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HOISTING MACHINE BRAKE LINKAGE STRAIN ANALYSIS

ANALIZA ODKSZTAŁCEŃ DŹWIGNI HAMULCA MASZYNY WYCIĄGOWEJ

The brake linkage of a hoisting machine is a very important component determining the safety of the hoisting machine's entire braking system. It is subject to weekly inspections. However, an efficiency test of brake performance is carried out every 6 months. Once every 3 years, a test must be carried out by an appraiser who pays particular attention to the executive and control components of the brakes as well as the strain - brake system and brake release components. The legal provisions regulating the testing of braking system linkages are not precise. So far, the control has been based on random measurement of strains using electrical resistance strain gauges stuck to the surface of the linkage. A new method for measuring the strains of the linkage has been proposed in the work. It is based on fibre optic strain sensors with Fibre Bragg Gratings (FBG). They are mounted using specially designed and tested holders for mounting on the brake linkage. They provide quick assembly and the measurement of strain in the direction parallel to the axis of the linkage. The structure of the holder also allows for the measurement in 4 positions turned every 90 relative to one another. Such a measurement enables a comprehensive analysis of strains and stresses in the brake linkage. In the work, it was shown that there is a complex state of strain and stress in the brake linkage. The previous procedures for linkage testing are inadequate in relation to this condition. An experimental and numerical method was proposed to assess the state of linkage stress. It should constitute the basis for the decision of the appraiser to allow the linkage for further use. The method proposed in the work also allows for continuous measurements of linkage strains as well as dynamic braking tests.

Keywords: brake linkage, strain, stress, fiber optic sensors

Cięgło hamulca maszyny wyciągowej jest bardzo ważnym elementem stanowiącym o bezpieczeństwie całego układu hamulcowego maszyny wyciągowej. Podlega ono cotygodniowej kontroli. Natomiast co 6 miesięcy przeprowadzana jest próba skuteczności działania hamulców. Raz na 3 lata badanie musi przeprowadzić rzeczoznawca, który szczególną uwagę zwraca na elementy wykonawcze i sterujące hamulców oraz układ cięgło-hamulec i elementy wyzwalające hamulce. Przepisy prawne regulujące badanie cięgien układów hamulcowych nie są precyzyjne. Dotychczasowa kontrola polega na wyrywkowym pomiarze odkształceń za pomocą tensometrów elektrooporowych przyklejanych do powierzchni cięgła.

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W pracy zaproponowano nową metodę pomiaru odkształceń cięgła. Oparta jest ona na światłowodowych czujnikach odkształceń z siatkami Bragg'a. Są one mocowane za pomocą specjalnie zaprojektowanych i przetestowanych uchwytów do mocowania na cięgle hamulca. Zapewniają one szybki montaż następnie pomiar odkształcenia w kierunku równoległym do osi cięgła i łatwy demontaż. Konstrukcja uchwytu umożliwia także pomiar w 4 położeniach obróconych względem siebie co 90 stopni. Taki pomiar umożliwia kompleksową analizę odkształceń i naprężeń w cięgle hamulca. Powinna ona być podstawą do podjęcia decyzji przez rzeczoznawcę o dopuszczeniu cięgła do dalszej eksploatacji. Zaproponowana w pracy metoda umożliwia także ciągłe pomiary odkształceń cięgła jak również przeprowadzanie prób dynamicznych hamowania.

Słowa kluczowe: cięgno hamulca, odkształcenia, czujniki światłowodowe FBG

1. Introduction

There are a number of legal acts describing the role of strains in the braking system of the hoisting machine. An example of such a legal act is the Polish Regulation of the Council of Ministers of April 30, 2004 on the admission of products for use in mining plants. According to subsection 1.1.6.1.3., The brake with the leverage force transmission system should be equipped with two pairs of brake shoes with separate ties and levers acting on two separate brake pads. In accordance with the following subsections of this regulation: The use of welded joints in linkages and pushers of the force transfer system and their ends is not permitted and Riveted and screw connections of linkages and pushers of the force transfer system cannot be made with rivets or countersunk screws. The linkage of the brake ballast should be forged in its entirety. It is not allowed to make the lower support pin for the brake ballast in the form of a separate part. Brake linkages and bolts of the brake force transfer system should be made of steel with a documented:

1) chemical composition;
2) tensile strength test;
3) impact test for steel on bolts.

The superior document on mining safety, for example in Poland, is the Ordinance of the Minister of Economy of 28 June 2002 concerning occupational safety and health, traffic regulation and specialised fire-fighting protective equipment in underground mining facilities. According to this document, putting the hoisting machine into operation requires the permission of the competent mining supervision authority. At the same time, this body exercises control over the hoisting machine and it is in their discretion to suspend the machine's operation if necessary. As previously mentioned, the control of brake linkage strains as an element determining the reliability of braking and the safety of the entire system is carried out once every 3 years. However, the legal provisions regulating the testing of braking system linkages are not clear and precise. The appraiser decides on the further use of the hoister on the basis of internal documents. The problems of the hoisting machine brake theory in a probabilistic approach were presented by Orlacz in his work (Orlacz, 1970), while Popowicz discussed the issues of mine transport in the context of shaft devices (Popowicz, 1953). In view of the importance of the brake linkage in the safety of the hoisting system, a new method of measuring strains using fibre optic sensors with the Fibre Bragg Grating was proposed. They are characterised by a much higher measuring accuracy (+/–1 μstrain), resistance to harsh environmental conditions, fatigue life and intrinsic safety, as white light constitutes the working medium. The technique used so far for measuring linkage strains based on electrical resistance strain gauges required temperature compensation and labour-intensive sticking of strain gauges to the surface of the linkage. The measurement was one-off, while during the next test, it was necessary to stick the strain gauges again, balance the strain gauge bridge, etc. In the work, a new solution enabling quick mounting of fibre optic sensors to a special holder mounted on the brake linkage was proposed. This solution significantly reduces the assembly time and also allows the multiple use of fibre optic sensors. This proves the universality of the solution. Sensors based on Fibre Bragg Gratings (FBG) are widely used as a reliable and non-destructive monitoring and control tool in numerous structures. They are most often used for continuous measurements of strains, displacements and stresses with simultaneous temperature measurement. Sensors for acceleration, pressure or even humidity measurement are currently available. They are used in multiple areas, including machine building, energy, aviation, construction and medicine. Kim et al. presented an interesting issue of Enhanced Strain Measurement Range of an FBG Sensor Embedded in Seven-Wire Steel Strands (Jae-Min Kim et al., 2017) introduced the new sensing technique of embedding an FBG sensor into the hollow king wire of a tendon, enabling the king wire to be used as a sensor as well as a prestressing. He also determined the values of forces found in wires (Kim et al., 2016) using FBG sensors. The issue of health monitoring of the structure has been presented in detail in by Majumder et al. (2008). In his work (Selvarajan, 2010), A. Selvarajan discussed fibre optic sensors and their applications. Research on FBG fibre optic cables is conducted all over the world, including in Great Britain, Canada, China or India (Selvarajan, 2010; Kashyap, 2008; Majumder et al.; Othonos & Kalli, 1999). In Poland, the three universities dealing with this subject are the Kielce University of Technology, the Lublin University of Technology and the University of Bielsko-Biała.

The team centred around W. Wójcik was one of the first to implement the FBG fibre optic cables for diagnostic purposes. In one of works, published as early as in 2003, he presented the concept of a sensor for measuring stress distribution and temperature using just Fibre Bragg Gratings (Wójcik et al., 2005; Wójcik & Kisała, 2004a, 2004b). Together with Zbigniew Lach and Piotr Kisała (Kisała & Wójcik, 2004a, 2004b; Wójcik et al., 2007a, 2007b), he presented an interesting concept of measuring stresses along the length of the grating. C. Kaczmarek analysed the application of Fibre Bragg Gratings in laser strain sensors (Kaczmarek, 2010). In 2006, Z. Kaczmarek published a monograph on all fibre optic sensors and measuring transducers (Kaczmarek, 2006). A. Sikora presented a number of interesting FBG fibre optic tests (Sikora, 2010). She is the author of the work on the use of Fibre Bragg Gratings in the measurement of quick-change mechanical excitations, as well as many other scientific articles in this field (Kaczmarek & Sikora, 2008). The implementation of FBG fibre optic cables in mining to measure forces in compensating ropes was presented in the works (Juraszek, 2013, 2018). Previously, no attempt was made to apply them to other mining elements, i.e. hoisting machines or braking systems. From this point of view, the presented paper is characterised by innovation.

2. Brakes of Hoisting Machines

The brakes of hoisting devices have a significant impact on the confidence and safety of movement in the shaft. Braking must be carried out in a quick, reliable and precise manner, without impacts and without causing excessive loads on any of the shaft hoister components. After selecting the mine on which the tests would be carried out, it was necessary to choose a specific shaft, the related hoisting machine, and the object to be tested, i.e. the braking system. A direct review of selected machines was necessary. Therefore, all work related to measurements was divided into three stages:

1. Local inspection – inspection, preparation for measurements,
2. Carrying out measurements,
3. Control measurements.

The object of analyses and tests were brakes with a set of shoes with a lower shortening linkage in the "Nowe Brzeszcze" Coal Mine based in Brzeszcze.

Brzeszcze is a city in the Oświęcim region, southern Poland. Although territorially it belongs to the Małopolskie Voivodeship, it is a geological part of the Upper Silesian Coal Basin. In the mine, the exploitation of coal deposits is carried out entirely by means of a longwall system with caving. All exploitation walls are equipped with a housing as well as high-efficiency longwall shearers and scraper conveyors. The mine has 8 active shafts: the main production (skip) airshaft, 3 material and transportation airshafts, and 4 ventilation shafts. Analysing the shafts in the "Nowe Brzeszcze" Coal Mine, the most interest related to testing the brake linkage was evoked by the material and transportation shaft Andrzej II as well as the main production shaft Andrzej V. It was significantly challenging to conduct the tests on the main shaft due to its continuous exploitation.

In the first step, a local inspection of the Andrzej II shaft was carried out. The shaft met the previously formulated criteria. In the further stage, the Andrzej V shaft was verified. The Andrzej V shaft is more expanded compared to the Andrzej II shaft. The only one problem to be solved was its continuous 24-hour operation. The measurement itself is assumed to be quite short (taking a few minutes), yet the preparation, including both methods of electrical resistance strain gauges and FBG fibre optic cables, required longer standstill of the hoisting machine due to the safety of the person conducting the test.

Fig. 1. The Andrzej V East shaft braking system

As a result, the Andrzej V shaft was selected after a series of analyses (Fig. 1). The main purpose of the tests was to determine the actual strain values of the braking system components, including its linkage. The analysed brake is a dual SSW brake with a set of shoes with a lower shortening linkage (described above). Due to the complexity of the issue, a linkage connecting the brake shoes was tested as the component most exposed to strains, being taken under the supervision of the Underground Mining Research and Surveillance Centre in Mysłowice-Brzezinka at the same time. The method of measuring strains presented in the work using FBG fibre optic sensors is versatile and can be used to investigate the strain of other brake components. Next, a description of a complex fast-acting SSW brake (with a floating lever) was presented. The brake drive is a pneumatically-weighted drive by Siemens-Schuckert Werke. An especially important feature of this braking system is that it allows quick operation thanks to the so-called the floating lever, excluding the aggregation of the safety and manoeuvring brake at the same time. The diagram of a brake drive with a floating lever is shown in Fig. 2.

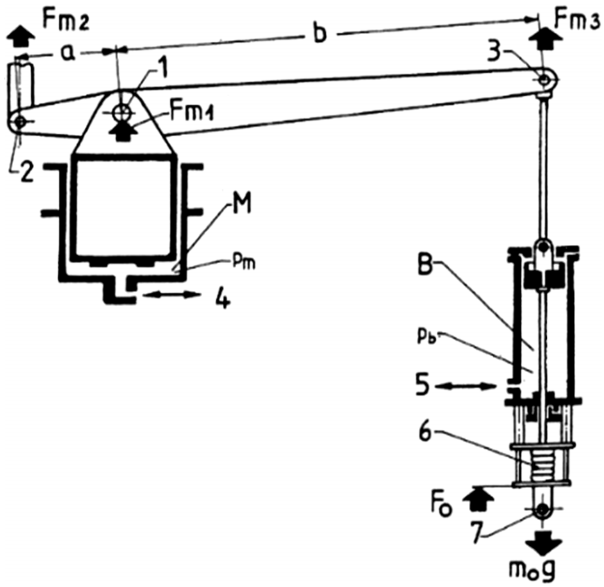

Fig. 2. SSW brake drive. Cylinders with a floating lever. 1,2,3 – points of force application, M – space of the manoeuvring cylinder, B – space of the safety cylinder, 4 – connection with the pressure regulator, 5 – connection with the safety slider, 6 – elastic buffer, 7 – ballast suspension, Fo – initial force

The pistons of safety and manoeuvring cylinder are connected with a joint two-arm lever (B, M, Fig. 2). The drive pushing upwards enables programming of the two-stage safety braking. This is especially important for friction machines as it allows braking during movement within the limits of the rope slip hazard, and then immobilising the hoister. Rigid self-aligning brake shoe assemblies are the most commonly used in hoisting machines. They are designed as straight or curved brake shoes with an upper shortening or lower shortening linkage. The lower shortening system usually consists of four straight shoes and two oblique linkages (Fig. 3). This assembly is prepared for the pushing drive (for the force directed upwards).

The greatest disadvantage of this system is the statically indeterminable distribution of forces. In the calculations, the equality of forces in both linkages is assumed, which is nearly unobtainable in practice, even with very careful periodic shortening of the linkages. The difference in the centricity, smoothness or elasticity of both tracks affects the asymmetry of the occurring forces. If one of the linkages breaks, it is impossible to predict whether the shoe assembly will

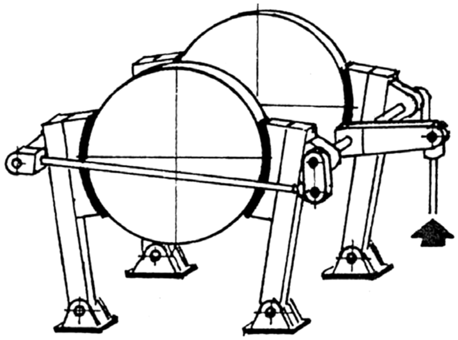

Fig. 3. A lower shortening brake shoe assembly with a pushing drive (seemingly dual)

retain even a partial braking ability. That is why the control of force transmitting components is so vital. The strains should be made in such a way that the design stresses are low. In practice, most of these types of shoe assemblies only meet the condition of 5-fold certainty in relation to the strength limit. Unfortunately, such a solution does not guarantee full fatigue life. The tests were carried out in accordance with the previously prepared experimental research plan, which is shown schematically in Figure 4.

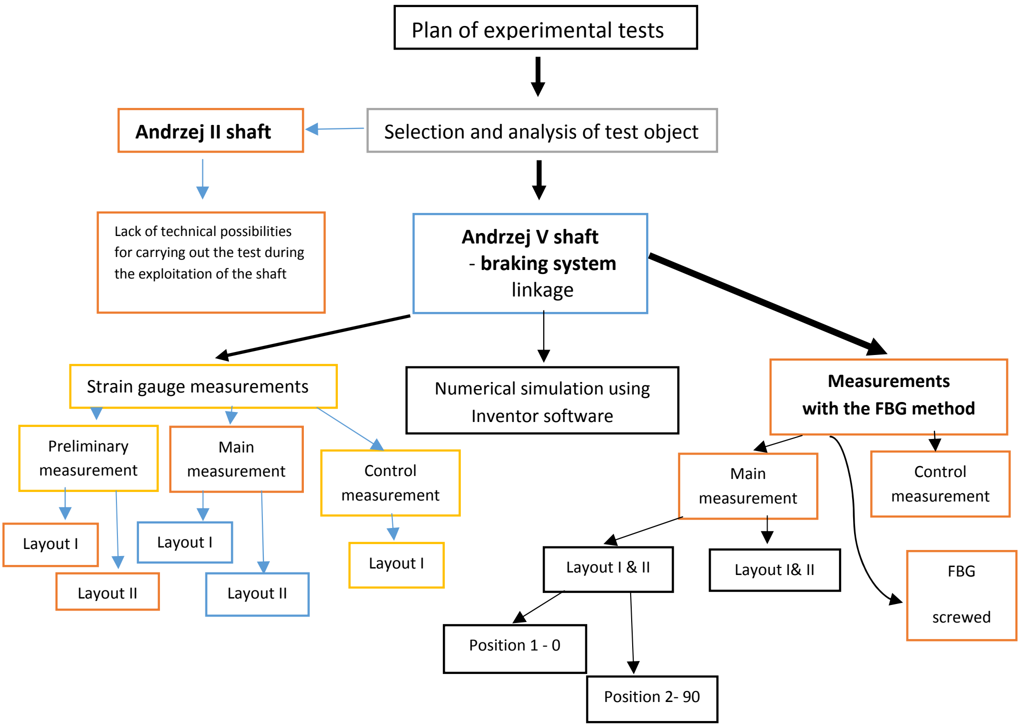

Fig. 4. Schematic plan of experimental tests

3. Strain measurements of the hoisting machine brake linkage

In the mine conditions, a number of modifications had to be introduced in relation to the tests carried out with fibre optic sensors in laboratory conditions. A new technical solution was proposed involving the placement of a fibre optic sensor in specially designed removable and reusable holders. Such a solution made it possible to use fibre optic sensors multiple times, significantly shortening the time of testing and reducing the cost of testing the linkage. The analysis of installation time of the measurement system indicated that the optimal solution is a rotary holder with one fibre optic sensor. After overcoming a number of technical problems occurring on the mine, the following corrections to the original measurement system were also introduced:

1) the measurement base of a reusable optical fibre in the range of 80-1000 mm was adopted.
2) a two-piece holder allowing "tighten" the optical fibre after the shoes have been installed, as it is possible that the incorrect assembly method may damage the optical fibre.
3) An additional optical fibre was added and stuck to the surface, similarly to the strain gauge. Such a solution minimised the influence of distance from the surface, which is important for the measurement results in case of bending.
4) the simultaneous measurement of the pressure in the hydraulic cylinder with the measurement of the linkage strains were introduced.

The diagram of the measuring system with the fibre optic sensor L = 1000 is shown in Fig. 5.

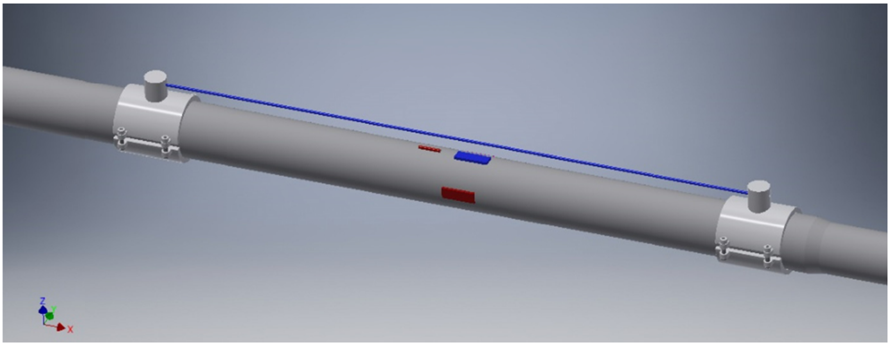

Fig. 5. Diagram of the measurement system – position no 1-0°

For such a measurement system selected, braking tests were carried out during which an online recording of the linkage strains was carried out both on the linkage's surface and by means of a fibre optic sensor located at a distance e from the surface of the linkage. The results of strain measurements in the first measurement cross-section for strain sensors stuck on the surface of the linkage are shown in Table 1.

These are the exact values of strains occurring on the surface of the linkage. In order to simplify the installation of sensors, mainly including the elimination of the labour-intensive process of sticking the sensors to the surface of the strain and significant reduction of testing costs, a reusable fibre optic sensor attached to the linkage by means of a special was proposed as

TABLE 1

The values of strains, stresses and forces acting in individual strain gauges

Sensor Number	Normal Strain ε_T [µStrain]	Normal Stress σ_T [MPa]	Normal Force F_{Ti} [kN]
S1	151	30.2	237.19
S2	74	14.8	116.24
S3	139	27.8	218.34
S4	218	43.6	342.43

mentioned above. However, the axis of the reusable fibre optic sensor is spaced from the surface of the linkage by a distance of e = 29 mm. This necessitates the introduction of corrective coefficients depending also on the angular position of the holder with respect to the upper vertical position. The test results for positions 0 and 180 are shown in the next section.

4. Preliminary Measurment of Brake Linkage Srain

The results of strain measurements are shown in the following sequence:

a) dependence of the pressure value in the hydraulic device of the brake on the linkage strain value; The highest-pressure value in the hydraulic system amounted to 400 MPa, while the highest value of strain amounting to 218 µstrain was recorded for the T4 sensor. The value of 150 µstrain was recorded by the T1 sensor, while the lowest strain value of approx. 72 µstrain was indicated by the T2 sensor, which constitutes only 33% of the greatest strain occurring on the circumference of the linkage. Therefore, there is a significant strain difference between the readings of the sensors placed on the circumference of the linkage. The relationship between pressure [MPa] and strain is non-linear, while the process of loading and unloading the system generates hysteresis shown in Fig. 6.

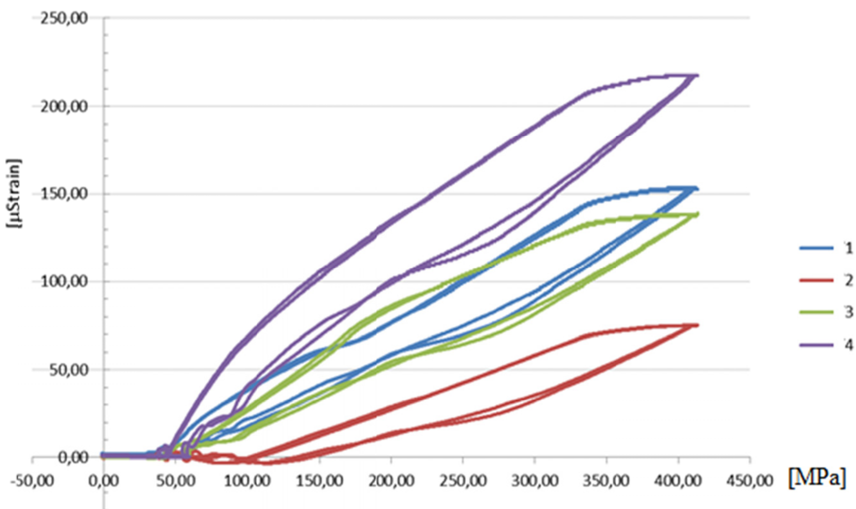

Fig. 6. Dependence of the linkage strains on the pressure in the brake system

b) dependences of the linkage strain at 4 measuring points distributed every 90 degrees on its circumference from the time of measurement (time measuring points) in the process of loading and unloading repeated twice. It can be noticed that the greatest strains occur for the upper vertical position and the smallest ones for the horizontal position with the rotation by 90, Fig. 7.

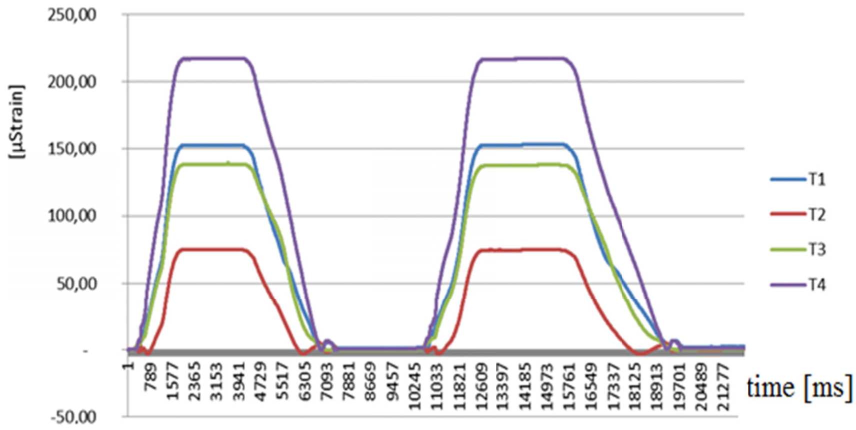

Fig. 7. Linkage strain distribution for 4 measuring points in position I

c) comparing the value of recorded strains of the FBG sensor 2 stuck to the surface of the linkage in relation to the strains registered with the reusable FBG sensor 1. The reusable FBG sensor showed the higher strain amounting to 190 µstrain, whereas the reference sensor registered the strain of 159 µstrain. Therefore, the correction coefficient for position 1 for a reusable sensor amounts to k1 = 0.836. The comparison of strain values for two sensors is shown in Fig. 8.

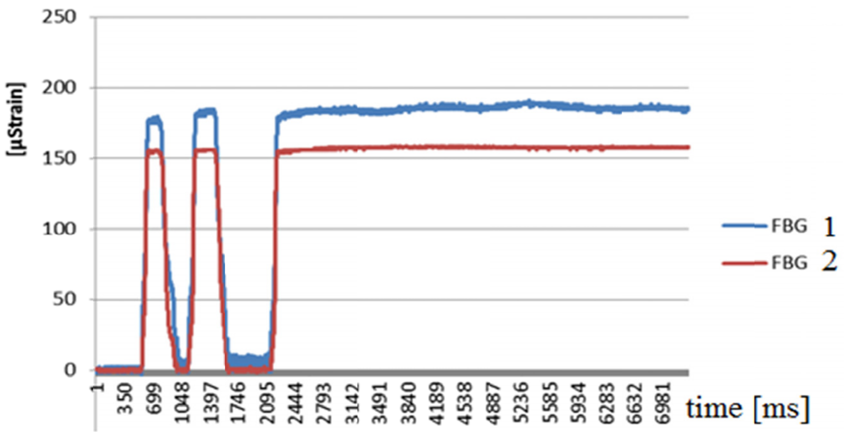

Fig. 8. Comparison of strain values for sensors 1 and 2

Next, the analogous results of strain measurements for position 3 were presented, i.e. the measurement system was rotated by 180 degrees in relation to position no 1. The position of the holder was shown both on the diagram and on the tested object, Fig. 9 and 10.

Fig. 9. The holder in the 180-degree position

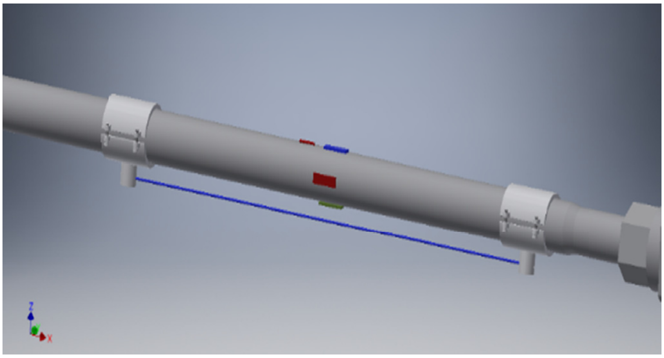

Fig. 10. Diagram of the holder mounting

From the practical point of view, the relationship between the strains of the reference sensor stuck to the surface of the linkage and the strains of the FBG sensor in the rotary holder are the most interesting. For the case of position no 3, the strains of the FBG sensor screwed into the rotary holder are almost the same as of the stuck sensor. The correction coefficient for position no 3 amounts to k3 = 0.968 (Fig. 11).

5. Enhanced strain measurements of FBG sensors in linkange

Due to different strain values on the circumference of the linkage, the following method was proposed for measuring the strains of the linkage. It consists in carrying out measurements

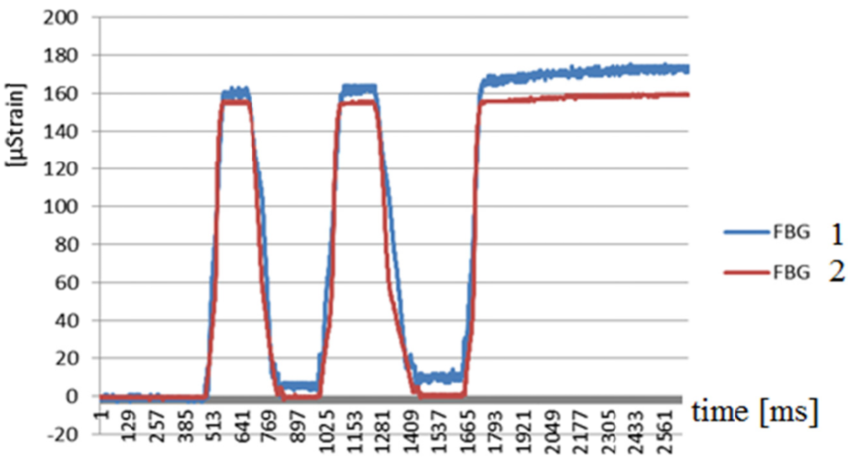

Fig. 11. Comparison of the determined linkage strains using sensor 1 and 2 for position 3

in two different planes spaced from the mounting bolts by L = 1000 mm, where an even distribution of stresses should occur according to Saint-Venant's Principle. The measurements in these planes would be carried out for four different angular positions of the holder fixing the fibre optic sensor. During the first measurement of the given brake linkage, the fibre optic strain sensors with the Fibre Bragg Grating should be stuck to the selected points of the linkage and the modified solution described above should be applied. It consists in placing two fibre optic sensor in specially designed removable and reusable holders. The sensors were placed every 180 degrees in the holder, Fig. 12. Such a solution made it possible to use fibre optic sensors multiple times, significantly shortening the time of testing.

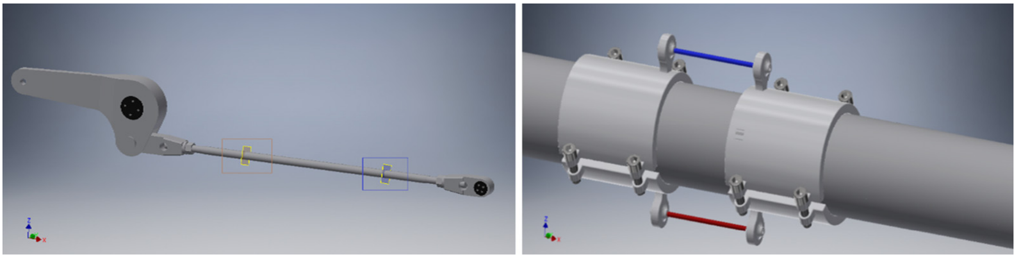

Fig. 12. Mounting fibre optic cables in the holder on the linkage – position 1

The preliminary braking tests made it possible to determine the strain values for the two analysed cross-sections spaced by 1000 mm away from the mounting point on both sides of the linkage and 4 positions on the circumference of the linkage: upper and lower vertical as well as left and right horizontal. The test results for position I are shown in Fig. 13. The highest strain values amounting to 173 μStrain. were recorded for the horizontal and upper vertical position 126 μStrain. The lowest ones for the two remaining measuring positions amount to 107 and 76 μstrains, respectively.

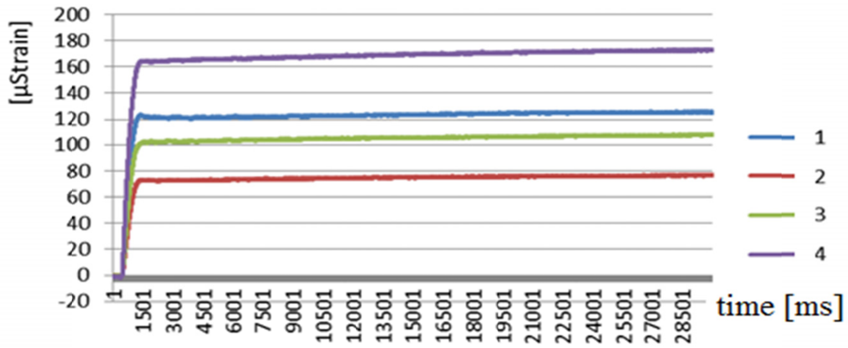

Fig. 13. Linkage strain values in 4 points of the first measurement cross-section

In the second position, similar strain values were obtained, yet they were approximately 10% higher than the values in the first position. The resulting uneven distribution of strains and the associated stress distribution should be qualified to a complex state of strain and stress. This situation causes that the current regulations regarding the measurement of linkage strains should be verified. In order to evaluate the stress of the linkage in the selected cross-section, an appropriate stress hypothesis should be used. A homogeneous plastic material constitutes the material of the linkage. Hence, the Huber-Mises-Hencky energy hypothesis can be proposed. Further studies of linkage strains concerned three different cases of braking, which were carried out one after the other. They were:

1. Manoeuvring braking,
2. Activation of the safety circuit during manoeuvring braking,
3. Two-stage safety braking.

The results of measurements in the two analysed cross-sections of the linkage are shown in Figures 14 and 15. The highest strain values were recorded for sensor no 1, amounting to 243 µstrain. The proportions between the strain values of sensor no 1 and the other sensors 2, 3, and 4 stayed the same as in the trial test. In the case of a two-stage safety braking, the first stage of braking constitutes 80% of the linkage strain corresponding to the second braking stage.

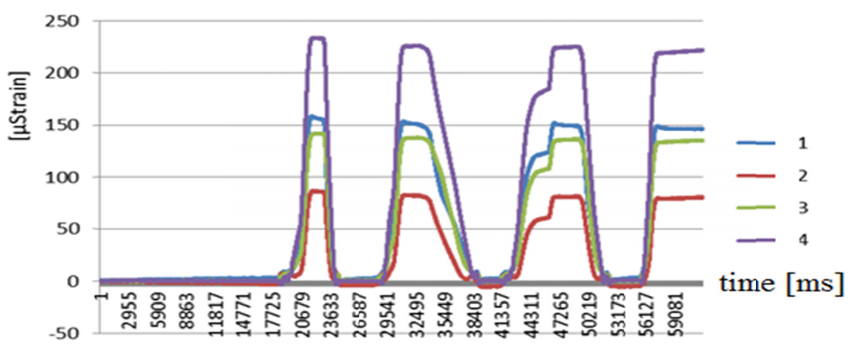

Fig. 14 Linkage strain distribution – layout I

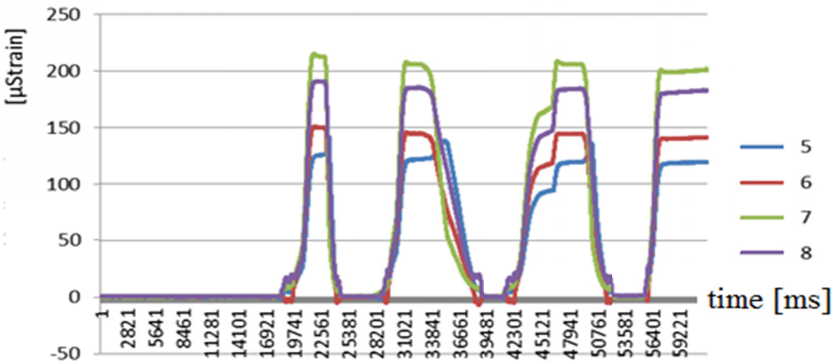

Fig. 15. Linkage strain distribution – layout II

The unevenness of strains for individual angular positions of strain sensors is shown in Fig. 16. The linkage changes its position during operation; however, it should only be stretched, clamping the brake shoes, according to the design assumptions. When analysing pie charts (Fig. 16 and 17), it can be noticed that the linkage strains are uneven. The strains in the first cross-section do not correspond to the strains in the second cross-section of the linkage. The strains between the cross-sections I and II are as if shifted in phase by 90 degrees. The reason for this situation may be the initial imperfections of the linkage axis resulting from its warping or twisting. Such a complex situation complicates the assessment of the linkage stress.

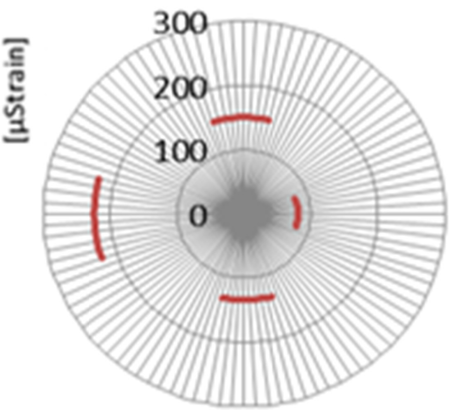

Fig. 16. Strains in cross-section I

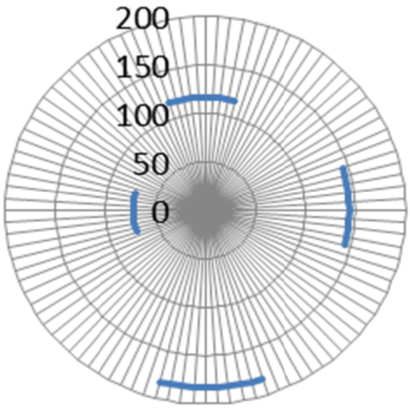

Fig. 17. Strains in cross-section II of the linkage

In order to properly assess the stress of the linkage, the experimental and numerical method is proposed. Experimental research will allow to determine the actual values of strains on the circumference of the linkage in its two cross-sections. These values will also constitute boundary conditions in the linkage model built using the finite element method. An example of the implementation of the strain boundary conditions in the numerical model of the strain is shown

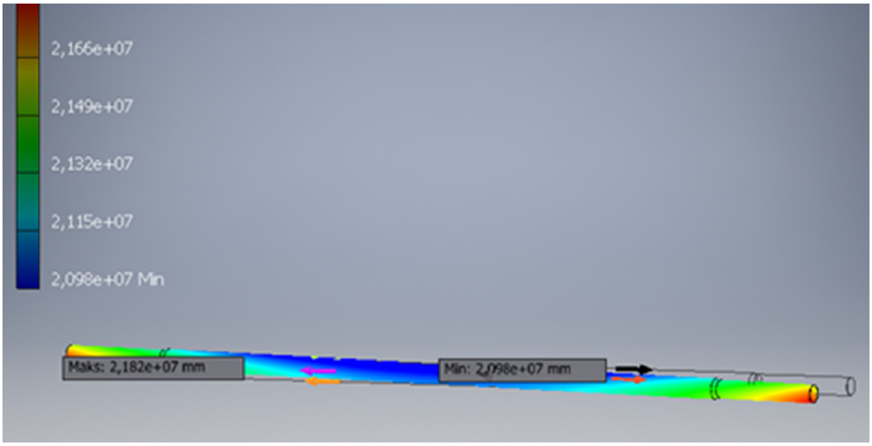

Fig. 18. Strain boundary conditions in the FEM model of the linkage

in Fig. 18. To evaluate the stress of the entire linkage, at least 8 measurements must be carried out in the tested linkage. The experimentally determined strain values at individual measuring points will constitute boundary conditions for the FEM numerical model. The numerical simulation will allow to indicate the most stressed places in the brake linkage.

6. Conclusions

In conclusion, after a series of tests of the dual SSW brake with a set of shoes with a lower shortening linkage of the hoisting machine in the Andrzej V shaft of the "Nowe Brzeszcze" Coal Mine based in Brzeszcze, the following conclusions can be made:

- A new and innovative system for measuring the strains of the hoisting machine brake linkage with the use of reusable fibre optic sensors, characterised by versatility and considerable accuracy of measurement, was proposed in the work
- The test results were validated with the use of classical strain gauge systems as well as fibre optic systems stuck to the surface of the linkage
- The tests have clearly demonstrated that the strain and stress distributions occurring in the brake linkage are strongly uneven. This changes the current view regarding the periodic tests of the brake linkage
- Unevenness in the stress distribution forces the measurement in at least 4 measurement points distributed every 90^0 on the circumference of the linkage in two cross-sections
- Determining the stress of the linkage in such an uneven stress distribution requires the use of experimental and numerical methods. The actual strain values determined would be the boundary conditions for the FEM numerical model.
- The measurement of strains by means of optical fibre cables with Fibre Bragg Gratings is intrinsically safe since the working medium is light, being an additional attribute in relation to electrical resistance strain gauge measurements.

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