frac{a}{c} \right)^3 \right] . \tag{17}$$

The derivate functions (dK_a/da and dK_c/da) have the following form (see (18) – (28)):

$$\frac{dK_a}{da}=\frac{d\sigma}{da}\left(1+\left(\left(\frac{R_a}{R_i}\right)^2-1\right)\right)Y_a\sqrt{a}+2\sigma\frac{R_a}{R^2{}_i}Y_a\sqrt{a}+ \\ +\sigma\left(1+\left(\left(\frac{R_a}{R_i}\right)^2-1\right)\right)\frac{dY_a}{da}\sqrt{a}+\frac{1}{2}\sigma\left(1+\left(\left(\frac{R_a}{R_i}\right)^2-1\right)\right)\frac{Y_a}{\sqrt{a}}. \tag{18}$$

$$\frac{dK_c}{da}=\frac{d\sigma}{da}\left(1+\left(\left(\frac{R_a}{R_i}\right)^2-1\right)\right)Y_c\sqrt{a}+2\sigma\frac{R_a}{R^2{}_i}Y_c\sqrt{a}+ \\ +\sigma\left(1+\left(\left(\frac{R_a}{R_i}\right)^2-1\right)\right)\frac{dY_c}{da}\sqrt{a}+\frac{1}{2}\sigma\left(1+\left(\left(\frac{R_a}{R_i}\right)^2-1\right)\right)\frac{Y_c}{\sqrt{a}}. \tag{19}$$

where

$$\frac{d\sigma}{da}=-2\frac{R_a}{R^2{}_i}\frac{p}{\left[\left(\frac{R_a}{R_i}\right)^2-1\right]^2}, \tag{20}$$

$$\frac{dY_a}{da}=\frac{1}{2t\left(1-\frac{a}{t}\right)^{\frac{3}{2}}}(Y_1+Y_2+Y_3)+\frac{1}{\sqrt{1-\frac{a}{t}}}\left(\frac{dY_1}{da}+\frac{dY_2}{da}+\frac{dY_3}{da}\right), \tag{21}$$

$$\frac{dY_c}{da}=\frac{1}{2t\left(1-\frac{a}{t}\right)^{\frac{3}{2}}}(Y_4+Y_5+Y_6)+\frac{1}{\sqrt{1-\frac{a}{t}}}\left(\frac{dY_4}{da}+\frac{dY_5}{da}+\frac{dY_6}{da}\right), \tag{22}$$

$$\frac{dY_1}{da}=\left[-0.3944-0.9223\left(\frac{a}{c}\right)+1.00992\left(\frac{a}{c}\right)^2\right]\frac{1}{c}+ \\ +\frac{1}{t}\left[-0.78383-0.4868\left(\frac{a}{c}\right)-0.57149\left(\frac{a}{c}\right)^2+1.1149\left(\frac{a}{c}\right)^3\right]+, \\ +\frac{a}{t}\left[-0.4868-1.14298\left(\frac{a}{c}\right)+3.3447\left(\frac{a}{c}\right)^2\right]\frac{1}{c} \tag{23}$$

$$\frac{dY_2}{da}=2\frac{a}{t^2}\left[0.04206+13.568\left(\frac{a}{c}\right)-23.844\left(\frac{a}{c}\right)^2+11.147\left(\frac{a}{c}\right)^3\right]+ \\ +\left(\frac{a}{t}\right)^2\left[13.568-47.688\left(\frac{a}{c}\right)+33.441\left(\frac{a}{c}\right)^2\right]\frac{1}{c}, \tag{24}$$

$$\frac{dY_3}{da}=3\frac{1}{t}\left(\frac{a}{t}\right)^2\left[0.48946-18.201\left(\frac{a}{c}\right)+33.969\left(\frac{a}{c}\right)^2-17.301\left(\frac{a}{c}\right)^3\right]+ \\ +\left(\frac{a}{t}\right)^3\left[-18.201+67.938\left(\frac{a}{c}\right)-51.903\left(\frac{a}{c}\right)^2\right]\frac{1}{c}, \tag{25}$$

$$\frac{dY_4}{da}=\left[0.232-0.56968\left(\frac{a}{c}\right)+0.189165\left(\frac{a}{c}\right)^2\right]\frac{1}{c}+$$
$$+\frac{1}{t}\left[1.2214-7.6912\left(\frac{a}{c}\right)+10.601\left(\frac{a}{c}\right)^2-4.9324\left(\frac{a}{c}\right)^3\right]+, \quad (26)$$
$$+\frac{a}{t}\left[-7.6912+21.202\left(\frac{a}{c}\right)-14.7972\left(\frac{a}{c}\right)^2\right]\frac{1}{c}$$

$$\frac{dY_5}{da}=2\frac{a}{t^2}\left[-3.1601+25.091\left(\frac{a}{c}\right)-41.651\left(\frac{a}{c}\right)^2+21.397\left(\frac{a}{c}\right)^3\right]+, \quad (27)$$
$$+\left(\frac{a}{t}\right)^2\left[+25.091-83.302\left(\frac{a}{c}\right)+64.191\left(\frac{a}{c}\right)^2\right]\frac{1}{c}$$

$$\frac{dY_6}{da}=3\frac{1}{t}\left(\frac{a}{t}\right)^2\left[1.6496-20.361\left(\frac{a}{c}\right)+35.868\left(\frac{a}{c}\right)^2-18.949\left(\frac{a}{c}\right)^3\right]+. \quad (28)$$
$$+\left(\frac{a}{t}\right)^3\left[-20.361+71.736\left(\frac{a}{c}\right)-56.847\left(\frac{a}{c}\right)^2\right]\frac{1}{c}$$

During the calculation of the stress intensity factors (K_a and K_c) and crack propagation sensitivity indexes (dK_a/da and dK_c/da) the same input data is used from the previous case study (Table 1) to compare the results and make a decision which defect is more dangerous in the point of view of K and dK/da values.

The obtained results can be seen in Figure 8., 9., 10. and 11.:

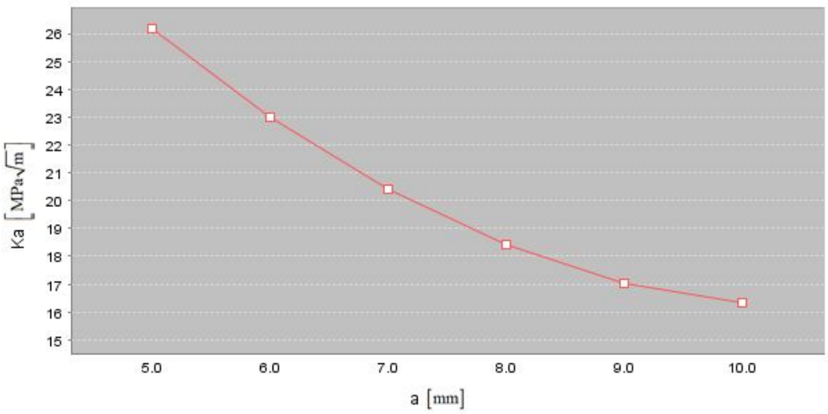


Figure 8. The K_a stress intensity factor changes as a function of the crack length

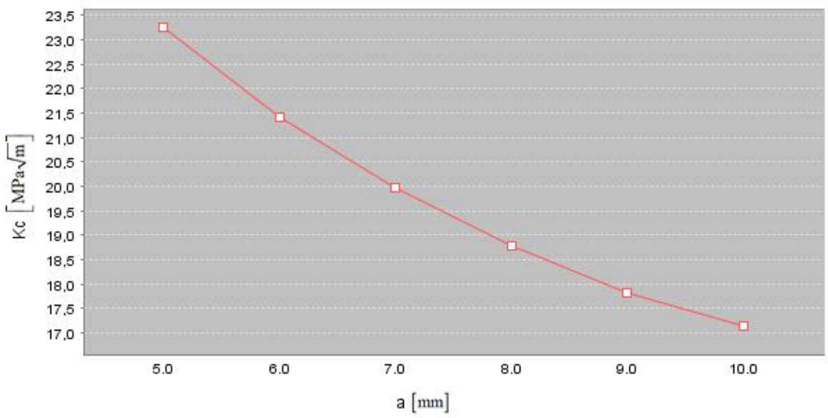


Figure 9. The K_c stress intensity factor changes as a function of the crack length

On the basis of the results the axial crack is the most dangerous from the two analyzed cases. The stress intensity factor is more than twice at the axial crack configuration, and the CPSI value also higher in this case, which means increased NDE level (more often and more precise measurement).

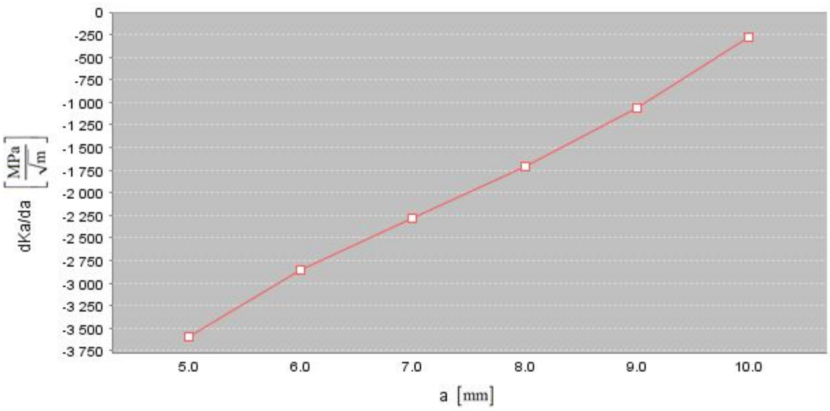


Figure 10. The changes of the dK_a/da crack propagation sensitivity index as a function of the crack length

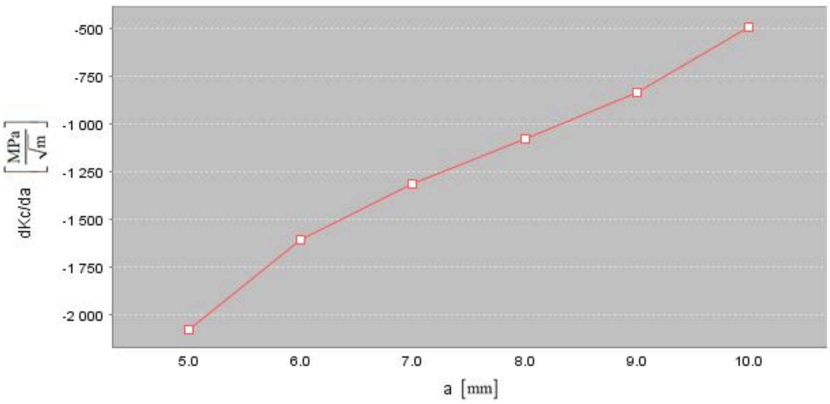


Figure 11. The changes of the dK_c/da crack propagation sensitivity index as a function of the crack length

Conclusions. Based on the calculated results it can be stated that various uncertainties can be allowed in case of changing crack length during the crack growth measuring.

Considering the aim of this paper and the presented results, the following conclusions also can be drawn:

1. The reliability assessment of cracked structural components needs to be based on the co-operation of specialists working in the field of NDT-Mechanical Testing-Fracture Mechanics.
2. A system for characterisation of crack propagation sensitivity index (CPSI) of the construction elements for quasistatic and cyclic loading conditions has been proposed.
3. The application of the crack propagation sensitivity index of the construction elements provides the possibility to join the reliability assessment calculation and the reproducibility of the NDT or crack growth resistance test results.
4. The effect of surface cracks on the reliability of structural components is more dangerous than that of other types of cracks, and therefore mechanical description and detection of surface flaws have to be central problems.

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