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RELIABILITY AND LIFETIME ANALYSIS FOR A CRACKED CYLINDER OF AMMONIA UNIT COMPRESSOR

ANALIZA POUZDANOSTI I PREOSTALOG VEKA CILINDRA KOMPRESORA ZA AMONIJAK SA PRSLINOM

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- crack
- finite element method
- temporary repair
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Ključne reči
- kompresor za amonijak
- prslina
- metoda konačnih elemenata
- privremena popravka
- ocena integriteta i veka

Abstract

Fitness for service analysis can be an answer to questions about possible safe operation when a flaw is detected either during service or scheduled shutdown. In some cases repair may not be an option due to the lack of resources, access within the original shutdown window, lack of repair part, or the risk of further damage during the repair itself. However, the methodologies and numerical tools are developed, engineers have to face difficulties during the analysis of old parts due to the lack of reliable information about the material, load history or environmental effects. In the present case a crack is found in a giant, more than 20 years old, gas compressor, between one of the inlet valve seats and the cooling pipe row. A failure analysis of a cracked cylinder of the compressor was made using complex numerical and experimental methods. The operating parameters and probable lifetime (due to crack propagation) on reduced pressure are given based on the results of the investigations.

Izvod

Analiza podobnosti za upotrebu može biti odgovor na pitanje mogućnosti sigurnog rada kada se otkrije greška tokom eksploatacije ili planiranog zaustavljanja pogona. U nekim slučajevima popravka nije rešenje zbog nedovoljnih resursa, pristupa kroz predviđene otvore, nedostatka rezervnih delova ili zbog rizika oštećenja tokom same opravke. Međutim, razvijeni su postupci i numerički alati, takvi da inženjeri treba da se suoče sa problemom u analizi starih delova zbog nedostatka pouzdanih podataka o materijalu, istorije opterećenja i uticaja okoline. U razmatranom slučaju, prslina je otkrivena u velikom kompresoru za gas, starom više od 20 godina, između sedišta jednog od ulaznih ventila i sistema cevi za hlađenje. Analiza otkaza kompresorskog cilindra sa prslinom je izvedena korišćenjem složenih numeričkih i eksperimentalnih metoda. Radni parametri i verovatni preostali vek (zbog rasta prsline) pri smanjenom pritisku su određeni na osnovu rezultata ovih istraživanja.

INTRODUCTION

A crack was found between one of the inlet valve seats and the cooling pipe row (Figs. 1 to 3) of a giant gas compressor. The crack face was situated almost in the plane of symmetry. The crack was dangerous, because it reached the cooling pipe and in this case H_2 would get into the cooling system, what could cause a fatal explosion. Since the customer did not have another cylinder, and its replacement with a new cylinder would take about one month, the interruption of production would lead to significant loss of income and the unit operator asked how to keep the unit in production until eventual replacement. The consequences of a potential accident increased the importance of safety issues. Although hydrogen leakage had been stopped by closing the two nearest cooling pipes by applying through-wall bolts, the safe operating conditions and possible lifetime had to be determined. The answer was to be made in a few days so only engineering methods with limited numerical validation were applicable.

The geometry data and last loading conditions were given by the customer, but the material type and previous load history were questionable. There was no information on the possible time of crack initiation, so crack propagation could take place in long or short time. Due to the relatively high operating speed of the cylinder (330 rpm) both, long and short propagation processes could be expected. Based on preliminary calculations and available information on material data, high cycle fatigue crack propagation was the only possible damage mechanism for the observed crack. The fatigue load amplitude was low.

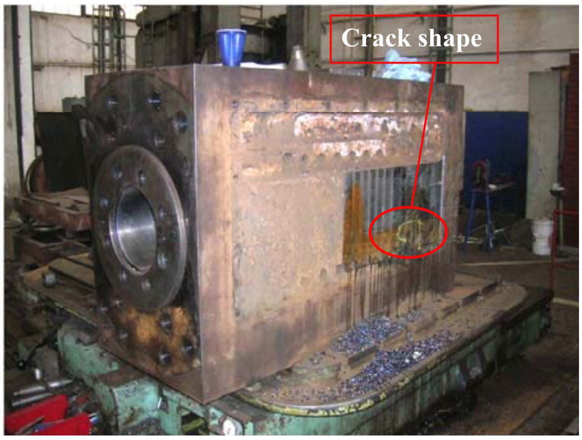

Figure 1. The 3rd stage cylinder and crack location and shape detected by ultrasound
Slika 1. Cilindar trećeg stepena i oblik prsline, otkriven ultrazvukom

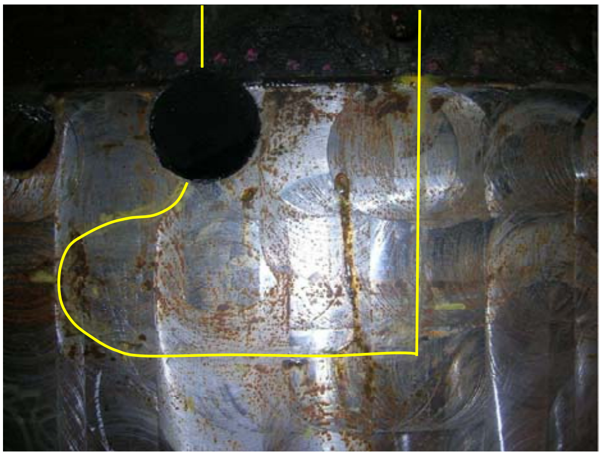

Figure 2. Crack on cylinder surface
Slika 2. Izgled prsline na površini cilindra

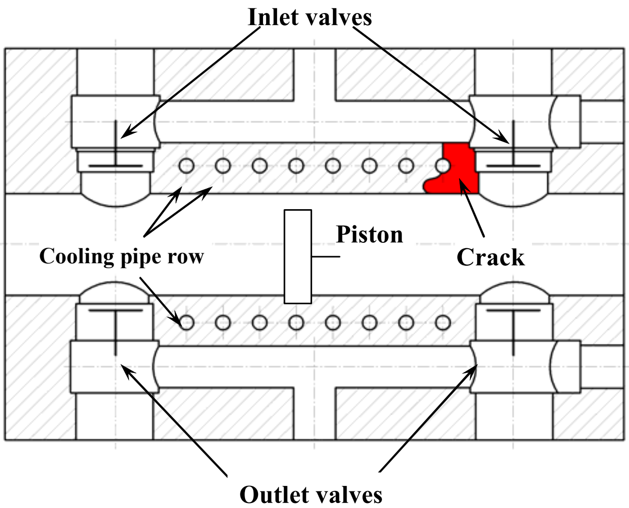

Figure 3. Cross-section of cylinder with marked crack
Slika 3. Poprečni presek cilindra sa označenom prslinom

So the objective of the work was to find answers to the following questions:

1. Is there any plastic collapse danger due to the reduction of the ligament?
2. Can the bolts increase the force to tighten the unit enough to close the crack?
3. Can maximum operational pressure cause brittle fracture?
4. Can the crack propagate? What is the maximum applicable pressure difference?
5. How long can the crack propagation be controlled and monitored?

The following calculations were performed to answer posed questions:

– Finite element method (FEM) calculation of test pressure effect (284 bar, static), with and without reinforcement.
– FEM calculation of operational pressure effect (200/80 bar, alternating), with and without reinforcement.
– Stress intensity factor (K_I) estimation analytically based on FEM results for test and operational pressure. Estimation of K_I change and crack growth rate during operation.

MATERIAL PROPERTIES

The material of the cylinder is 1.7225 according to instruction manual, equivalent to 42CrMo4 steel. Its properties are determined from Refs. /1-3/ and the EQUIST database, but without any quality assurance data.

Table 1. Material parameters.
Tabela 1. Karakteristike materijala

Yield stress	Tensile strength	Fracture toughness	Stress intensity factor threshold	Paris law coefficient	Paris law exponent
$R_{p0.2}$	R_m	K_{Ic}	ΔK_{th}	C	m
MPa	MPa	MPa·m$^{0.5}$	MPa·m$^{0.5}$		
500	750–900	60–100	5–10	$1.11\cdot10^{-11}$	2.36

STRUCTURE GEOMETRY AND FEM CALCULATION

Geometry data are given by the customer, who recommended to repair the cracked part by tighten joint increasing screw force. The cracked and adjacent cooling pipes had been enclosed, new bores drilled, threaded, and reinforced by M33 bolts. The reinforcement model is given in Fig. 4.

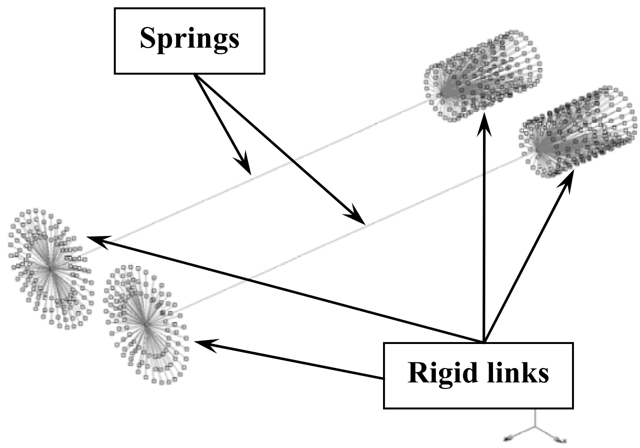

Figure 4. Reinforcement (springs and rigid links)
Slika 4. Ojačanje (opruge i krute veze)

The mesh for FEM model of the linear elastic material is created by 10-node parabolic 3D tetrahedral elements (160 650 elements with 247 013 nodes). Figure 5 shows the crack face, loaded by outlet pressure (200 bar), as well as the surfaces (light blue colour). The light yellow surfaces in

Fig. 6 were loaded by inlet pressure (80 bar). The crack face was situated 20 mm from the symmetry plane. The constraints were on the bottom plane.

At first, FEM calculation was carried out without taking into consideration the effect of the bolts and this showed that the stresses at normal operational pressure (200/80 bar) are lower than the yield stress, so plastic deformation could not cause failure. Only a small plastic zone was found around the crack front.

Reinforcements have been taken into consideration for the next calculation. As an illustration, these results for the equivalent von Mises stress, calculated for normal operational pressures around the crack and cooling pipe row with crack and reinforcement are shown in Figs. 7 and 8. It was found that the stress decreases about 6–8% near the crack due to the reinforcement, but this is not enough to close the crack so further crack propagation could take place.

Eigen-frequency calculations were performed on the cracked cylinder body to estimate the additional load from vibration of the power equipment, for an operational speed of 333 min^{-1}. Table 2 shows the first ten eigen-frequencies calculated for the cylinder body.

Table 2. Eigen-frequencies.
Tabela 2. Sopstvene frekvencije

Number	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Value,Hz	175.3	625.6	758.1	773.6	810.8	1223	1368	1657	1783	1874

The frequency from power equipment (5.55 Hz) was much lower than the eigen-frequencies, therefore resonance during the operation does not develop. This means, the dynamic effects do not have to be taken into consideration.

Since no global or local damage of plastic collapse is found, the cracked section can accept the applied load.

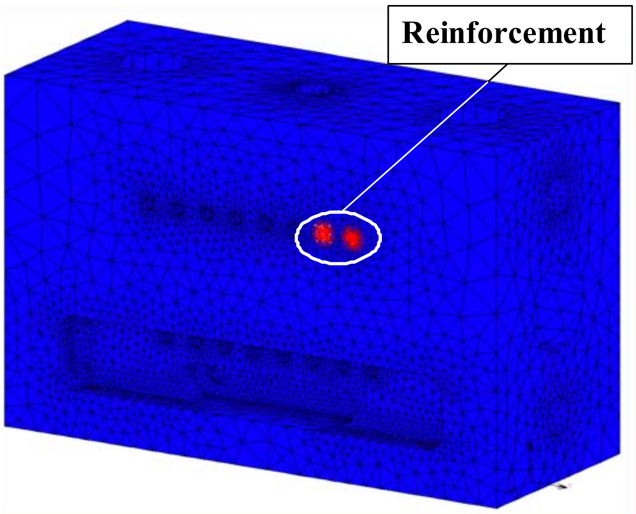

Figure 5. FEM mesh and the reinforcement
Slika 5. FEM mreža i ojačanje

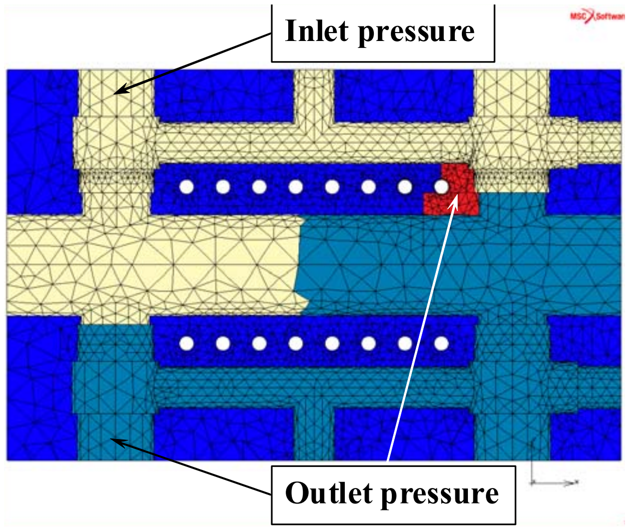

Figure 6. Cross-section of cylinder with crack (red marked)
Slika 6. Poprečni presek cilindra sa prslinom (crveno)

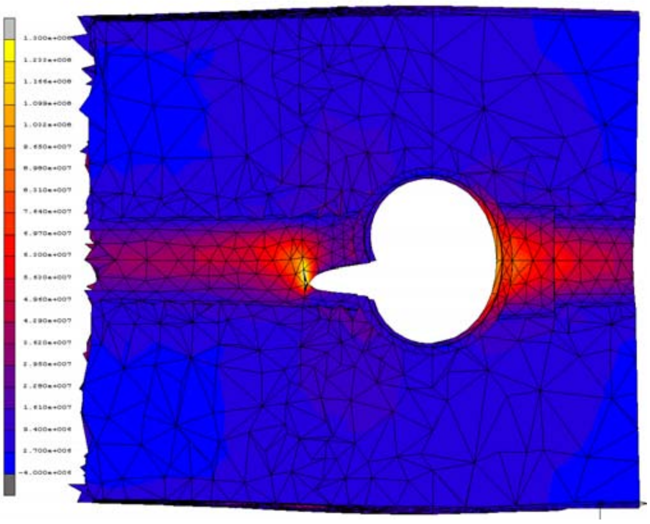

Figure 7. Equivalent von Mises stress around the crack with reinforcement.
Slika 7. Ekvivalentni Mizesov napon oko prsline sa uračunatim ojačanjem

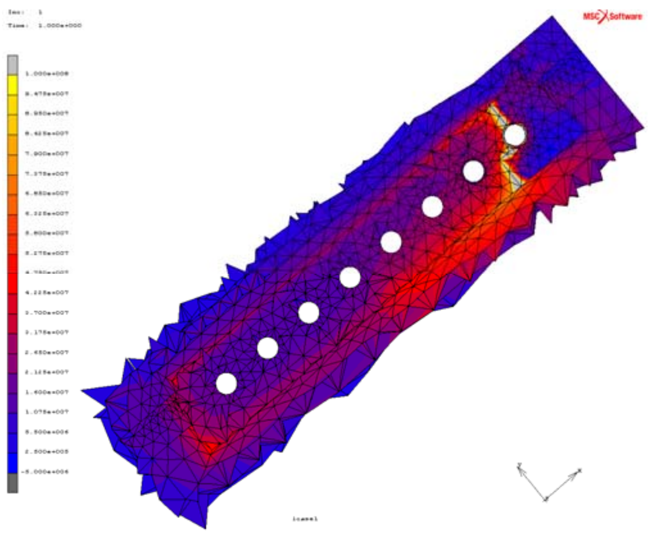

Figure 8. Equivalent von Mises stress around the cooling pipe row with crack and reinforcement.
Slika 8. Ekvivalentni Mizesov napon oko niza cevi za hlađenje sa prslinom i uračunatim ojačanjem

Stress scale distribution: bottom point 0 MPa, top point 250 MPa. Magnification of deformations 600×.
Raspodela skale napona: donja tačka 0 MPa, gornja tačka 250 MPa. Uvećanje deformacije 600×

FRACTURE MECHANICS ANALYSES

Fracture mechanics analyses were performed for brittle fracture and calculated crack propagation. The simplified plane-strain model (Fig. 9) is applied and verified by FEM for analytical fracture mechanics analysis.

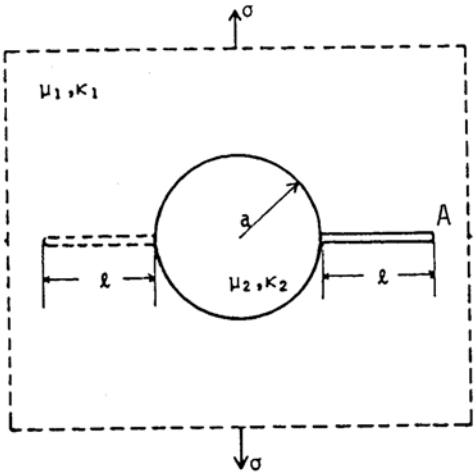

Figure 9. Simplified model of the crack
Slika 9. Uprošćeni model prsline

The analytical stress intensity factor solution for the simplified model is based on the well-known formula, /4/:

$$K_{IA} = F_{IA}(\sigma + p)\sqrt{\pi l} \qquad (1)$$

where: K_{IA} –stress intensity factor; the value F_{IA} –from Table 3 (linear interpolation is applied); σ – nominal stress; p – pressure; l – crack length.

Table 3. Geometry parameters.
Tabela 3. Geometrijski parametri

l/a	1	1.5	2
F_{IA}	1.306	1.127	1.031

FEM analysis (Fig. 10) was applied to validate the model from Fig. 9 at minimal operational pressures, (outlet/inlet 120/60 bar). Difference in stress intensity factor is acceptable: for analytical model $K_{I\text{analytical}}$ = 17 MPa·√m, for FEM calculation $K_{I\text{FEM}}$ = 14.1 MPa·√m, indicating that the analytical model is applicable for this case.

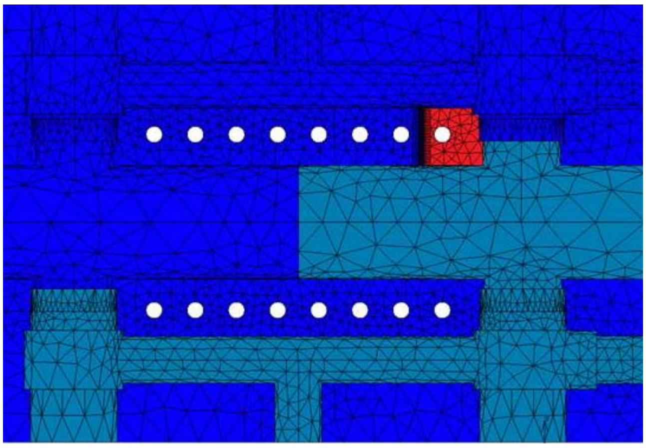

Figure 10. FEM model for verification of simplified crack model.
Slika 10. FEM model za verifikaciju uprošćenog modela prsline

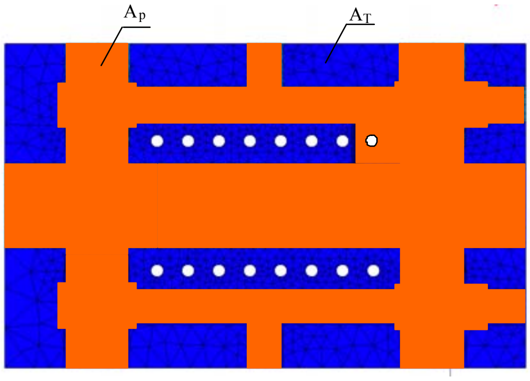

Figure 11. Scheme for brittle fracture evaluation
Slika 11. Shema za ocenu krtog loma

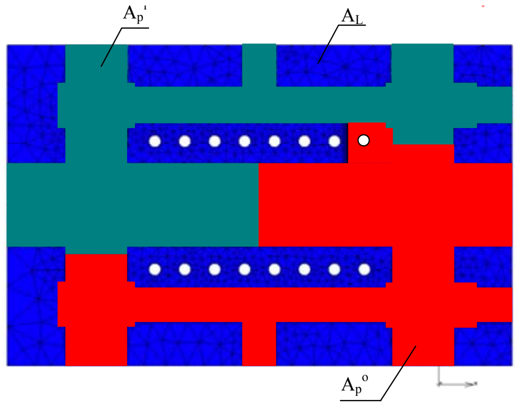

Figure 12. Cross-section of cracked cylinder for J-integral calculation
Slika 12. Presek cilindra sa prslinom za proračun J integrala

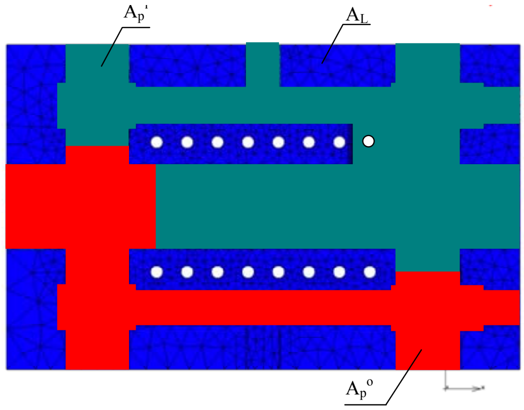

Figure 13. Minimum load for the cross section.
Slika 13. Minimalno opterećenje u preseku

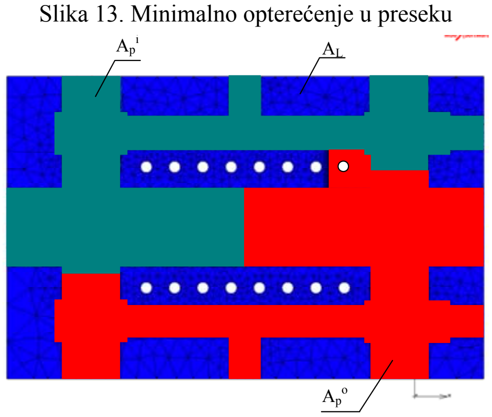

Figure 14. Maximum load for the cross section.
Slika 14. Maksimalno opterećenje u preseku

Applying proof pressure test p_{test} = 284 bar the risk of brittle fracture is evaluated (Fig. 11). Obtained value for stress intensity factor K_I = 47.5 MPa√m is below minimum fracture toughness value, K_{Ic} = 60–100 MPa√m (Table 1), indicating that brittle fracture is not probable.

The nominal stress is calculated based on the ratio of the inlet (i) and outlet (o) pressure p loaded area A to the ligament section (Figs. 12–14) as follows:

$$\sigma = p_i \frac{A_p^i}{A_L} + p_o \frac{A_p^o}{A_L} \quad (2)$$

Crack growth is analyzed by Paris-Erdogan Eq. (3).

$$\frac{dl}{dN} = C\left(\Delta K_{eff}\right)^m \quad (3)$$

where: C, m – parameters of crack growth curve, and ΔK_{eff} is calculated using FITNET FFS Procedure, /5/:

$$\Delta K_{eff} = \frac{\left(\Delta K - \Delta K_{th}\right)}{(1-R)} \quad (4)$$

taking into account the relations given in Fig. 15.

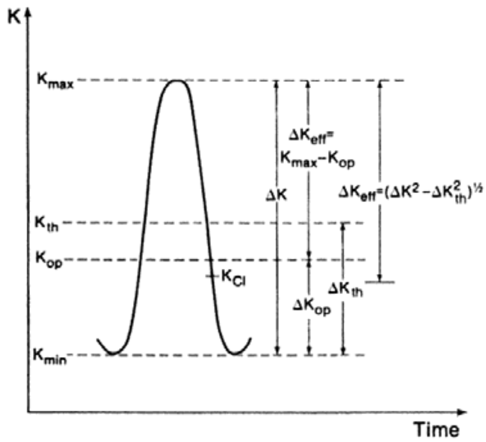

Figure 15. Dependencies for determination of ΔK_{eff}, /5/.
Slika 15. Zavisnosti za određivanje ΔK_{eff}, /5/

It is clear that the range of threshold stress intensity factor ΔK_{th} has to be considered. Operating the structure at normal pressures (200/80 bar), the crack propagation is probable and the crack can reach the next cooling pipe in 8 days. Crack growth vs. time is sensitive to the uncertainty in the ΔK_{th}, C and m due to very high cycles.

Crack growth models that contain ΔK_{th} give results with unacceptable scatter if ΔK is relatively small, for low load, followed by high cycles number. For that, operating conditions are limited to keep ΔK as close as possible to the threshold as the technology allows.

At minimal operating pressures (120/60 bar) crack growth is not expected since ΔK is only 4.58 MPa√m < ΔK_{th}, although the threshold value is uncertain. Operation at these pressures is not economical, so investigation is carried out after 15 days to check the crack size and position (Fig. 16): crack did not grow, so some load increase is possible, and a minimum economical operating condition (150/80 bar) is analysed, with ΔK_{th} about 5 MPa√m, enabling acceptable crack length increase Δl = 6.5 mm. Since ΔK_{th} value is uncertain, the longer operation should be based on next ultrasonic tests, which have shown that the crack is stable, and real ΔK_{th} is higher than the applied one.

Table 4. Crack growth at normal operation pressures (200/80 bar).
Tabela 4. Rast prsline pri normalnom radnom pritisku (200/80 bar)

Time	l	Δl	K_{min}	K_{max}	ΔK_{eff}
Day	m	m	[MPa·m$^{0.5}$]	[MPa·m$^{0.5}$]	[MPa·m$^{0.5}$]
0	0.098		18.207	27.366	12.42789
1	0.111	0.013	18.401	27.658	12.71977
2	0.124	0.027	18.879	28.376	13.43779
. . . .					
8	0.262	0.164	25.230	37.923	22.98405

l is crack length

Table 5. Crack growth at economical pressures (150/80 bar).
Tabela 5. Rast prsline pri ekonomičnom pritisku (150/80 bar)

Time	l	Δl	K_{min}	K_{max}	ΔK_{eff}
Day	m	m	[MPa·m$^{0.5}$]	[MPa·m$^{0.5}$]	[MPa·m$^{0.5}$]
1	0.098		16.201	21.545	1.384
2	0.098	1.32E-04	16.203	21.547	1.386
3	0.098	2.64E-04	16.205	21.550	1.389
. . . .					
45	0.104	6.43E-03	16.278	21.646	1.485

CONCLUSIONS

Lifetime analysis is carried out for a cracked cylinder of a giant compressor by complex numerical and experimental methods to ensure minimal continuous production for the period before replacement.

Based on FEM calculations, the opening of the crack at test pressure (284 bar) is about 0.13 mm, and it decreases by 6–8% due to reinforcement. Plastic collapse of the ligament cannot occur but calculations for brittle fracture and crack propagation are required.

For calculation of stress intensity factor, the analytical approach is used. Crack surfaces loaded by outlet pressure are considered in the calculations. The method is verified by numerical calculation.

Brittle fracture is not probable, since K_{Ic} value of the material is higher than the applied K_I value for test load.

Fatigue crack propagation will probably be the main damage mechanism of the cylinder due to the variation of K_I during the load cycle.

The crack can propagate at normal operational pressure (200/80 bar) since ΔK is higher than ΔK_{th} threshold value. The cylinder can operate only 8 days on normal operational pressure (200/80 bar).

At economical pressure (150/80 bar), the cylinder can operate only after inspections prove the crack to be stable. Longer operation can be based on ultrasonic tests.

Finally it was possible to keep the unit in operation until the replacement became possible and about 2-3 million Euros are saved, since the cracked compressor operated safely for more than 2 months!

However the case study shows that further effort is needed to develop methodologies to handle cases that are close to threshold conditions, or for long term/high cycle cases.

After 15 days operation, inspection has validated the calculations and the applied data, checking crack size and position.

After the next 15 days of operation, ultrasonic tests verified the crack is stable.

Figure 16. Experimental verification of crack growth.
Slika 16. Eksperimentalna provera rasta prsline

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