ISSN 1330-3651
UDC/UDK 620.191.33 : 621.513-222] : 519.61

AMMONIA FACTORY GIANT COMPRESSOR CRACKED 3rd STAGE CYLINDER FAILURE ANALYSIS

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Original scientific paper

Failure analysis of a giant compressor cracked cylinder has been performed using complex numerical and experimental methods. Further operating parameters for expected lifetime (with regard to the crack propagation) at reduced pressure are given based on the results of the investigations.

Keywords: *Crack, crack propagation, compressor, FEM, fatigue, fracture, lifetime*

Analiza otkaza napuknutog cilindra trostupanjskog velikog kompresora u tvornici amonijaka

Izvorni znanstveni članak

Analiza otkaza napuknutog cilindra velikog kompresora napravljena je pomoću složenih numeričkih i eksperimentalnih metoda. Temeljem rezultata istraživanja određeni su radni parametri za daljnji rad i vjerojatni radni vijek (s obzirom na širenje pukotine) pod smanjenim tlakom.

Ključne riječi: *Pukotina, širenje pukotine, kompresor, metoda konačnih elemenata, zamor, lom, vijek trajanja*

1
Introduction
Uvod

A crack was found between one of the inlet valve seats and cooling pipe row (Fig. 1-2) of a giant gas compressor. The crack face was situated almost in the symmetry plane.

Figure 1 *The 3rd stage cylinder and crack shape measured by ultra-sound*
Slika 1 *Trostupanjski cilindar i oblik pukotine izmjeren ultrazvukom*

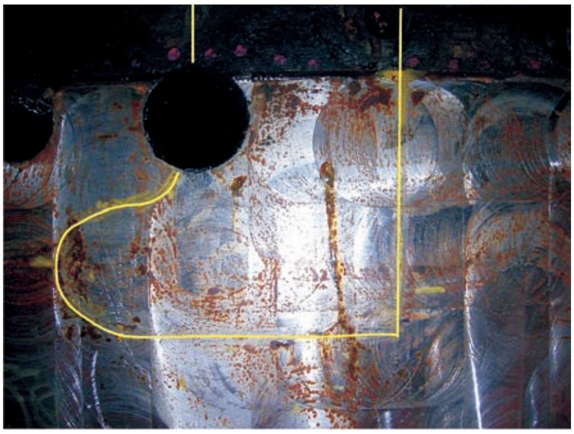

Figure 2 *Crack shape on cylinder surface measured by ultra-sound*
Slika 2 *Oblik pukotine na površini cilindra izmjeren ultrazvukom*

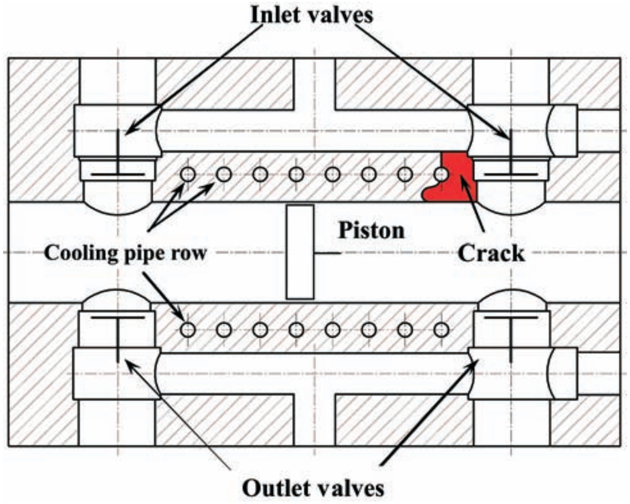

Figure 3 *Cross-section of cylinder with crack*
Slika 3 *Poprečni presjek cilindra s pukotinom*

The crack was dangerous, because it reached the cooling pipe and in this case H_2 might get into the cooling system, where it could be exploded. The customer did not have another cylinder to replace it, and the manufacturing of a new one would take about one month. Stopping the production process would be very expensive. These were the reasons, why the customer wanted to know, how the cracked cylinder could be operated safely until it was replaced by a new one. The Hydrogen leakage had been stopped by closing the two nearest cooling pipes by fastened through-wall bolts.

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

- Is there any plastic collapse danger due to the reduction of the ligament?
- Can the bolts reinforce the house enough to close the crack?
- Can maximum operational pressure cause brittle fracture in static case?
- If yes, then what is the maximum pressure without brittle fracture?
- Can the crack propagate at maximum pressure difference due to the alternating pressure?

operation for low crack propagation?

- What is the time interval of the crack propagation control?

The following calculations were performed to answer the questions:

- FEM calculation at test pressure (284 bar, static), with and without reinforcing.
- FEM calculation at operational pressure (200/80 bar, alternating), with and without reinforcing.
- K_I estimation analytically based on FEM results for test pressure and operational pressure.
- Estimation of K_I changing during operation.
- Estimation of crack propagation rate.

2
Material properties
Svojstva materijala

Material of the cylinder house is 1.7225 equivalent 42CrMo4 steel and its properties have been determined by references [1, 2, 3] and EQUIST database.

Table 1 *Material properties*
Tablica 1 *Svojstva materijala*

$R_{p0,2}$, MPa	R_m, MPa	K_{Ic}, MPa$\cdot$m^{0,5}
500	750-900	60 - 100

ΔK_{th}, MPa$\cdot$m^{0,5}	C	n
5-10	$1{,}11\times10^{-11}$	2,36

3
Structure geometry
Geometrijska struktura

The geometry data were given by the customer. The FEM model of cylinder is shown in Fig. 4-5. The mesh has been created by 10-node parabolic 3D tetrahedral elements. Number of elements was 160650 with 247013 nodes. Linear elastic material model has been applied.

The customer recommended repairing the cracked part by screw reinforcing. The over cracked and the adjacent cooling pipe (in Fig. 5) has been enclosed, rebored, threaded, and the structure reinforced by M33 bolts to detain the crack propagation.

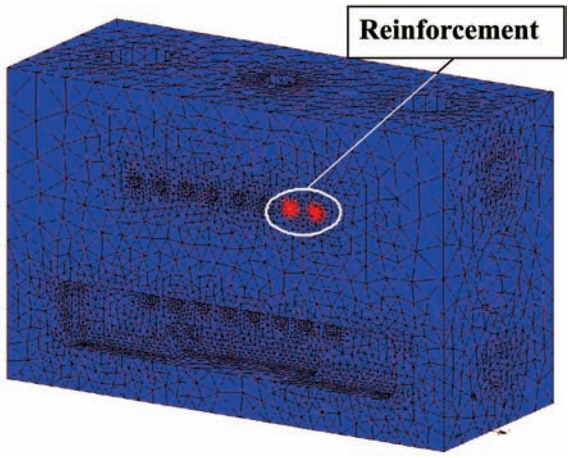

Figure 4 *FEM mesh and the reinforcement*
Slika 4 *MKE mreža i ojačanje*

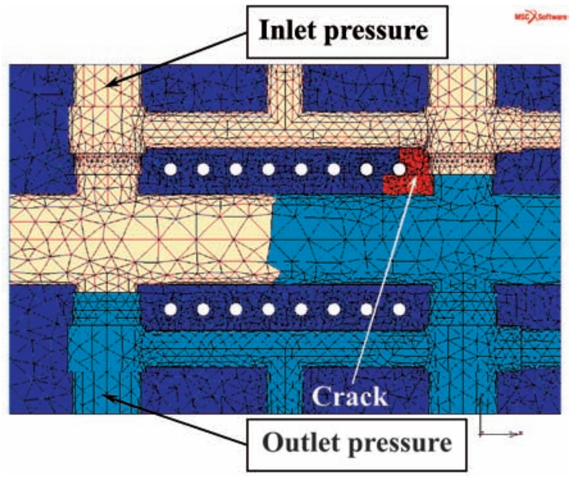

Figure 5 *Cross-section of cylinder with crack for stress calculation*
Slika 5 *Poprečni presjek cilindra s pukotinom za računanje naprezanja*

The reinforcement bolts were modeled by springs and links (Fig. 4). Fig. 5 shows the crack face loaded by outlet pressure, and the surfaces also loaded by outlet pressure. The light surfaces in Fig. 5 were loaded by inlet pressure. The crack face was situated 20 mm from the plane of symmetry. The constraints were on the bottom plane of the body.

The normal operational pressures:

- inlet pressure: 80 bar
- outlet pressure: 200 bar.

4
FEM results
FEM rezultati

At first the calculation was carried out without taking into consideration the effect of the bolts. The results in Fig. 6-9 were calculated with normal operational pressures. The stresses at normal operational pressure were lower than the yield stress, therefore plastic deformation could not cause the damage of the structure. Only a small plastic zone could be found around the crack front.

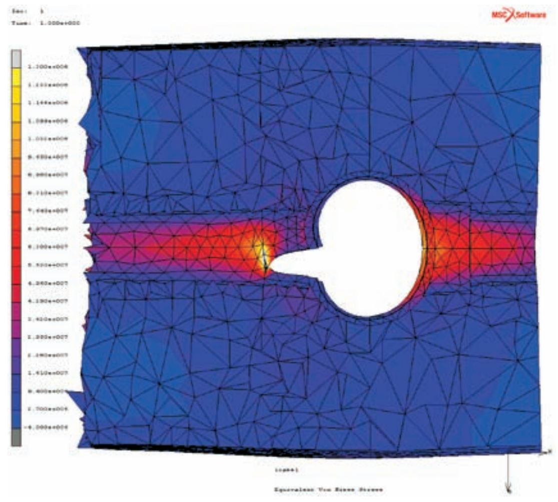

Figure 6 *Equivalent von Mises stress result around the crack without reinforcement (strains in 600× magnification)*
Slika 6 *Rezultat ekvivalentnog von Mises-ovog naprezanja oko pukotine bez ojačanja (deformacija - povećana 600×)*

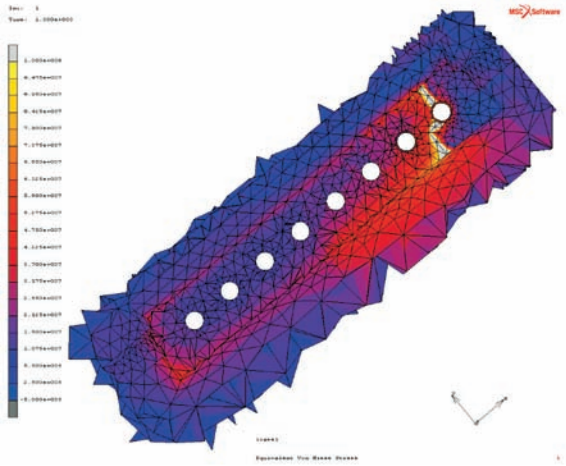

***Figure** 7 Equivalent von Mises stress result around the cooling pipe row with crack without reinforcement*
***Slika** 7 Rezultat ekvivalentnog von Mises-ovog naprezanja oko reda cijevi za hlađenje sa pukotinom bez ojačanja*

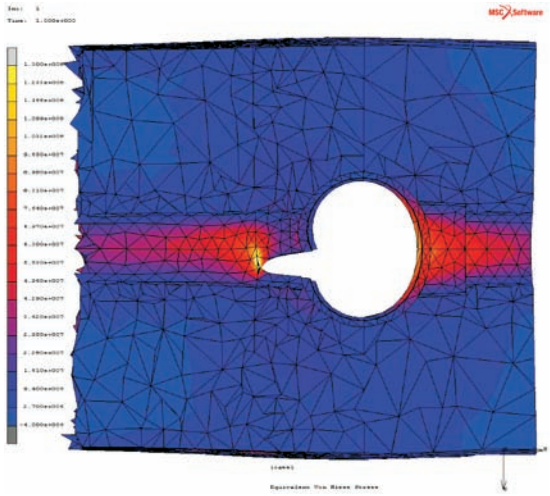

***Figure 8** Equivalent von Mises stress result around the crack with reinforcement (strains in 600x magnification)*
***Slika 8** Rezultat ekvivalentnog von Mises-ovog naprezanja oko pukotine s ojačanjem (deformacija - povećana 600x)*

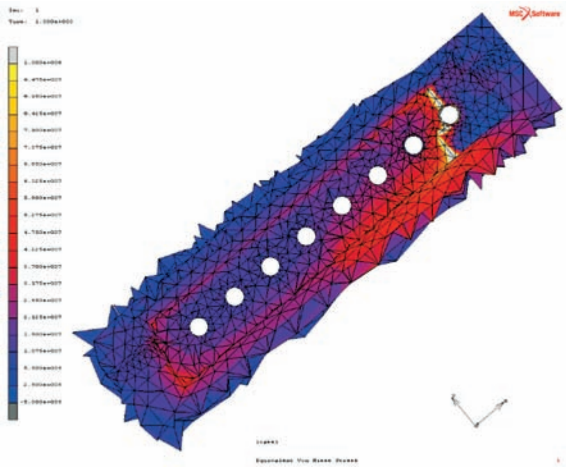

***Figure 9** Equivalent von Mises stress result around the cooling pipe row with crack and reinforcement*
***Slika 9** Rezultat ekvivalentnog von Mises-ovog naprezanja oko reda cijevi za hlađenje sa pukotinom i ojačanjem*

The reinforcements have been taken into consideration for the next calculation. Comparing the stresses in Fig. 6 and in Fig. 8 it can be shown that the stresses decreased by about 6-8 % near to the crack due to the reinforcement but it is not enough to close the crack so further crack propagation can take place.

Eigen-frequency calculation was performed on cracked cylinder body to point out the additional load by power equipment vibration. The revolution number of power equipment was 333 1/min. Table 2 shows the first ten eigen-frequencies of cylinder body.

***Table 2** The first ten eigen-frequencies of cylinder body*
***Tablica 2** Prvih deset vlastitih frekvencija tijela cilindra*

Number of eigen-frequency	Value of eigen-frequency/ Hz
1.	175,3
2.	625,6
3.	758,1
4.	773,6
5.	810,8
6.	1223
7.	1368
8.	1657
9.	1783
10.	1874

Power equipment frequency (5,55 Hz) was much lower than the eigen-frequencies, therefore resonance during the operation did not develop, so dynamic effects did not have to be taken into consideration.

5
Fracture mechanics analyses
Analize mehanike loma

Fracture mechanical analyses were performed for brittle fracture and crack propagation calculation. Simplified plane-strain model as shown in Fig. 10 has been applied for the analytical fracture mechanical analysis. The model has been verified by FEM calculation.

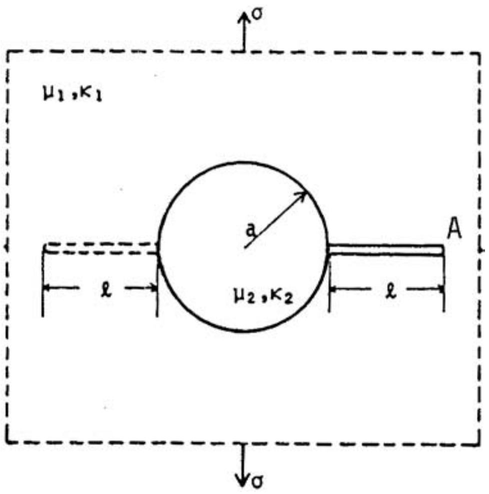

***Figure 10** Simplified model of the crack*
***Slika 10** Pojednostavljen model pukotine*

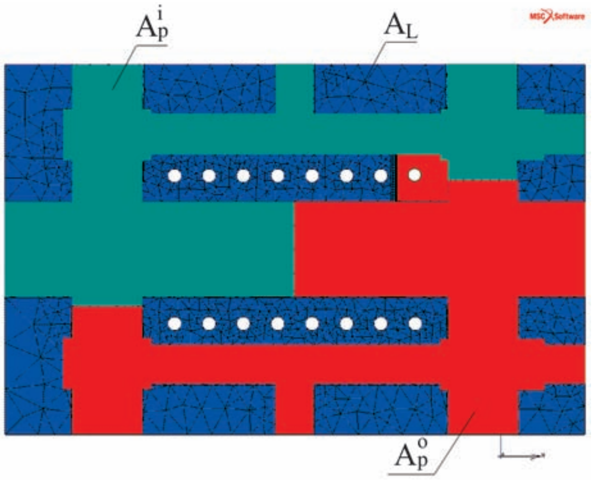

Figure 11 *Cross-section of cylinder with crack, for J-integral calculation*
Slika 11 *Poprečni presjek cilindra s pukotinom, za računanje J-integrala*

The analytical stress intensity factor solution for simplified model based on the Stress Intensity Factors Handbook [4]:

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

where: K_{IA} - Stress intensity factor, F_{IA} - from Table 3 (linear interpolation is applied), σ - nominal stress, p - pressure, l - crack length.

Table 3
Tablica 3

l/a	1	1,5	2
F_{IA}	1,306	1,127	1,031

The nominal stress was calculated based on the ratio of the inlet and outlet pressure loaded area to the ligament section (Fig. 11) as follows:

$$\sigma = p_i \cdot \frac{A_p^{\mathrm{i}}}{A_{\mathrm{L}}} + p_o \cdot \frac{A_p^{\mathrm{o}}}{A_{\mathrm{L}}} \tag{2}$$

The stress intensity factor was calculated analytically for the minimal operational pressures, where inlet pressure 60 bar, outlet pressure: 120 bar. In this case the stress intensity factor was 17 MPa·m^{0,5}. The FEM calculated stress intensity factor was 14,1 MPa·m^{0,5} based on the model in Fig. 11. Good agreement between analytically and FEM calculated stress intensity factors means the analytical model is applicable for this case.

In the first analysis the pressure was a test pressure of normal operational pressure. The inlet and outlet pressure were the same p_{test}=284 bar. The fracture toughness of material was K_{IC}=60-100 MPa·m^{0,5}. Using equation (1) at test pressure, the K_{I}=47,5 MPa·m^{0,5} < K_{IC} for material, therefore brittle fracture of structure was not probable.

The second analysis was the estimation of crack propagation. The crack propagation speed was calculated by Paris-Erdogan equation (3).

$$\frac{\mathrm{d}l}{\mathrm{d}N} = \mathrm{C}(\Delta K)^{\mathrm{n}} \tag{3}$$

where: C, n – parameters of crack extension curve, ΔK – change of stress intensity factor due to load cycle, dl/dN – crack length extension unit in load cycles.

If change of K_{I} is smaller than the ΔK_{th} value the crack should not propagate, but this value was uncertain so the most conservative 5 MPa·m^{0,5} was taken into consideration.

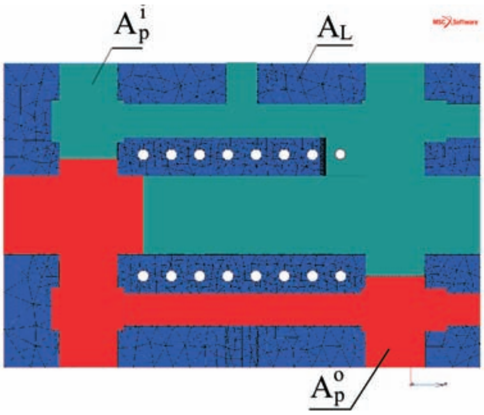

Figure 12 *Minimum load for the cross section*
Slika 12 *Minimalno opterećenje za poprečni presjek*

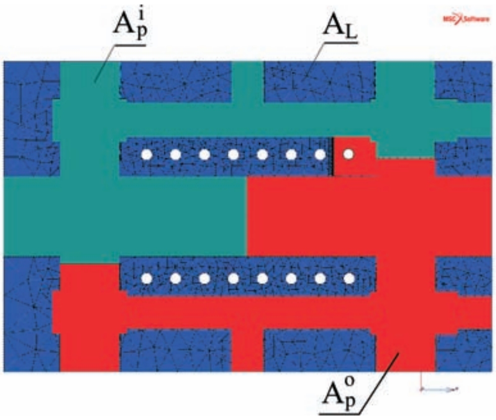

Figure 13 *Maximum load for the cross section*
Slika 13 *Maksimalno opterećenje za poprečni presjek*

Table 4 *Results of crack propagation at normal operational pressures (200/80 bar).*
Tablica 4 *Rezultati širenja pukotine pri normalnim radnim tlakovima (200/80 bar)*

Time, days	l, m	Δl, m	$K_{\min}$, MPa·m^{0,5}	$K_{\max}$, MPa·m^{0,5}	ΔK, MPa·m^{0,5}
0	0,098		18,207	27,366	9,160
1	0,101	0,003	18,259	27,444	9,186
2	0,104	0,007	18,297	27,501	9,205
13	0,145	0,047	19,352	29,088	9,736

Table 5 *Results of crack propagation at minimal operational pressures (120/60bar).*
Tablica 5 *Rezultati širenja pukotine pri minimalnim radnim tlakovima (120/60 bar)*

Time, days	l, m	Δl, m	$K_{\min}$, MPa·m^{0,5}	$K_{\max}$, MPa·m^{0,5}	ΔK, MPa·m^{0,5}
0	0,098	-	12,452	17,032	4,580
1	0,098	0,001	12,460	17,042	4,583
2	0,099	0,001	12,467	17,052	4,585
45	0,129	0,031	12,993	17,772	4,779

Using the structure at normal operational pressures (200/80 bar), the crack propagation would have been probable and the crack could have reached the next cooling pipe in 11 days. At minimal operational pressures (120/60 bar) the crack would probably not have been able to propagate , since $K < K_{\mathrm{th}}$, but even if it had propagated, the propagation length would have been only l=31 mm in 45 days, so the required lifetime should have been performed.

However the operation at minimal operational pressures (120/60 bar) is not economical. So after 15 days operation, investigation was carried out to check the crack size and position. The measurements validated the calculations and the applied data since no crack extension was found. So the minimum economical operation condition (150/80 bar) was analyzed.

Table 6 *Results of crack propagation at minimal economical pressures (150/80 bar)*
Tablica 6 *Rezultati širenja pukotine pri minimalnim ekonomičnim tlakovima (150/80 bar)*

Time, days	l, m	Δl, m	$K_{\min}$, MPa·m^{0,5}	$K_{\max}$, MPa·m^{0,5}	ΔK, MPa·m^{0,5}
0	0,098	-	16,201	21,545	5,343
1	0,098	0,001	16,216	21,563	5,348
2	0,099	0,002	16,229	21,581	5,352
45	0,143	0,046	17,200	22,872	5,672

K value is small, higher than the minimum K_{th} (5 MPa·m^{0,5}) value so the crack might be able to propagate, but the propagation length would be l=46 mm. In this case the crack might propagate over the next cooling pipe. The estimated lifetime at increased operational pressure was 28 days. The structure could be used at increased operational pressure (150/80 bar). The applied K_{th} value was uncertain and quite conservative. The longer operation should be based on further ultra-sonic tests certifying that the crack is stable. The stable crack can show that the real K_{th} value is higher than the applied one.

6
Conclusions
Zaključci

The lifetime analysis has been carried out for a cracked cylinder of giant compressor by complex numerical and experimental methods to ensure suitable minimal continuous production for the period til the replacement is found.

Based on FEM calculations, the opening of crack at test pressure (284 bar) was about 0,13 mm, and it decreased by 6-8 % due to reinforcement, therefore the leakage of a large quantity of ammonia gas at high pressure was not probable in correction time interval. Plastic collapse of the ligament could not occur but for brittle fracture and crack propagation fracture mechanics calculation had to be carried out.

For the calculation of stress intensity factor, analytical approach has been used. The crack surfaces loaded by outlet pressure have been supposed in calculations. The applied method has been verified by numerical calculation.

Brittle fracture of structure is not expected, since K_{Ic} value of material is higher than the K_{I} value calculated from the applied test loads.

The fatigue crack propagation will be probably the main damage mechanism of cylinder due to the K_{I} value variation due to the load cycle.

The crack can propagate at the normal operational pressure (200/80 bar) since the K is higher than the K_{th} threshold value. The cylinder can operate only 11 days at normal operational pressure (200/80 bar)

The cylinder can operate until the required lifetime at lower operational pressure, and additional periodic ultra-sonic inspection of crack propagation can be basic for economical operation.

At economical operational pressure, the cylinder can probably operate 28 days, but this operational pressure is recommended only after inspections proving that the crack is stable at minimal operational pressure. Furthermore even longer operation can be based on further ultra-sonic tests.

7
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