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Assessment and Increasing of Lifetime and Time of Safe Operation of Machines and Equipment by the Experimental Methods of Mechanics

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Abstract. Failures of machines and equipment are mostly caused by crossing the critical states that are defined by limit values of stresses and deformations in locations of critical loading. The paper is focused on the development of methods for the analysis of failure cases in the supporting elements of mechanical systems by the quantification of strain and stress fields using experimental and numerical methods of mechanics. The suggested treatments will be used for the reliability and residual life assessment of machines and equipment.

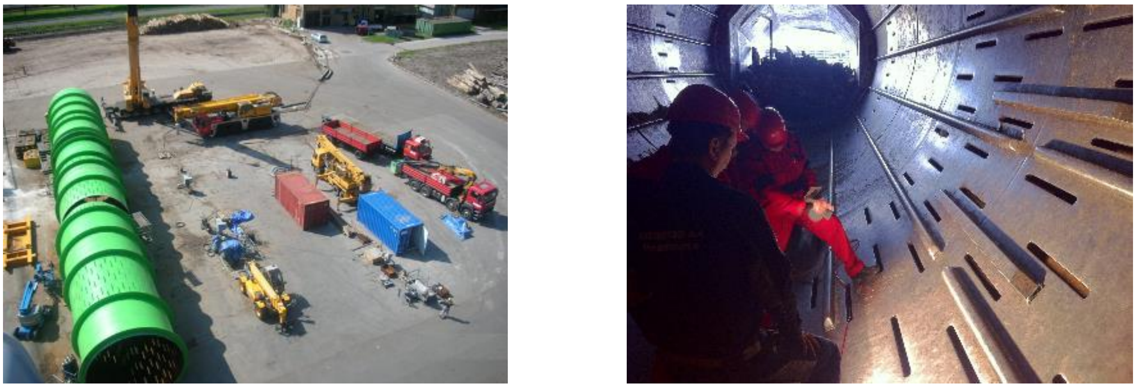
Introduction

Despite of fact that over the last decades' numerical methods (mainly finite element and boundary element method) have been widely spread for the solution of mechanical and mechatronic systems, computer solutions are improved on the basis of the experimentally obtained results and modelling techniques. Experimental methods of mechanics on the one hand allow to specify in more details the parameters being input into computations (e.g. time-dependent charts of load forces, influence of boundary conditions). On the other hand, application of modern experimental methods (electronic speckle interferometry (ESPI) [1], digital image correlation (DIC) [2-5], reflection photoelasticimetry (Photostress method) [6,7] and so on) allow to analyse displacements and stresses on the surface of machine parts in real conditions of loading and positioning. However, there exist areas of mechanics (e.g. area of residual stress determination), where experimental treatments are dominant and necessary for evaluation of real stress and deformation states in the supporting elements of machines and equipment [8].

The paper presents applications of methods of experimental mechanics for assessment and increasing of lifetime and safe operation of machines and equipment, where beside operational loading important roles play residual stresses created in the structure or its part due to production technology, assembling, joints, temperature influences, or as a result of their overloading. The residual stresses are superposed to the stresses resulting from actual loading of a structure and they can significantly influence the resulting stress state. This fact can have significant influence on the lifetime of mechanical parts of machines and equipment, as well as mechanical and biomechanical systems, therefore, the knowledge of residual stresses is important for the assessment of actual state of the investigated element. The authors describe methods of their measurements, including quantification and including solution of real applications of mechanical, mechatronic and biomechanical systems. The important advantage of the authors’ workplace is the possibility to verify the results obtained from numerical simulations using several experimental methods (strain-gages, DIC, PhotoStress, ESPI, fatigue tests, ...). The authors’ workplace is focused on the development of experimental methods of mechanics and their application to the solution of scientific and research tasks and tasks for practice. Next are given selected tasks solved for practice, the aim of which was to assess the lifespan and reliability and safe operation of the given equipment.

Analysis of probable reasons of cracks initiation on a barking drum

A barking drum serves for debarking of logs with length varying from 2.5 m to 6.0 m [9]. The apparatus consists of a drum body, driving and supporting tyres, housing and exhausting system. In the drum, wood logs up to 700 mm in diameter can be processed, maximum capacity of the equipment is 320 m^3 per hour, and angular velocity of the drum during debarking is about 5 rpm [9]. The body of the drum is designed as a cylindrical shell and consists of two parts (front and rear, Fig. 1), which are driven by a system of tyres (Fig. 2) with drives controlled by frequency changers. Rotation of the drum leads to debarking of logs inside the drum. One block of drives consists in most cases of sixteen tyres located on circumferential and longitudinal directions of the drum cylinder.



a) b)

Fig. 1 View of the barking drum a) before assembly, b) inside view

Fig. 2. Powered tyres and their connection to gearbox

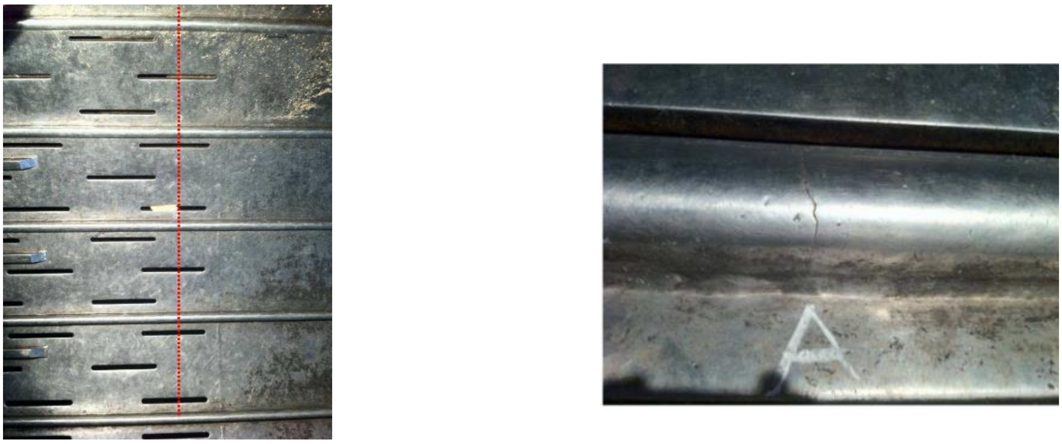
During operation of the drum cracks were detected near stress concentrators in the frontal part of the drum cylindrical shell (Fig. 3). In order to establish the reasons for these failures, it was necessary to determine the levels of residual stresses near the cracks. On the basis of information gained from the customer, study of the assembly of the barking drum, as well as from the analysis of the barking drum, taking into account also time and space conditions, the authors came to the conclusion that the most suitable and relevant locations for application of strain-gages for the hole-drilling method were the places where the cracks were, i.e. where due to welding the residual stresses were high, or in places where stresses were increased by the change of thickness after welding of the rib in locations of holes for bark removal. Locations with a high number of cracks gave relevant evidence that the residual stresses were high and accordingly there were locations for application of strain-gages for the hole-drilling.

Fig. 3 Cracks on the drum beginning in the location of stress concentrator

The drilling of holes was carried out by apparatus RS 200 using strain-gage rosettes RY 21-3/120 (Fig. 4). The process of the hole drilling was performed in ten steps by 0.5 mm and the resulting hole depth 5 mm. The hole diameter was 3.2 mm. The released strains were registered in each step of measurement by strain-gage equipment P3 [10-12].

Fig. 4 Process of hole-drilling in location 2

After inspection of the internal space of the drum additional cracks were detected by authors on a number of blocks. They are marked red in Fig. 5. All cracks lie on one plane that is perpendicular to the drum axis.



a) b)

Fig. 5 Cracks on prisms in the frontal part of the drum a) location of failures, b) detail view of the crack shape

After analysis was found out that reason of breaking of ribs in one plane can be a fact that supporting and powered tyres are do not lie on one line along the drum. Such positions lead to the additional loading that was simulated by prescribed movement of supporting point by 10 mm upwards or dawnwards. In the computational model, the loading was realized by self-weight of drum and weight of processed wood in accordance with defined power of barking drum. In order to have simple model, the holes were not modelled and accordingly the stress concentrators were removed. However, such stress concentrators are parts of drum. By the computation was determined that this movement of support can lead to stress amplitudes in blocks on the level approximately 100 MPa (Fig. 6). By such computation the authors documented possible causes of failure initiation. In one cross-section.

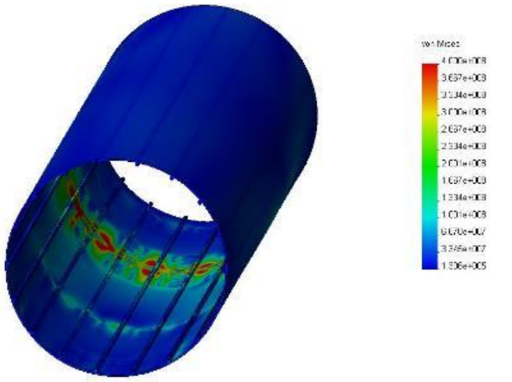


Fig. 6 Field of equivalent von Mises stresses - displacement 10 mm upward

On the basis of the thorough analysis it can be stated that:

a) Measurement of residual stresses in five locations shows that levels of residual stresses are very high. They reach 130 MPa. The stresses have character of tensile stresses and they are oriented mostly in the direction of the drum axis. High levels of residual stresses decrease stress amplitudes and these consequently invoke failures in prisms and welds.
b) The simulations confirmed that crack orientations correspond to the directions perpendicular to the directions of principal tensile normal stresses.
c) The newly detected cracks in prisms can result from inaccurate positioning of supporting and drive units.
d) The existing cracks (even if they are near the welds) cannot be considered as a result of low strength of fillet welds. It was documented by the strength of a unit length of a weld which is satisfactory and in no point the resultant force acting inside the unit length of the weld exceeds the proposed nominal value.

Analysis of crack initiation in the press frame and optimization of the frame for ensuring its further safe operation

After several years of operation of the press (Fig. 7a) used for cutting and forming of side panels of washing machines, there were detected cracks in vertical columns of the press frame (Fig. 7b). Taking into account operational conditions it was necessary to operatively analyse the causes of crack initiation in the columns of the press frame and on the basis of such analysis to propose measures in order to ensure its further failure-free operation. The paper presents the results that were reached during solution of this problem.

During press operation two operations are accomplished simultaneously in one working cycle (one ram stroke of the press), cutting from a sheet of the rectangular shape and forming the cut piece from the previous operation. From the analysis of loading of individual operations, it was found out that maximum load acting on the press ram was F_s=1800 kN during cutting and F_o=1200 kN during forming, i.e. for simultaneous execution of both operations the maximum force acting on the press ram reached 3000 kN. According to the data gained from the operator, the press force limiter was adjusted to the force magnitude in the interval from 3200 kN to 3500 kN during the whole period of its previous operation. Despite the above-mentioned fact there were detected cracks in three columns of the press approximately after ten years of operation (with approximately $8 \cdot 10^6$ working cycles).

a) b)

Fig. 7 a) General view of the press, b) cracks in the column of the press frame

The cracks were initiated in the bottom part of the press frame in the locations of transition of columns to the bottom crossbeams of the press frame. The columns had a closed rectangular cross-section created from the sheets and the cracks were spread through the whole thickness of the sheets that form the column walls. Inspection of the crack lengths showed that the carrying cross-sections of columns were decreased by 30 to 40% by cracks.

For the assessment of various reasons of crack creation on the columns of the press it was necessary to quantify the levels of residual stresses in their neighbourhood. Residual stresses occur also in the structures without loading and they can be caused by machining, assembling, but mostly by operational overloading. The residual stresses are superimposed to stresses from operational load and they can under certain circumstances (magnitude and character) cause failure of the structure. The levels of residual stresses in material can be determined by several methods. One of them is a hole-drilling method. Fig. 8 shows that the strain-gages were applied in the neighbourhood of the cracks on the inner walls of the columns with the aim to gain better knowledge about residual stress levels in the observed areas. For the measurement of residual strains, the hole-drilling equipment RS-200 was used [11-14]. For the measurement self-compensating strain-gages 1-RY-21-3/120 with radius 5.15 mm were used, and the diameter of the drilled hole was 3.21 mm. The depth of the drilled hole was 5 mm and the drilling was carried out in ten steps, each with length of 0.5 mm.

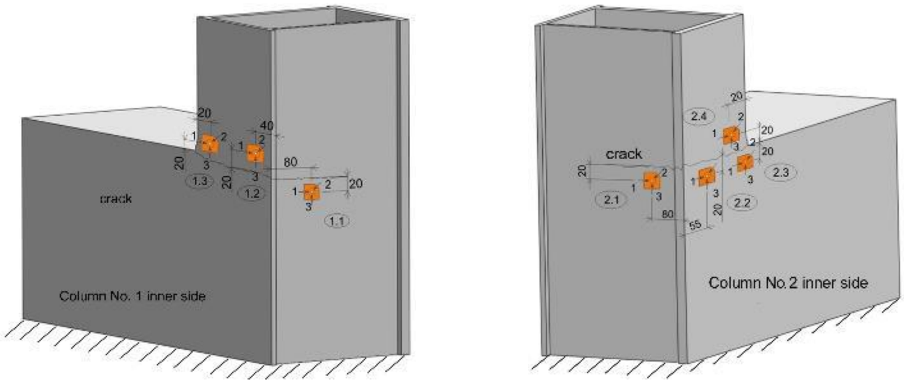


Fig . 8 Locations of applied strain-gages on columns 1 and 2 of the supporting press frame

Fig. 9a shows application of the strain-gage rosette and the location of taking material specimen for determination of mechanical properties of the material. From Fig. 9b the direction of crack propagation is obvious, it is marked red.

a) b)

Fig. 9 a) Application of strain-gage rosette, b) direction of crack spreading

Computed values of residual stresses determined from measured strains released by drilling on the inner sides of the column walls did not exceed 40 MPa. All values were positive, i.e. they supported growth of cracks. Their magnitudes on the sidewalls lay in the interval 20 - 40 MPa that clearly documented the fact that they were not produced during manufacturing of the frame. It can be assumed that they resulted from the loading during operation of the press. Taking into account their magnitudes they could be considered as direct reasons of cracks initiation, because during the operation of the press vanishing loading was invoked for which the middle stress was equal to half of the stress amplitude.

Beside quantification of residual stresses, the stress and deformation analysis was carried out by the finite element method. Computation was performed for a whole loading force in the ram 3500 kN (maximal allowable force determined by force limiter). This force was divided into two parts 2100 kN for cutting and 1400 kN for forming. In order to identify stress concentrators in the locations of cracks there was utilized geometrical symmetry of the frame and the computations were performed on the quarter, more loaded part of the frame. This increased precision of computation by application of smaller finite elements in the critical part and at the same time it decreased the time of computations. Boundary conditions supposed symmetrical loading of the press, which represented adverse state of loading in comparison with a real state. Stress concentration in the area of cracks is apparent from the field of equivalent stresses in Fig. 10. In this computation, a sharp corner (without rounding) was considered in the junction of the column to the crossbeam.

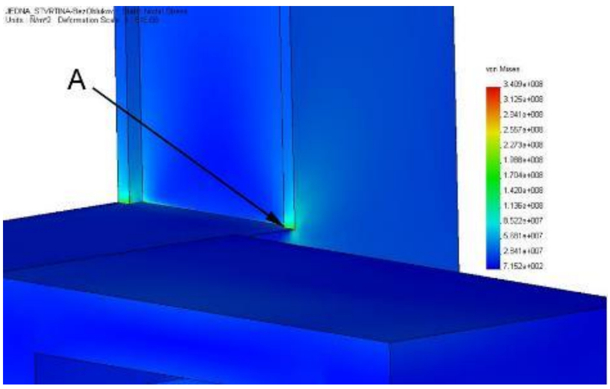


Fig. 10 Field of equivalent stresses in the location of the column to the bottom beam.

From the numerical computation of the press frame by the finite element method it obvious that in the junction of the frame column with the bottom crossbeam (location A in Fig. 10) the extreme stress concentration with maximal equivalent stress 273 MPa is located. Maximum stress is initiated on the inner wall side 30 mm thick in the location of a sharp (not rounded) corner. The analysis shows that cracks in the supporting structure of the press were initiated in the sharp corners of connections of the columns and the bottom beams and this was supported by unsuitable geometry and bad purity of the material used.

From the analysis of the results it follows that the cracks in the structure of press frame arose in sharp corners of the junction of the press columns and the bottom crossbeams and they were probably caused by inappropriate geometry of the press frame and low purity of the material. For the analysis of press frame strengthening, in order to ensure further operation of the press without failures, the finite element method was used. The stress analysis by the FEM showed that rounding of corners with radius 40 mm in locations of the junction of steel sheets on the columns with the bottom crossbeams (location A, Fig. 10) significantly decreased maximum value of equivalent stresses.

On the basis of the above-mentioned facts it was proposed to provide (after welding of cracks) strengthening of the press frame by welding eight plates made of material S355 to all columns (one on inner and outer side of each column). Fig. 11 shows the proposed shape of one stiffening plate.

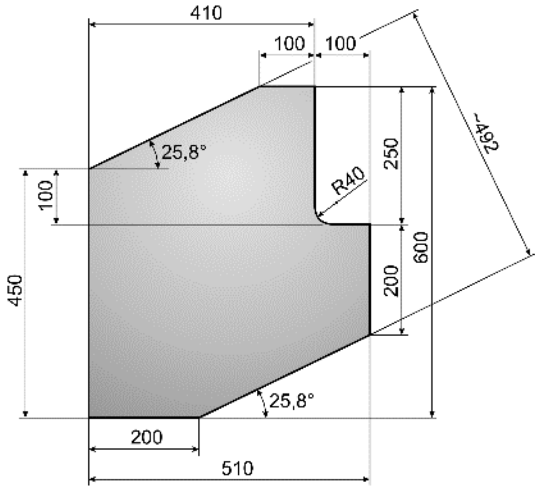


Fig. 11 Shape and dimensions of strengthening plates for inner side of columns.

Stress analysis showed (Fig. 12) that maximum equivalent stresses did not exceed 190 MPa, i.e. strengthening decreased stresses by approximately 30%. This was enough for further safe operation of the press.

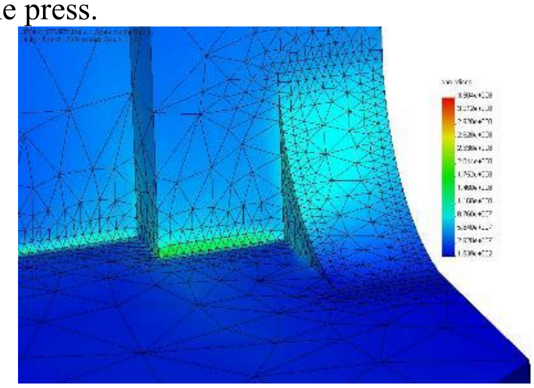


Fig. 12 Detail of field of equivalent stresses on the press frame after modifications

On the basis of numerical and experimental analysis of the press frame it can be stated:

a) Numerical analysis of the press frame showed that occurrence of sharp corners (without rounding) in the junction of the columns and the bottom crossbeams caused (in case of maximum allowable loading of the ram 3500 kN) equivalent stresses 273 MPa.
b) The residual stress levels according to ASTM E 837-01 on the sidewalls of the columns did not exceed 40 MPa and they lay in the interval from 20 to 40 MPa. Residual stresses on frontal walls of the columns did not exceed in absolute value level 62 MPa and these stresses were invoked by operation of the press.
c) Crack initiation in inner corners of the columns (location A, Fig. 10), and also in other locations could be most probably caused by overloading during operation. This did not occur during regular technological process of pressing (cutting and forming), but as a result of inappropriate position of a semi-finished product and accordingly to formation of additional forces during movement of the ram. However, this case does not have to be connected with infunctionality of a force limiter.
d) Another possible reason of cracks initiation was low purity of the press frame material that was documented by probably rolled out sulphides and consequent occurrence of lamellar splitting of the material.
e) Strengthening of the bottom parts of the columns by welded plates will result in decreasing of maximum equivalent stresses by approximately 30%, which is enough for further safe operation of press.

Stress and deformation analysis in critical joints of the bearing parts of the mobile platform using tensometry

At present, there has been a rapid advancement in the use of new materials and modern technologies in the design and technical improvement of robotic systems. Methods of numerical modelling are most commonly used in the design and development of load-bearing parts of mechanisms. When designing complicated mechanical systems such as robotic systems, it is often difficult to correctly define boundary conditions that correspond to the actual operational state using the results obtained through numerical modelling. The paper presents methods of verification of the results obtained by numerical modelling in the selected load-bearing component of a six-leg robot from the experimental measurement using tensometry with the aim to take into account the strength and stiffness parameters of the load-bearing part in order not to jeopardize safe and reliable operation of the mobile robotic platform.

The paper describes application of numerical and experimental methods of mechanics in the design of a mobile service robot of middle category (Fig. 13) which consists of two basic parts a mobile platform that enables autonomous motion in the rough terrain and ruins with payload capacity for the body weight 400 kg, max. speed 3 or 5m/s and climbing ability 45°, a robotic arm with 6 degrees of freedom and nominal load capacity 200 kg. Functional (physical) models of the above-mentioned modules were optimized by simulation computer models and tested in real conditions using experimental methods of mechanics.

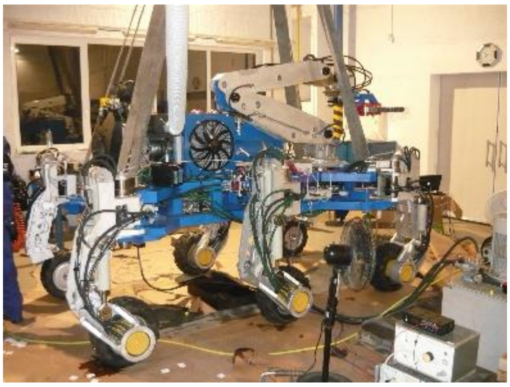


Fig. 13. Mobile service robot of middle category

Robotic systems can be considered as complex mechanical systems not only in terms of kinematics but also from the point of view of the analysis of various stress and strain states due to a variety of operational loading. Multiple bearing elements were considered by numerical modelling using finite element method when designing and optimizing the bearing structure of the mobile platform. Main bearing parts of the mobile platform were designed in such a way as to ensure that their loading did not exceed the computational strength of the given material and that the deformations that occurred satisfied the required function.

To verify the results obtained using experimental methods of mechanics, a robot leg was chosen. The finite elements method was used to identify critical areas for the application of strain-gages. The robot leg was loaded at the place of the suspension of the wheel. Various combinations of the positions of individual robot legs were considered in the calculations. Fig. 14 shows the above-mentioned model of the outstretched robot leg with boundary conditions.

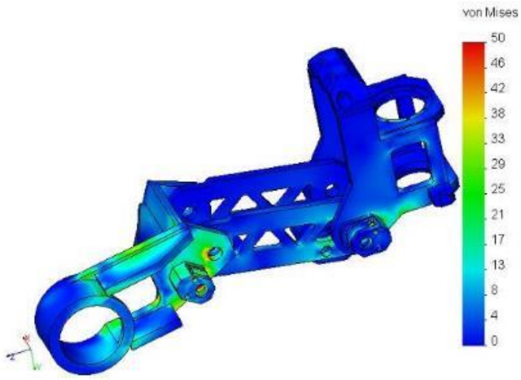


Fig. 14 Fields of equivalent von Mises stresses in MPa, material aluminium alloy

For the purpose of experimental measurement, a leg of the mobile robot (Fig. 15) was chosen, where strain-gages were applied. Strain-gages XY91-10/120 connected to the half-bridge were used [10]. Measuring grids of the strain-gage were positioned in the direction of the axis of the leaned leg. Compensation sensors were directed perpendicularly to the axis of the active sensors. Time records of the relative deformations in the selected areas were recorded by SPIDER8 measurement unit with Catman software.

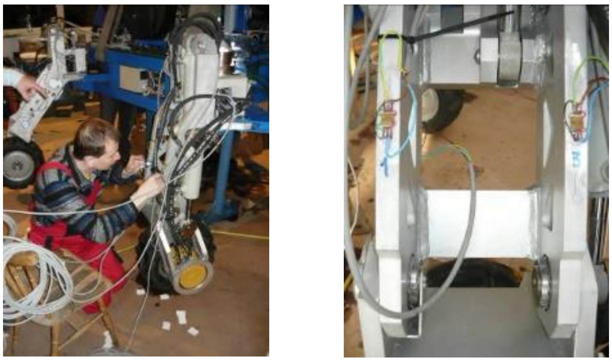


Fig. 15 Application of strain-gages on the leg of the mobile robot

The next part gives the results of the selected measurements of relative deformations and stress in the individual measured places at the selected modes of the leg loading (Fig. 16). Fig. 17 shows charts of stresses in the locations of applied strain-gages for the defined operation regimes.

Fig. 16 Selected position of robot legs during experimental measurement.

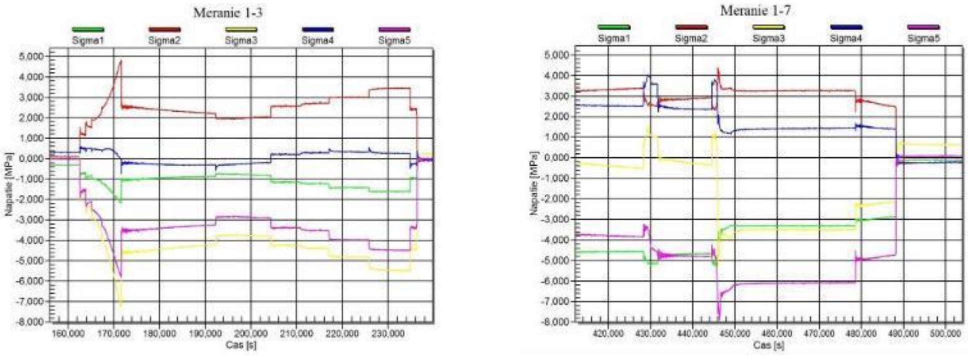


Fig. 17 Courses of time-dependent stresses in the locations of measurements under selected regimes of leg loading

In spite of the fact that nowadays great emphasis is placed on the optimization of the shape and geometry of the bearing parts of machinery and equipment in order to reduce their weight, it is necessary to state that when designing bearing parts of the mobile robotic systems of manipulators it is essential to pay close attention to the rigidity parameters of the used components. It is very important in terms of exact positioning of the end elements of the mobile robotic systems designated for application in tough conditions of rescue works, natural disasters, fires, decontamination of surfaces from toxic materials, etc., where accuracy is top priority.

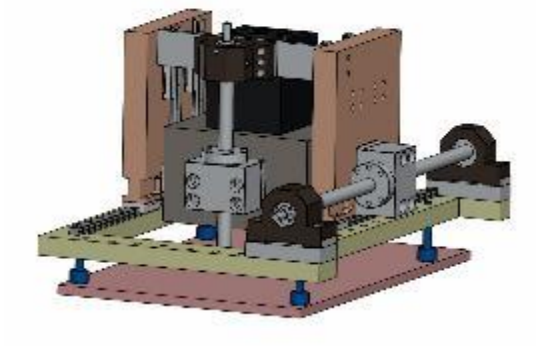
Authors presents the method of verification of the results obtained using numerical modelling by experimental measurement performed in the defined areas on the robot leg of the mobile platform in different positions at the operational loading. Based on the stress values obtained by experimental measuring it can be concluded that the proposed shape, geometry and material of the robot leg in terms of hardness and strength are sufficient and the mobile platform can be safely operated without restrictions.

Conclusions

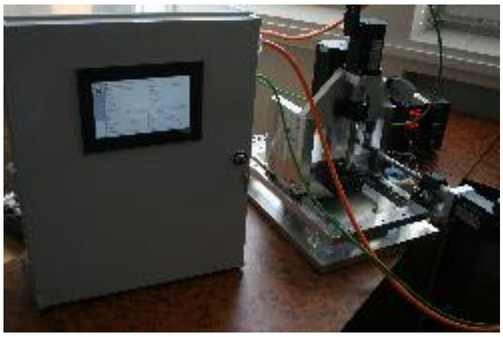
As mentioned above, experimental procedures dominate in the area of determination of the residual stress in machine parts. The hole-drilling or ring-core methods are most widely spread that are being continuously developed. The development of such methods is caused on the one hand by elaboration of the hole-drilling and ring-core method, by development of new equipment and on the other hand by increasing precision of the measured and released strains [15,16]. Significant attention is devoted to elaboration of methods for determination of residual stresses in the vicinity of weds [17,18].

The authors' workplace has been dealing with quantification of residual stresses by hole-drilling method for several decades. The experience gained not only in laboratories, but also during measurements for practice were applied in the proposal of new methodology and procedures of determination of calibration coefficients as well as processing and evaluation of measured data by the newly developed program MEZVYNA. The program was developed in the authors' workplace equipped with state-of the-art measurement systems SINT MTS-3000, RS200 and SINT MTS-3000 Ring-Core [19].

Taking into consideration the top level hardware and software equipment of the workplace in various areas of experimental methods of mechanics (strain-gage measurements, PhotoStress, DIC, ESPI), it is possible to verify the results using different methods and to create new treatments and methods that will be applied for solution of practical problems [20,21]. As the authors have extensive experience in the area of applying optical methods in the stress and deformation analysis near concentrators, they decided to design equipment for quantification of residual stresses by the hole-drilling method (strain-gage measurements) in combination with optical methods (PhotoStress, DIC) (Fig. 18).



a)



b)

Fig. 18 a) model of proposed hole-drilling equipment, b) real model of hole-drilling equipment with control unit for precise positioning

An advantage of the newly developed precise positioning equipment is a possibility to verify results gained by experimental methods based on different physical principles. For the creation of methods which are used for determination of residual stresses uniformly or non-uniformly distributed along the thickness of structural supporting members with the aim to refine and improve the existing treatments, the authors proposed and built hydraulic loading equipment necessary for verification of procedures used for quantification of residual stresses in thick specimens (Fig. 19).

a) b)

Fig. 19 Hydraulic loading equipment a) computer model, b) real model including control panel and hydraulics

The authors of the paper in cooperation with other researchers from their workplace reached the results that provide a comprehensive knowledge base for development of new methods for continual evaluation of the reliability of key supporting elements of machines and equipment as well as creation of methods and programs for quantification of residual stresses using sensors for continual quantification of vibration, etc. They proposed and developed experimental procedures focused on deformation and stress analysis of supporting systems of mechanical systems with the aim to apply them for the assessment of the reliability and residual lifespan of machines and equipment. The authors analysed a broad range of problems that influence lifespan and reliability of machines and equipment (static and dynamic loading, influence of stress concentrators, problems of vibrations, residual stresses and so on) in such a way as to consider as many factors occurring during the operation as possible [22-28]. The advantage of the authors' workplace is the fact that due to the state-of-the-art equipment in various areas of experimental mechanics (SINT MTS-3000, RS 200, FL/Z-2, Q300, Q450, Quantum, Gen5i, P3, Pulse) as well as software (Ansys, Abaqus, NX, SolidWorks, Matlab, Adams, nCode) it is possible to evaluate the obtained results and propose new methodology using synergy effects of numerical and experimental methods.

Acknowledgement

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