MECHANICS AND CONTROL
Vol. 31 No. 4 2012
http://dx.doi.org/10.7494/mech.2012.31.4.164

Stanisław Wolny*, Bogusław Ładecki*

ENDURANCE ANALYSIS OF KOEPE PULLEYS WITH PERIPHERAL RIBS

SUMMARY

There are numerous hoisting installations operated in Polish mines that are equipped with winding gear incorporating a Koepe pulley reinforced with peripheral ribs, where the symptoms of fatigue cracking are often revealed. Current repairs of those areas help mitigate for this undesirable phenomenon for a short time only. In order to eliminate this problem, steps have been taken to identify the origins and propagation patterns of fatigue cracks in Koepe pulleys. A numerical model of a Koepe pulley is developed and the endurance analysis is performed by the FEM method, preceded by a dynamic analysis of the normal duty cycle of the hoisting installation. The results of dynamic and endurance analyses are verified through experimental testing on a real object, involving force and stress measurements taken at selected points on the Koepe pulley. Those measurement data provide the background for the fatigue endurance assessment and new re-designs of the Koepe pulley structure.

***Keywords**: dynamics, endurance, FEM, fatigue of material , experimental testing*

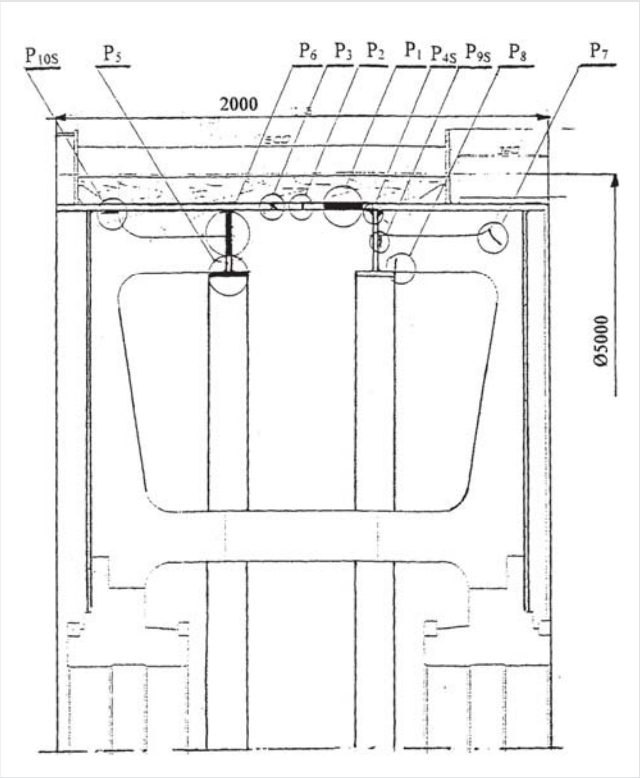
ANALIZA WYTRZYMAŁOŚCIOWA KÓŁ PĘDNYCH Z ŻEBRAMI OBWODOWYMI

W polskim górnictwie eksploatowana jest aktualnie pewna liczba wyciągów szybowych z maszynami wyciągowymi wyposażonymi w bębnowe koła pędne z żebrami obwodowymi, w konstrukcji, których stwierdzano występowanie pęknięć o charakterze zmęczeniowym. Bieżące naprawy wykonywane w obszarach występowania pęknięć, tylko doraźnie ograniczyły to zjawisko. W celu wyeliminowania tego problemu, podjęto kroki mające na celu zidentyfikowanie źródła powstawania i rozwoju pęknięć zmęczeniowych kół. W tym celu opracowano model numeryczny konstrukcji koła pędnego, dla którego wykonano analizę wytrzymałościową metodą elementów skończonych, która poprzedzona została analizą dynamiczną pracy urządzenia wyciągowego dla normalnego cyklu pracy wyciągu. Wyniki tych analiz – dynamicznej i wytrzymałościowej – zostały zweryfikowane eksperymentem na obiekcie rzeczywistym, poprzez pomiar sił oraz naprężeń w wybranych obszarach konstrukcji koła pędnego. Uzyskane rezultaty dały podstawę do wykonania oceny trwałości zmęczeniowej oraz opracowania koncepcji przeprowadzenia rekonstrukcji rozważanych konstrukcji kół pędnych.

***Słowa kluczowe**: dynamika, wytrzymałość, MES, zmęczenie materiału, badania eksperymentalne*

1. INTRODUCTION

There are numerous hoisting installations operated in Polish mines that are equipped with winding gear incorporating drum-type Koepe pulleys with two peripheral rings reinforcing the mantle (Fig 1). This type of drums reveal numerous fatigue cracks and periodic repairs do not eliminate the cause of crack-



Crack types detected on drums:
$P_1(P_{1S})$ – cracking of the mantle material (butt weld) in the direction of the generating line,
$P_2(P_{2S})$ – peripheral cracking of the mantle material (butt weld),
$P_3(P_{3S})$ – transverse cracking of the mantle material (butt weld),
P_{4S} – peripheral cracking of fillet weld connecting the web of the peripheral rib with the mantle,
$P_5(P_{5S})$ – cracking of the shelf (butt weld) of the peripheral rib,
$P_6(P_{6S})$ – radial or skewed cracking of the web (butt weld of the web or the fillet weld of the web bit) of the peripheral ribs,
P_7 – skewed cracking of a transverse reinforcing rib,
$P_8(P_{8S})$ – radial cracking of the transverse rib (butt weld of the transverse rib),
P_{9S} – cracking of a fillet weld connecting the transverse ribs with the web of the peripheral rib,
P_{10S} – cracking of a fillet weld connecting the transverse ribs with the mantle

Fig. 1. Schematic diagram of the Koepe pulley with peripheral reinforcing rings and the types of detected cracks

---

* AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Krakow, Poland; swolny@agh.edu.p

ing at those points. Fault detection tests help identify the types and intensity of fatigue cracking (Cichociński 2005, Ładecki 2008) – Figures 1–4 and the Non-Destructive Test data indicate that most fatigue cracking originate in the drum mantle area.

The quick rate of fatigue crack emergence and propagation and hence the necessity of frequent repairs of Koepe pulleys is responsible for poor safety features and inferior performance of the winding gear.

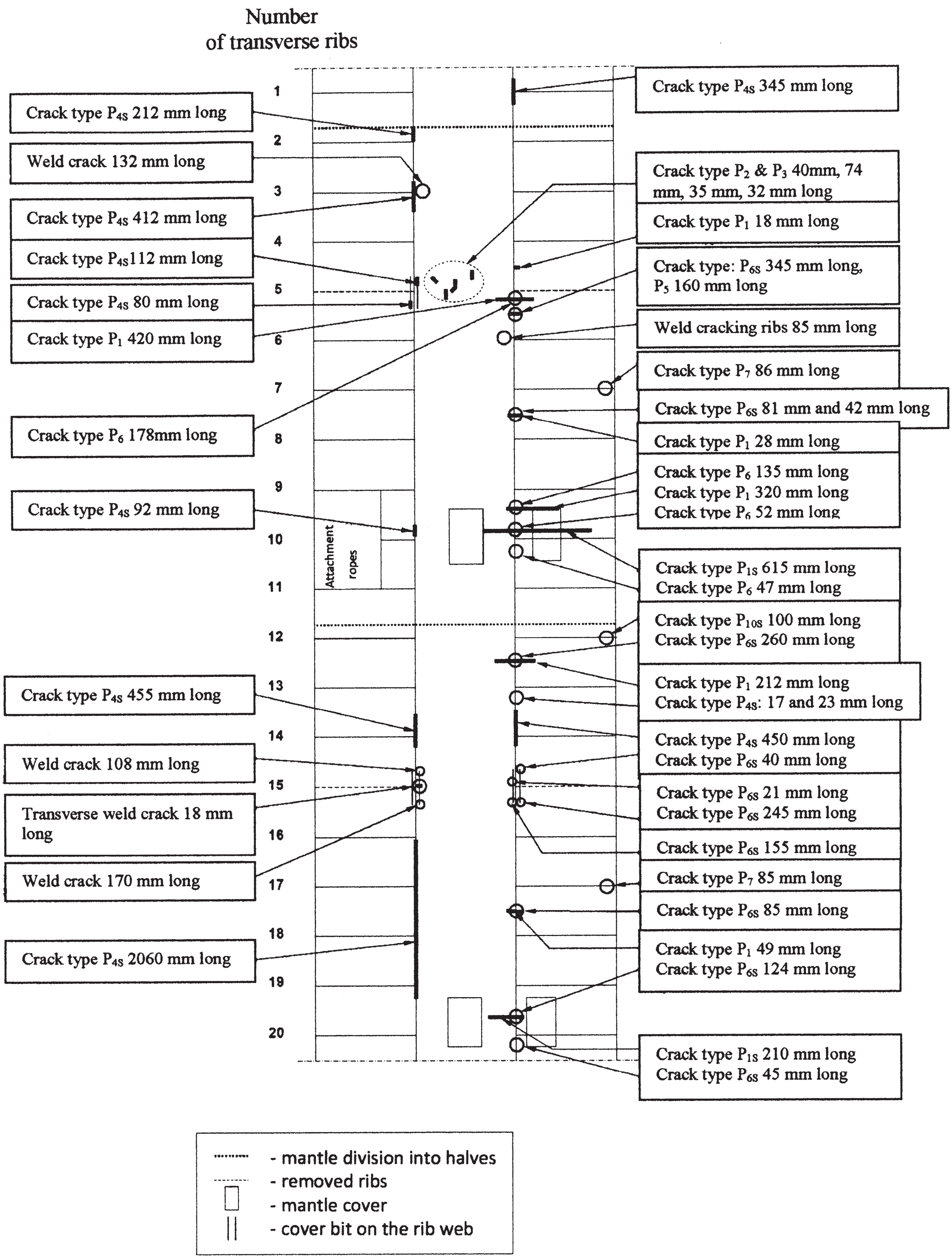


Fig. 2. Intensity of fatigue cracking revealed by fault detection tests of the drum

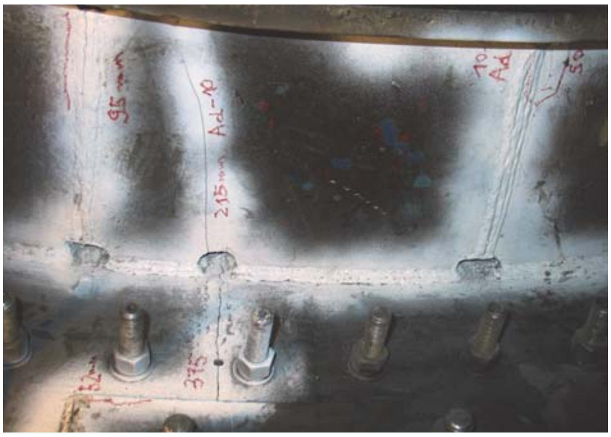


Fig. 3. Crack type: P_6 215 mm long, P_{6S} 95 and 50 mm long, P_1 375 mm long and cracking of the cover bit weld 52 mm long detected in the peripheral rib region by the magnetic powder inspection method

Fig. 4. Crack type P_7 86 mm through the transverse rib detected by the magnetic powder inspection method

Those considerations have prompted the Authors' attempts to evaluate the working order of the drums in the Koepe pulley structure, taking into account the fatigue wearing. The dynamic analysis of structural components of the hoisting installation is supported by the fatigue endurance analysis of the Koepe pulley, verified by strain (stress) measurements taken on a real object under the typical operating conditions in a colliery in Poland.

2. DYNAMIC LOAD ACTING ON A KOEPE PULLEY UNDER THE TYPICAL OPERATING CONDITIONS

The real loads acting on the pulley drum are obtained from the dynamic analysis of its operation throughout the typical duty cycle (Wolny 2009a). Since tower-type winding installations with pulley blocks are now in widespread use in Polish collieries, this analysis shall be confined to a this type of hoisting installation, shown schematically in Figure 5.

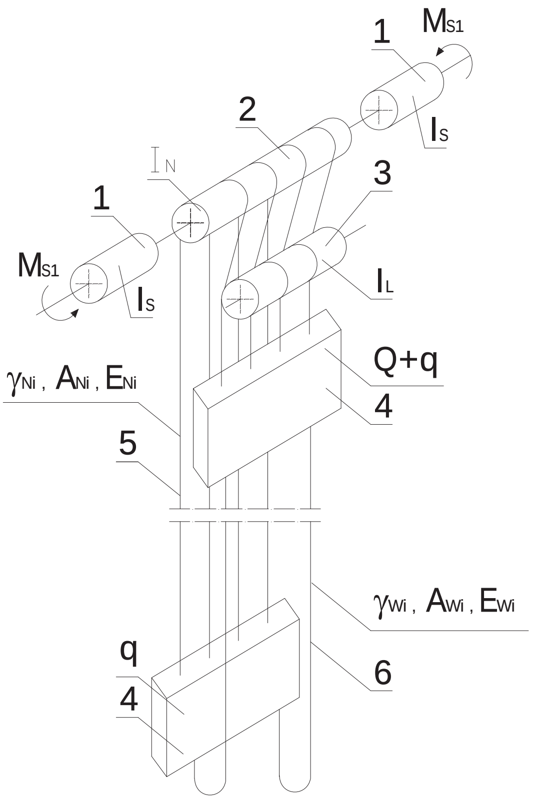


Fig. 5. Schematic diagram of the hoisting gear

The physical system incorporates:

- low speed *dc* motor,
- multi-rope pulley block with the diameter *D* and inertia moment I_N
- baffle wheel assembly
- skips (conveyance) with mass q and loading capacity *Q*,
- branches of parallel – arranged hoisting ropes with the density γN and tensile rigidity $A_N E_N$

Results of dynamic analyses (Wolny 2009a) and measurements taken on a real object (Wolny 2009b) provide the backgrounds for deriving analytical formulas to compute the maximal and minimal loads transmitted from the hoisting ropes onto the drum in the winding gear.

2.1. Maximal loading of the drum

The maximal loads are transmitted from hoisting ropes onto the drum at the instant a full conveyance begins to be hoisted from the bottom level and are given as (Wolny 2009b):

$$S_{\max} = S_{St}^{R} + \Delta S^{R}, \qquad (1)$$

where:

S_{St}^{R} – maximal static load transmitted from the rope onto the Koepe pulley in the start-up phase,

$$\Delta S^{R} = A_N E_N \frac{a_1}{a_N} \frac{8 l_N}{a_N} \left[1 - e^{-k}\right] \frac{1}{k}, \qquad (2)$$

$$k = \frac{A_N E_N}{M_2 a_N};\ M_2 = Q + q\ ,$$

a_1 – acceleration in the start-up chase,
a_N – velocity of elastic wave propagation in hoisting ropes,
l_N – hoisting rope length at the instant when the full conveyance begins to move upward from the bottom level.

2.2. Minimal loading of the drum

The minimal loads are transmitted from hoisting ropes onto the drum at the instant when the full conveyance approaching the station begins the braking phase and are given as (Wolny 2009b):

$$S_{\min} = S_{St}^{H} + \Delta S^{H}\ , \tag{3}$$

where:
S_{St}^{H} – static load transmitted from the hoisting ropes onto the Koepe pulley at the instant when the full conveyance begins to brake when approaching the top level.

$$\Delta S^{H} \equiv -A_N E_N \cdot \frac{a_2}{a_N} \cdot \frac{20{,}5 l^{*}}{a_N}\ , \tag{4}$$

l^* – hoisting rope length from the Koepe pulley to the conveyance at the instant when the braking phase begins in the normal duty cycle.

3. ENDURANCE ANALYSIS

The endurance analysis of the Koepe pulley in the winding gear is performed to obtain full information about the state of stress experienced in structural elements of the Koepe pulley under the operational loads. Finding the extreme values of stress components acting in the given element becomes the basis for endurance and fatigue life assessment (the maximal admissible length of service). Information about the stress values and distribution will be utilised to identify those areas where fatigue cracking is likely to occur due to high stress levels and where regular non-destructive tests are recommendable.

In the context of the above considerations, the endurance analysis is performed of Koepe pulley components by numerical methods (Cichociński 2005). The FEM approach is employed, supported by the ‘FEMAP’ and “NE/Nastran” programs and utilising the computational models of the drum composed of shell – type and solid elements to fully capture the geometry of the analysed structures.

Selected FEM results are shown in the form of contour plots of displacement and stress distributions in the drum model. The drum displacement is shown in Figure 6 and the plots of reduced stress σ_H, derived in accordance with the Huber – Miseses hypothesis, are given in Figure 7 (for the mantle) and Figure 8 (the diaphragm and side disc). Computer simulations reveal that extreme stresses occur in the areas where fatigue cracks appear and propagate and the stress values registered in the drum regions fall in the range from 45 MPa to 70 MPa.

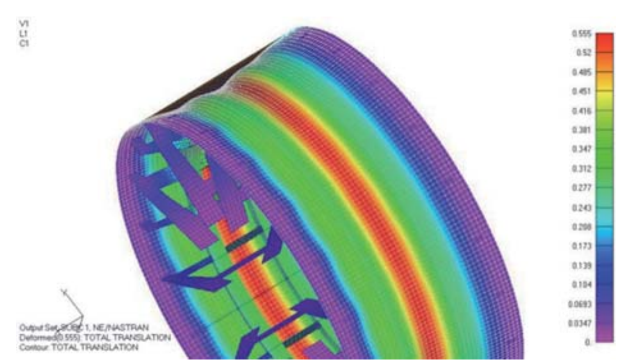


Fig. 6. Deformations of the drum mantle and distribution of displacement [mm] (original design)

Fig. 7. Reduced stress distribution σ_H [MPa] on the mantle’s interior surface

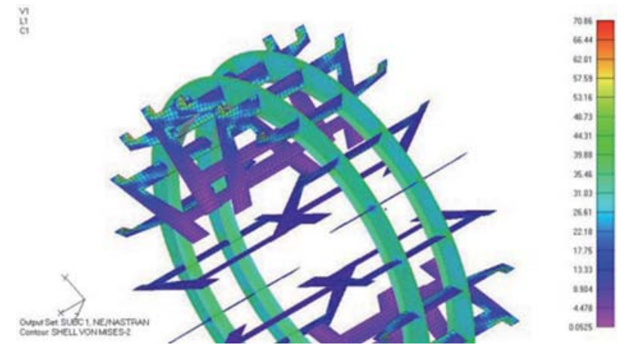


Fig. 8. Reduced stress distribution σ_H [MPa] in the rings and peripheral ribs

4. TENSOMETRIC MEASUREMENTS

Measurements of service stress and strain in a Koepe pulley operated in a colliery in Poland are taken by the tensometric method (Cichociński 2005). The locations of sensors is shown in Figure 9. Tensometric sensors 1,2 are used to measure peripheral stresses on the shelves of reinforcing rings, strain sensors 3, 4, 5, 6 measure the peripheral and transverse stresses in two regions on the drum mantle. Measurements are taken under the controlled service conditions: loading at the bottom station, the skip travel upward with full kinematic parameters, unloading at the top station and downward ride of an empty skip with full kinematic parameters. Measurement results obtained from sensors 2 and 5 are shown in Figures 10 and 11. Measurement data reveal that in each duty cycle of the drum the peripheral stresses registered by sensors 1, 2, 3, 5 are compressive stresses whilst the transverse stresses measured by sensors 4 and 6 are tensile stresses. Stress levels measured with particular sensors are summarised in Table 1 and compared with admissible stress levels for the given drum design and operating conditions as specified in the technical standard PN-B-03200:1990.

Measurement data compiled in Table 1 reveal that the normative stress levels are vastly exceeded at all control points.

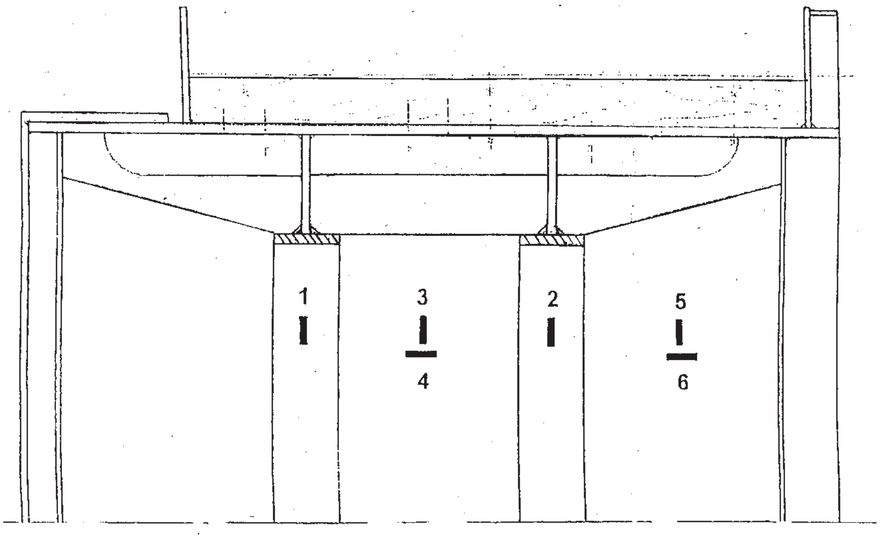


Fig. 9. Strain sensor arrangement on the drum

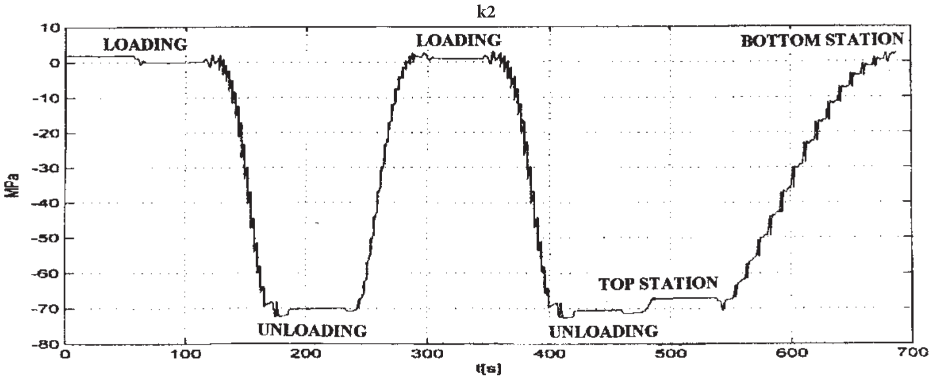


Fig. 10. Stress in the function of time, measured by sensor 2

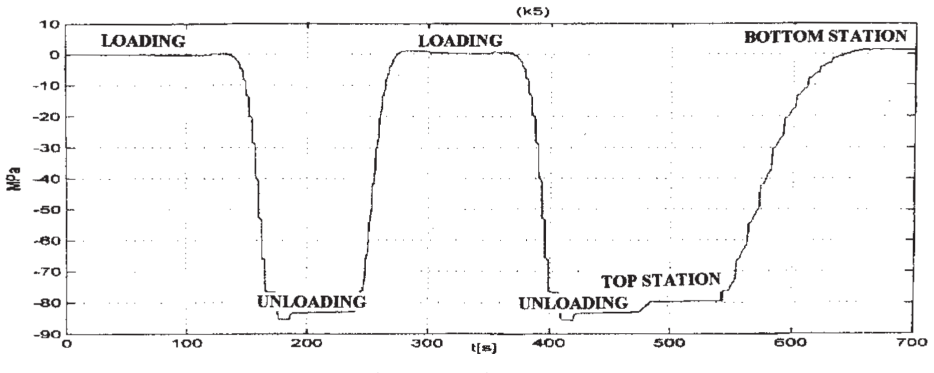


Fig. 11. Stress in the function of time, measured by sensor 5

Table 1

Stress levels obtained by tensometric measurements

Sensor	Stress range Δσ [MPa]		Admissible level exceeded by [%]
	Measured	Admissible	
1	49	36	36
2	72	36	100
3	118	57	107
4	90	57	58
5	86	57	51
6	98	57	72

5. DRUM RE-DESIGN

Results of FEM simulations and stress measurement data clearly indicate that fatigue cracking is caused by insufficient load-bearing capacity and rigidity of the drum mantle. Several solutions aimed to improve the drum mantle resistance are explored. Finally, the option is chosen where one of the two reinforcing rings should be removed and replaced by three carefully spaced rings of smaller cross-section, as shown in Figure 12 (Cichociński 2005).

Selected results of numerical simulations graphed as plots of reduced stress along the generating line of the mantle are shown in Figures 13 and 14.

Numerical simulations data provides vital information about the stress and stress distribution in computational models. Radial displacements of the mantle in the re-designed drum is lower by 18.7%. Changes in registered stress levels are compiled in Table 2.

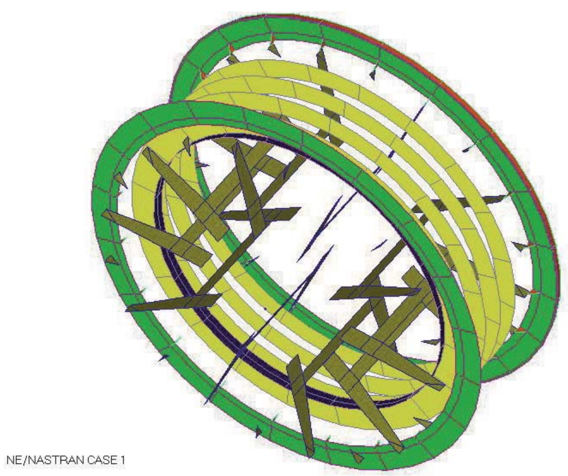


Fig. 12. Shape and arrangement of rings and ribs in a re-designed construction

Table 2

FEM results

Maximal reduced stress σ_H [MPa]	Model	
	Original design	Re-design
In the model	71	60
On the mantle's external surface	65	45
On the mantle's internal surface	55	49
On rings in contact with the mantle	55	49
On the rings' inside diameter	43	46

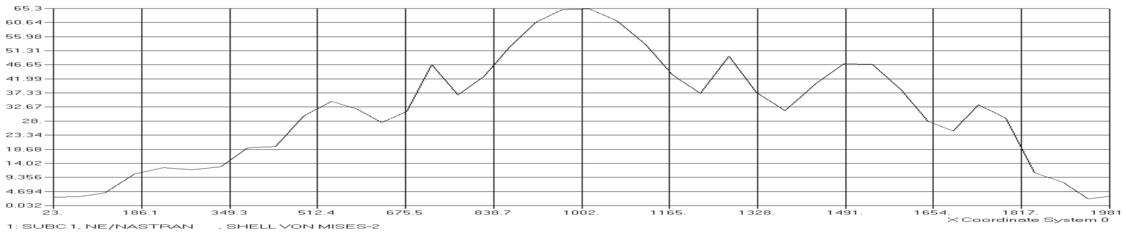


Fig. 13. Reduced stress σ_H [MPa] along the generating line of the mantle. Original drum design

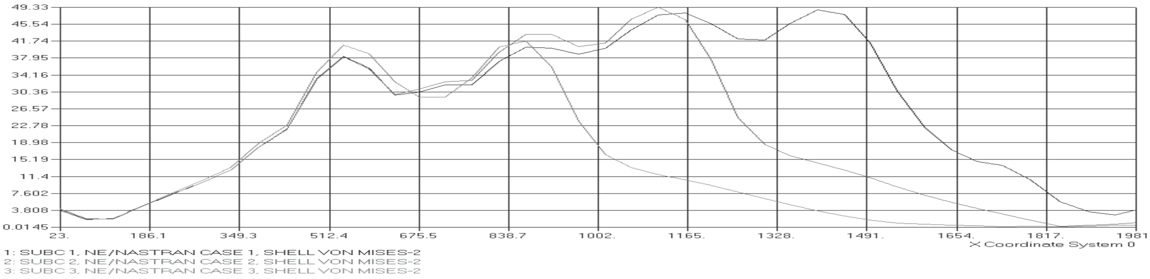


Fig. 14. Reduced stress σ_H [MPa] along the generating line of the mantle (for three cases of applied loading). Re-designed drum

6. FINAL CONCLUSIONS

Results of fault detection tests, FEM analyses and strain measurements clearly indicate that fatigue cracking is caused by insufficient load-bearing capacity and rigidity of the drum mantle. In order to improve the fatigue endurance of the Koepe pulleys, it is suggested that one of the existing reinforcing rings should be removed and replaced by three carefully spaced rings of smaller cross-section. Computer simulations of a re-designed drum reveal that radial displacements of the mantle are reduced by 18.7% and stress levels in the regions of the mantle decrease by 10.9–30.8%.

References

Cichociński A., Ładecki B., Podsiadło A., kier. Płachno M., 2005, *Wykonanie analizy, pomiarów oraz opracowanie sposobu naprawy maszyny wyciągowej skipowej*, Praca nr 5.5.130.490. AGH, Wydział Inżynierii Mechanicznej i Robotyki.

Ładecki B., Cichociński A., 2008, *Badania nieniszczące z analizą wytrzymałościową bębnów maszyn wyciągowych z obwodowymi pierścieniami usztywniającymi*, Materiały 37 KKBN. PTBNiDT SIMP.

Wolny S. 2009a, Dynamic Loading of the Pulley Block in a Hosting Installation in Normal Operating Conditions, Archives of Mining. Vol. 54. No.2, p. 261–284.

Wolny S. Płachno M., 2009b, *Experimental Verification of Bearing of Bearing Rope Loading in Typical Operating Conditions of the Hoisting Installation.* Archives of Mining Science. Vol.54 No.2, p. 531–542

Warunki techniczne projektowania, wykonania i odbioru złączy spawanych w obiektach, urządzeniach i maszynach górniczych 1982, Biuro Studiów i Projektów Górniczych, Katowice.

Załącznik nr 17 do Rozporządzenia Ministra Przemysłu i Handlu. 1995, Tom IV (szybowy). Wymagania w zakresie budowy i obsługi górniczych wyciągów szybowych, Wyd. „KADRA” Katowice 1995.

PN-B-03200:1990 – *Konstrukcje stalowe. Obliczenia statyczne i projektowanie.*