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EVALUATION OF STRESS INTENSITY FACTORS FOR CRACKS ON THE OUTSIDE OF THE YANKEE PAPER DRYER USING A 2D AXISYMMETRIC FEM MODEL

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ABSTRACT

In this paper the stress concentration factors are evaluated in 3 zones with cracks on the surface of the cast iron cylinder of the Yankee dryer using a axisymmetric 2D model created in the Ansys Workbench program. The values of the concentration factors are compared with the standardized critical values beyond which the operation does not have safety. The calculation is required in practice during the Yankee cylinder verification stages when non-dangerous cracks can be reconditioned by welding.

KEYWORDS: stress concentration factor, cracks

1. INTRODUCTION

Yankee dryer is an under pressure vessel used in the production of paper. On the Yankee dryer the paper goes from approximately 42–45% dryness to just over 89% dryness.

The Yankee dryer is an important component in the paper making process. It must withstand the paper layer throughout the drying process, in just a second remove up to 60% of the water contained in the paper layer.

The Yankee cylinder also serves as a pressure roller and must be evenly wrapped to have even pressure on paper layers. Using steam, the Yankee dryer uses about half the energy to dry the layers of paper after it passes the last press roll.

The surface of dryer must be mechanically and thermally uniform in order for the product to have good quality. During the drying process, the Yankee cylinder is exposed to high temperatures from the main system and the layer of chemicals used to adhere the Yankee paper layer and remove it.

The structure of the Yankee cylinder is loaded with steam under pressure at a high temperature of 1400C. The maximum pressure allowed in the cylinder operation is 5.6 ⟦10⟧^5 [Pa].

The steam supply system must maintain a temperature of 140 ° C on the inner surface of the cylinder. The temperature during operation on the outer surface of the cylinder changes when it comes into contact with the mixture; this temperature drops from 140 ° C to 95 ° C, while the covers and spindles maintain a temperature of 120 ° C, and on the inside surface of the parts of the assembly the temperature is kept at 140 ° C.

The maximum angular velocity the cylinder can reach is ω=2,85 [rad/sec].

The Yankee cylinder is a 6-piece demountable assembly, represented in Fig. 1.1 and 1.2. Component parts 1 and 6 are annular shafts assembled with cylinder caps 2 and 5 by means of screws; the inner cylinder 3 has the role of stiffening the structure. Yankee Cylinder - Part 4 of the assembly is attached with screws of the front elements (the curved lids).

The overall dimensions (Fig. 1.1) of the assembly are: the length of 7665.15 mm in the x-axis direction and the outer diameter 4267.2 mm

All elements of the assembly are made of steel except the Yankee cylinder which is made of cast iron.

The cast iron cylinder has a special sensitivity when cracks appear on its outer surface.

Material properties of structural steel and cast iron are given below.

I. Material properties of cast iron:

- Density ρ=7200 [kg/m^3] ;
- The coefficient of thermal expansion λ=1.1*⟦10⟧^(-5) [C^(-1)] ;
- Young modulus E=1.1*⟦10⟧^11 [Pa] ;
- Poisson ratio ν=0.28 ;
- Isotropic Thermal Conductivity K=52 W*m-1*C-1

II. Material properties of the steel:

- Density ρ=7850 [kg/m^3] ;

- The coefficient of thermal expansion $\lambda=1.2*10^{-5}$ $[C^{-1}]$;
- Young modulus $E=2*10^{11}$ [Pa] ;
- Poisson ratio $\nu=0.3$;
- Isotropic Thermal Conductivity K=60.5 W*m-1*C-1

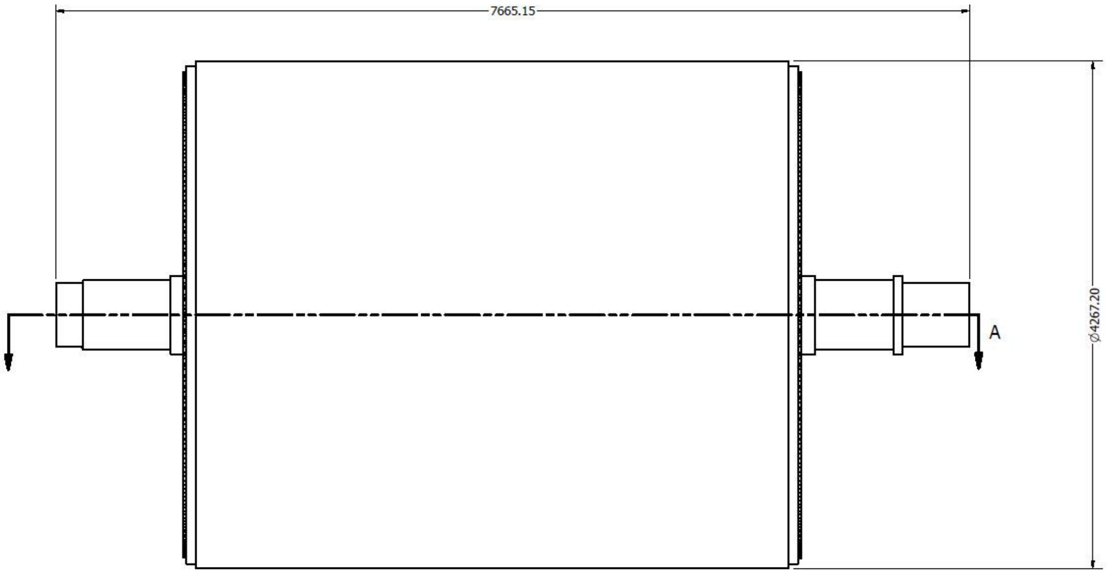

Fig. 1. *Yankee assembly – global dimensions [11]*

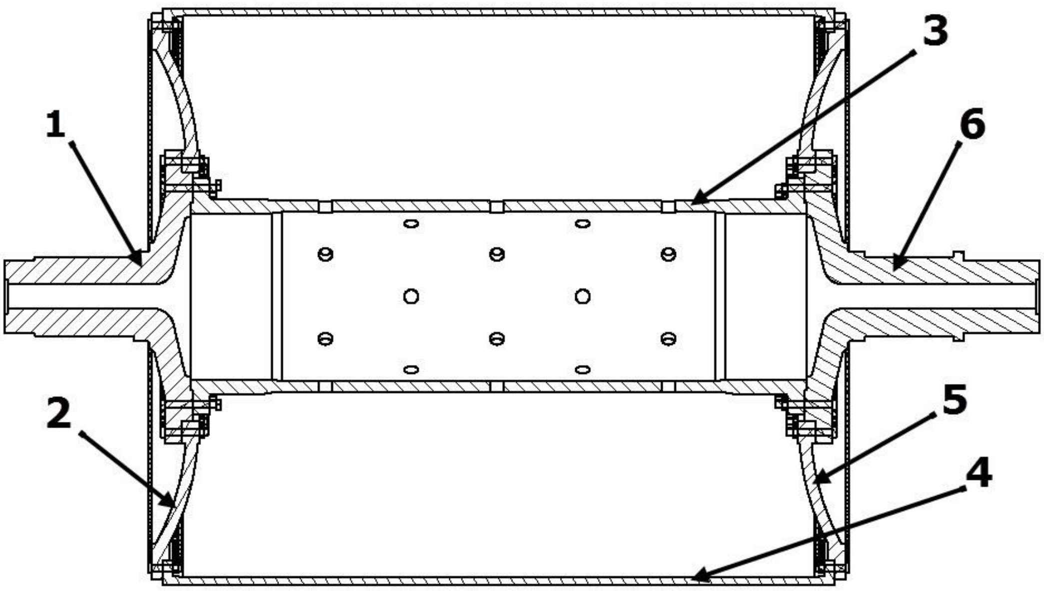

Fig. 2. *Section A-A of the Yankee ensemble; 1 and 6 - spindles, 2 and 5 caps, 3 - inner cylinder, 4 - outer cylinder [11]*

2. THE LOADING MODES OF A CRACK [2], [9]

Depending on the kinematics of the fracture (so, the relative motion of the two surfaces of cracks), the 3 (three) modes of crack displacement are shown in Fig.1.3.

● Mode I – The opening mode, where the crack surfaces move directly apart.

● Mode II – The sliding mode (in-plane shear), where the crack surfaces slide over one another in a direction perpendicular to the leading edge of the crack.

● Mode III – The tearing mode (out-of- plane shear), mode where the crack surfaces move relative to one another and parallel to the leading edge of the crack.

In general, the fracture is characterized by a combination of crack modes.

The way a crack propagates through the material is indicative for the fracture mechanism. Visual inspection of the fracture surface gives already valuable information. The next mechanisms are generally distinguished:

- shear fracture
- cleavage fracture
- fatigue fracture
- de-adhesion

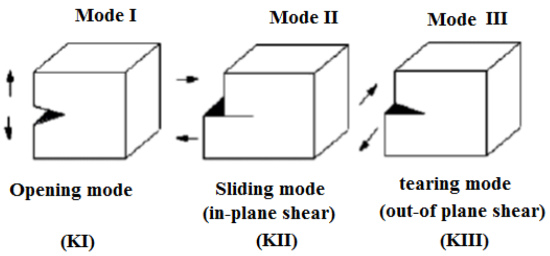

Fig. 3. *Three standard loading modes of a crack*

Typical parameters of fracture mechanics describe either the energy release rate or the amplitude of the strain and deformation fields in front of the crack tip.

The following parameters are widely used in the analysis of the fracture mechanics:

- Stress intensity factors;
- The energy release rates;
- J-integrals.

The stress intensity factors and energy release rates are limited to elastic-linear domain of the mechanics of fracture.

Considering a body of a nonlinear-elastic material containing a crack, the J integral is defined as,

$$J = \int_{\Gamma} wdy - T_i \frac{\partial u_i}{\partial x} ds \,, \tag{1}$$

where $w = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}$, the strain energy, $T_i = \sigma_{ij} n_j$, is the vector of traction loading, Γ is an arbitrary close contour around the crack tip, n is the versor of normal at contour, Γ, σ, ε, and u, are the stress, strain and displacement.

James Rice, J. R., 1968, has shown the *J* integral is independent of the contour and represents the energy release rate for materials having a nonlinear behavior [9]:

$$J \equiv \frac{d\Pi}{dA} \,, \tag{2}$$

where $\Pi = U - W$, the total energy is the difference between the strain energy, *U* and the mechanic work of the external forces *W*; A is the area of the crack.

The dimension of *J*- integral is:

$$Dim[J] = \frac{F}{L^2} L = \frac{Energy}{Area\ of\ the\ crack} \,. \tag{3}$$

For linear elastic materials, the integral *J* is actually the energy release rate, *G*, and both are related to the stress intensity factor *K* in the following form:

$$J = G = \begin{Bmatrix} \dfrac{K^2}{E} & plane\ stress \\ \dfrac{K^2}{E}\ 1 - \nu^2 & plane\ strain \end{Bmatrix} . \tag{4}$$

3. THE EVALUATION OF THE INTEGRAL J USING THE FINITE ELEMENT METHOD [9]

Evaluation of *J*-integral (the two-dimensional formulation) as a viable fracture criteria for linear elastic and elastic-plastic deformations. The two-dimensional J-integral formulation has been modified to include axisymmetric behavior as well as thermal gradients.

For an elastic fracture assessment, the stress intensity factors can be determined from the *J*-integral parameters:

$$K_I = \sqrt{E' J_I} \,;\ K_{II} = \sqrt{E' J_{II}} \,, \tag{5}$$

in which:

K_I and K_{II} are the stress intensity factors for modes *I* and *II*;

J_I and J_{II} are *J*-integral values for modes *I* and *II*;

J is the total *J*-integral value *J*: $J = J_I + J_{II}$;

$E' = E$ (plane stress);

$E' = \dfrac{E}{1 - \nu^2}$ (plane strain /axisymmetric)

I, *II* first and second (opening and shearing) crack modes; *E*, ν- Modulus of Elasticity and Poisson's ratio.

The *J*-integral parameters are path-independent. They can be obtained from any arbitrary closed path which starts from one crack surface, travels around the crack tip and ends on the other crack surface.

Because the crack tip introduces singularity it requires significantly, less mesh refinement than other fracture assessment techniques.

When the stress intensity in a brittle material reaches a particular value (critical one), K_c and then fracture occurs.

4. 2D MODELING OF THE YANKEE CYLINDER IN ANSYS WORKBENCH

Examples of crack modeling and calculation of stress concentration coefficients are given in the references [7], [8].

The 2D model with finite elements of the Yankee cylinder assembly was made in the Ansys Workbench program. Holes and mounting screws were not considered in the model.

There were provided 3 zones with cracks positioned as in Fig. 1.5 on the outside of the cast iron cylinder. The depth of the radial cracks in each area varies between 5mm-20mm, and their opening is in all cases of 4mm. Due to the double symmetry with respect to the axes OX (radial) and OY (axial) only a quarter of the model was created. The discretization of the model was made with axially symmetrical planar elements with three nodes and two degrees of freedom per node (translations along the two axes of the plane).

The geometry of the model specifying the areas with cracks and symmetry conditions is given in Fig. 5.

The discretization has taken into account the presence of cracks around which a fine automatic discretization was performed with 20 elements on the sides of the crack (Mesh sizing – number of division 20 and Behavior-hard) [10]. The meshing mode of the cracks in each of the 3 zones are shown in Fig. 1.6-Figure 8.

The symmetry conditions involve zero displacements outside the symmetry plane, and for the loads, the nominal operating conditions of the cylinder were imposed, i.e.: 5.6 *105N/m2 internal pressure, 2.85 rad /s the angular velocity and the thermal load resulting from the equilibrium analysis of the temperature distribution. (Fig. 11)

Considering the thermal and mechanical stress of the elements of the Yankee assembly, the calculation was performed in two stages:

- with the Steady-state Thermal calculation module (for obtaining the temperature distribution Fig. 1.10); The boundary conditions for the thermal calculation are given in Fig. 9.

- with the Static structural module (for obtaining the state of stresses and deformations with loads from temperature variations, applying the internal pressure and the angular velocity of the assembly). In Fig. 11 the boundary conditions for the static calculation are given.

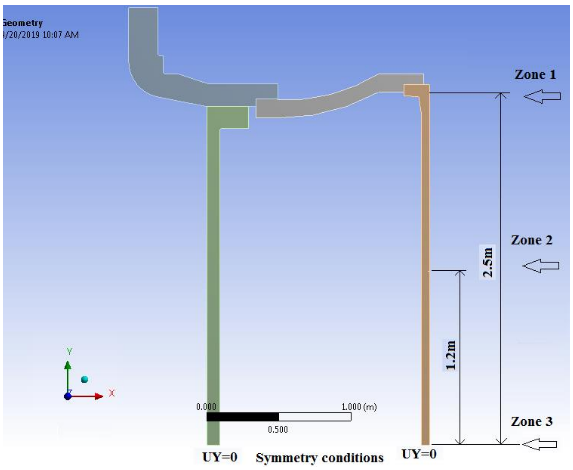

Fig. 5. *The 2D model of the Yankee cylinder assembly with the 3 zone where cracks were provided*

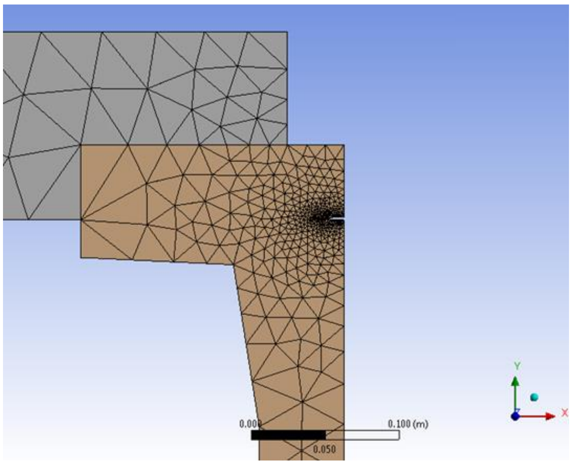

Fig. 6. *Discretization around the crack in Zone 1 (20 mm length)*

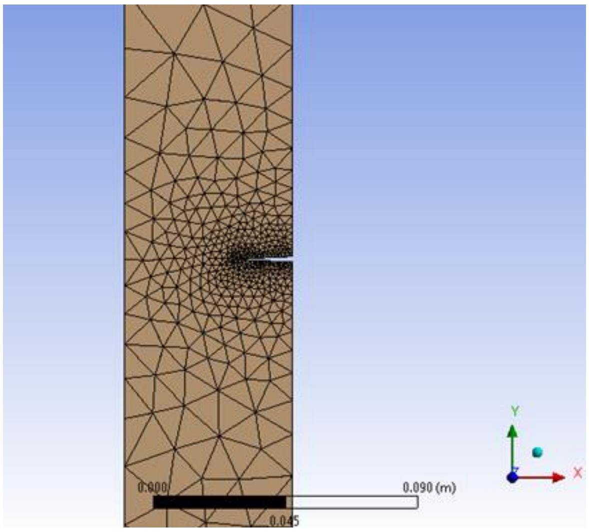

Fig. 7. *Discretization around the crack in Zone 2 (20 mm length)*

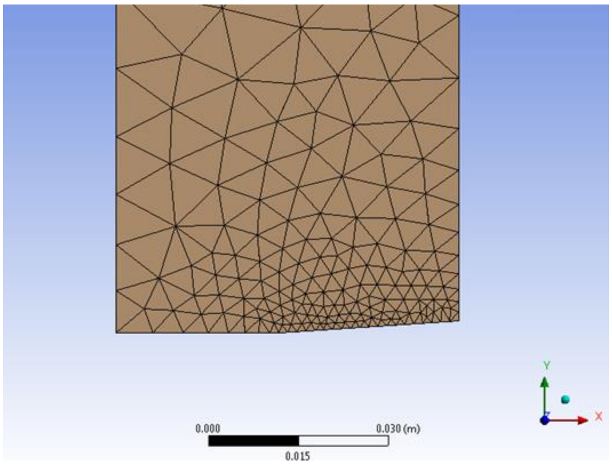

Fig. 8. *Discretization around the crack in Zone 3 (20 mm length)*

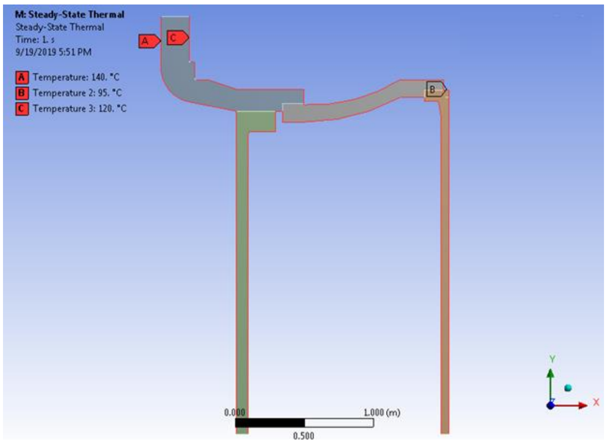

Fig. 9. *Boundary conditions for the Steady-state Thermal calculus*

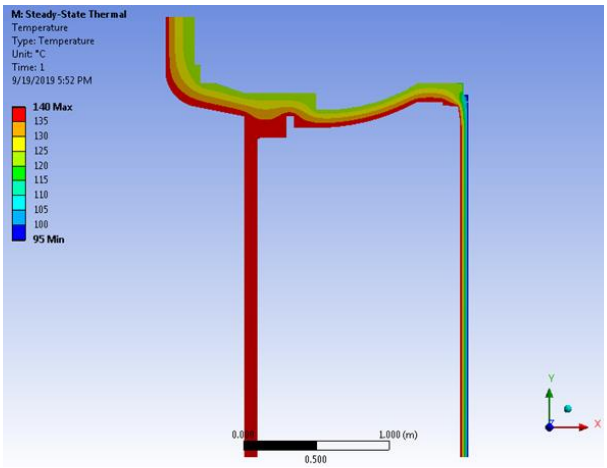

Fig. 10. *Temperature distribution on Yankee cylinder elements*

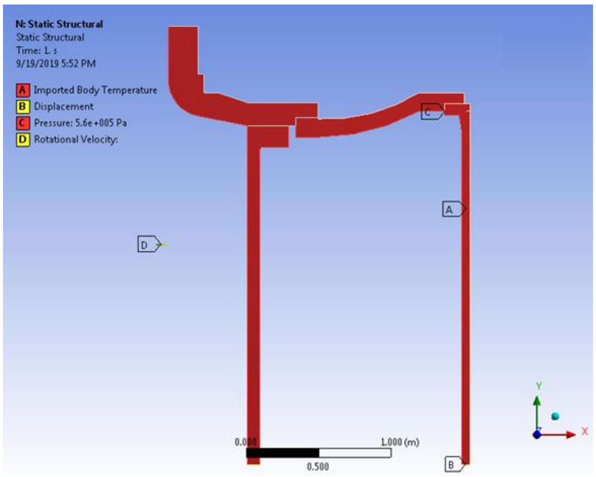

Fig. 11. *Boundary conditions for the Static structural calculus*

5. THE RESULTS FOR THE STRESS CONCENTRATION COEFFICIENTS K_I AND K_{II}

The stress concentration coefficients are automatically evaluated using the **Fracture> Pre-Meshed Crack** module in the **Static Structural** module [10]. The values of these coefficients for each zone separately and for three crack lengths are given in Tables 1-3, and their variations are represented in Fig. 12 (Zone 1), Fig. 13 (Zone2) and Fig. 14 (Zone 3).

The distributions of von Mises stresses for the cracks in the 3 zones, having maximum length considered are shown in Fig. 14a, Fig. 15a and Fig. 16a for the whole and in Fig. 14b, Fig. 15b and Fig. 16b as details near cracks.

The critical coefficient of concentration for the cast iron is within the range 6-20 106(Pa*m^(0.5)).

From the data in Table 1 (and Fig. 12) it can be observed that the stress concentration coefficients in Zone 1 are below the minimum value of the critical coefficient and therefore this area can be considered safe for cracks with depths up to 20 mm. The stresses at the tip of the crack in zone 1 are below 40 MPa.

The stress concentration coefficients in zone 2 have a combined effect keeping in the safety zone for cracks with depths below 20mm (data from table 2 and Fig. 13). The tensions at the tip of the crack in the Zone 2 is about 178 MPa.

In Zone 3 the stress concentration factors have an increasing tendency with increasing the crack length (table 3 and Fig. 14); for the crack with a length of 10 mm the K_{II} coefficient approaches the minimum value of the critical coefficient. And in zone 3, it is possible a combined action of the two modes of loading of the crack. The stresses at the tip of the crack in zone 3 are over 190 MPa.

Table 1. *The stress concentration coefficients K_I and K_{II} in Zone 1*

Length of the crack [mm] - Zone 1	K_I [Pa*m^(0.5)]	K_{II} [Pa*m^(0.5)]
5mm	4.41E+05	6.59E+05
10mm	6.37E+05	4.29E+05
20mm	8.08E+05	5.47E+05

Table 2. *The stress concentration coefficients K_I and K_{II} in Zone 2*

Length of the crack [mm]- Zone 2	K_I [Pa*m^(0.5)]	K_{II} [Pa*m^(0.5)]
5 mm	1.05E+06	26046
10 mm	1.51E+06	44030
20 mm	1.20E+05	2.21E+05

Table 3. *The stress concentration coefficients K_I and K_{II} in Zone 3*

Length of the crack [mm]- Zone 3	K_I [Pa*m^(0.5)]	K_{II} [Pa*m^(0.5)]
5 mm	3.26E+06	1.65E+06
10 mm	1.79E+06	5.92E+06
20 mm	4.86E+06	8.29E+06

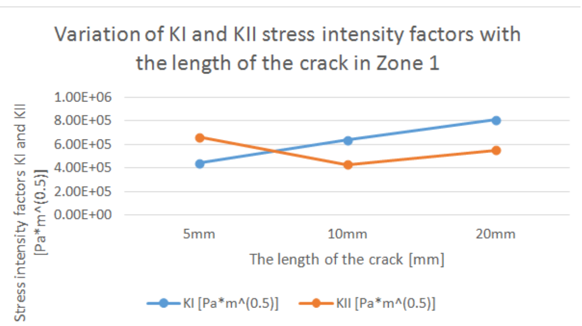

Fig. 11. *Variation of stress concentration factors K_I and K_{II} (Zone 1)*

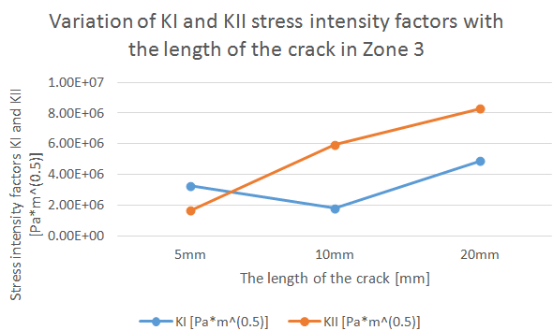

Fig. 13. *Variation of stress concentration factors K_I and K_{II} (Zone 3)*

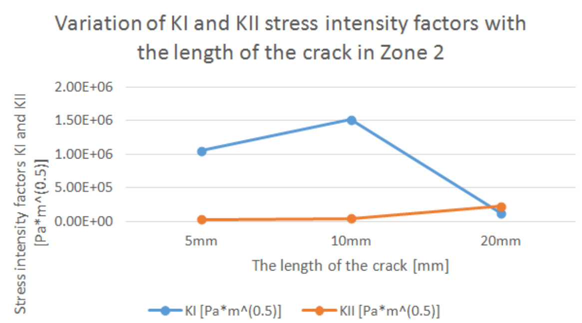

Fig. 12. *Variation of stress concentration factors K_I and K_{II} (Zone 2)*

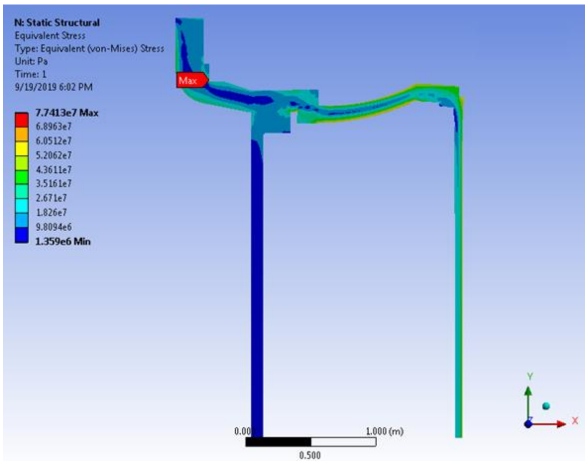

Fig. 14.a. *Distribution of von Mises stresses for the 20 mm crack case in Zone 1 (ensemble)*

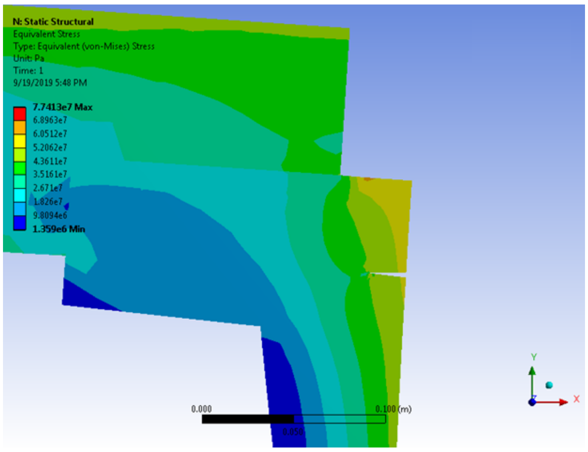

Fig. 14.b. *Distribution of von Mises stresses for the 20 mm crack case in Zone 1 (Detail)*

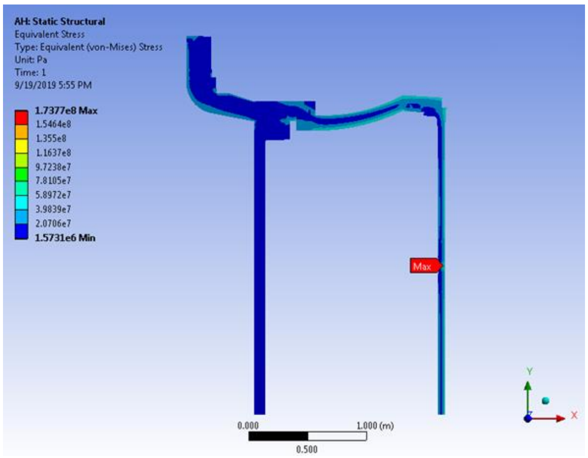

Fig. 15.a. *Distribution of von Mises stresses for the 20 mm crack case in Zone 2 (ensemble)*

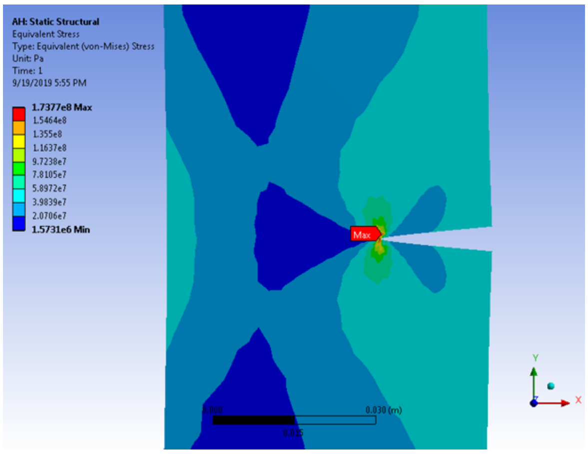

Fig. 15.b. *Distribution of von Mises stresses for the 20 mm crack case in Zone 2 (Detail)*

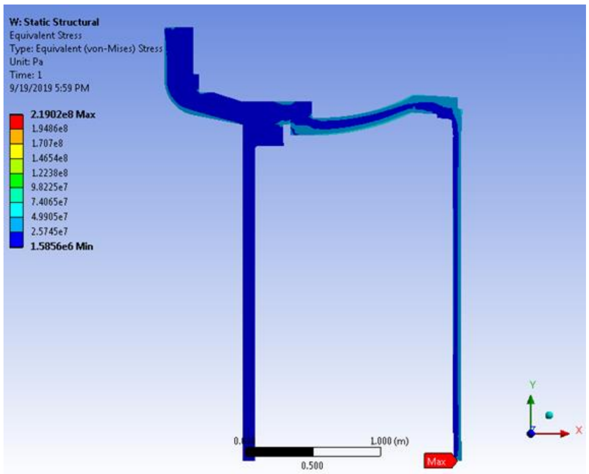

Fig. 16.a. *Distribution of von Mises stresses for the 20 mm crack case in Zone 3 (ensemble)*

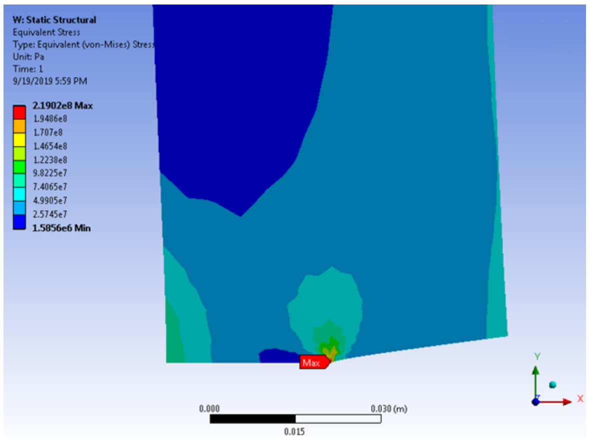

Fig. 16.b. *Distribution of von Mises stresses for the 20 mm crack case in Zone 3 (Detail)*

6. CONCLUSIONS

So, among the three zones on the outer surface of the Yankee cylinder only cracks in zone 1 are non-dangerous; these have the stress concentration coefficients corresponding to the first two modes of fracture below the minimum critical value of 6 *106 (Pa * m ^ (0.5)) (see the Table 1.1).

The cracks in the second zone are kept in the safety zone for depths below 20 mm.

In the third zone, cracks over 10mm length can expand at high speeds, and fracture can be achieved by opening and shearing (Table 3, Fig. 15).

Therefore the reconditioning by welding of the cast iron cylinder can be done only for cracks located in Zone 1.

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