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Stress measurements at load-bearing components of the shaft steelwork and the mine hoist frame in the Regis Shaft of the Wieliczka Salt Mine

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Abstract:

The study summarises the selection of dedicated techniques and procedures for measuring real stresses arising in shaft steelwork components due to car-shaft steelwork interactions as well as stresses at critical points of the car frame in the elevator installation in the Regis Shaft of the Wieliczka Salt Mine. The implemented solution and operational parameters of the hoisting installation in the Regis Shaft of the Wieliczka Salt Mine are summarised, the adopted measurement method and dedicated equipment are presented, focusing on the procedure for locating the critical points on the car frame and shaft steelwork. The purpose-built measurement set-up as well as the adopted stress measurement procedure and results are explained in detail.

Keywords: measurements, hoisting installation, mine elevator, stress, shaft steelwork, elevator car frame

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1. Introduction

With the plans to open a new tourist route "The Miners' Route", in anticipation of growing numbers of visitors to the site and aiming at improving the visitors' comfort and to adapt the facility to the needs of disabled visitors, the managers of the Wieliczka Salt Mine were in quest for safer and more economic means of transportation for visitors.

Following an in-depth analysis of formal requirements as well as technical and financial aspects, the management had two independent, single-door men-riding elevators installed in place of the traditional mine shaft hoist. This solution ensured better safety for passengers and well performed its function as a facility providing the effective transport of tourists in groups of 15, visiting the newly-opened site and entering through the Regis Shaft [1]. Two elevators were therefore installed in the shaft, each having the load-bearing capacity of 1600 kg or 21 persons. These are automatic, self-service elevators, and the access and maintenance operations are supervised via a dedicated electronic access-control system.

Since the elevators, installed in the Regis shaft, replaced the previously operated mine shaft hoist, all maintenance jobs, shaft inspections and testing of wall-mounted equipment in compliance with the current mining law are conducted whilst the elevator is running on inspection mode with the servicemen riding on top of the elevator car, and the travel is controlled from the control console on top of the car. A canopy is provided to shield the servicemen during the shaft inspection and equipment testing on top of the elevator cars.

2. Research methods

2.1. Elevator construction

Two PT21/40-19 elevators, used for hoisting personnel and materials, were installed in the northern and southern sections of the shaft [2].

The main components of each elevator facility include:

- Machine room 4400 mm in length, 4280 mm in width and 2700 mm in height, located on the level +9.27, with two identical drive units comprising a gearless winch MX18 with the friction pulley 690 mm in diameter, the LCE control panel, the drive panel MLB, two sets of rope slings for each elevator and overspeed governors for adjusting the speed of both the elevator car and counterweights;
- Elevator car-slide-guided on two rigid guide bars with roller guides;
- Counterweight sliding on two rigid guide bars with roller guides,
- 6 hoisting ropes to handle the elevator car, having the structure 8x19S-NCF 1570 PAWO F3 and diameter of 13 mm,
- 7 tail ropes in the hoisting machine 8x19 W 1570 PAWO F7, Ø16 mm in diameter.

In order that the shaft top facility should remain as a heritage asset, the conservation officer decreed that the winding tower +24.26 m high, located on the level +21.05 m and housing rope pulleys, should be brick-lined and maintained as a piece of architecture (Fig. 1).

Fig. 1. The top of the Regis Shaft [3]

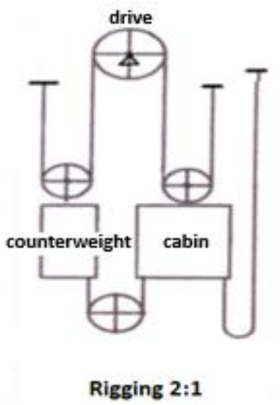

Fig. 2. Kinematic diagram of the elevator [3]

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The elevator in the northern-end section has three stops: on pit bank level +0.00 m, in the pit bottom on the level of rope drive sheave at -106.96 m, on the pit bottom level III at -127.65 m. The elevator system in the south-end of the shaft has four stops: at the shaft top at +3.42 m, on the pit bank level at +0.00 m, in the pit bottom level I at -57.94 m and level III at 127.65 m. A simplified kinematic diagram of elevators installed in the two shaft compartments is shown in Fig. 2.

A general view of the machine room is shown in Fig. 3 and the hoist shaft with wall-mounted equipment is shown in Fig. 4. Fig. 5 gives a vertical cross-section of the top part of the hoist tower, a view of the machine room and the upper section of the shaft.

Fig. 3. Machine room with installed gearless winches MX18 with the friction pulleys 690 mm in diameter [3]

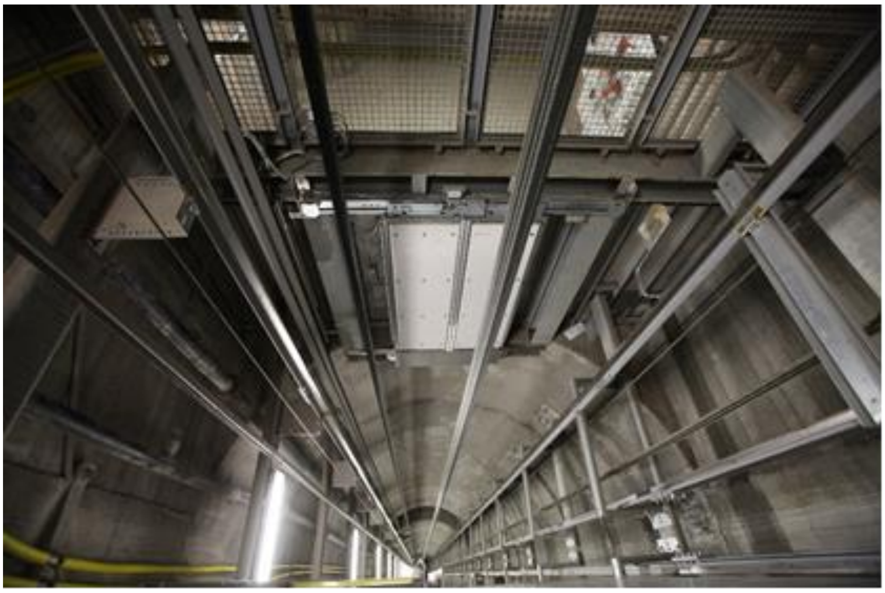

Fig. 4. The shaft with mounted guide bars – general view [1]

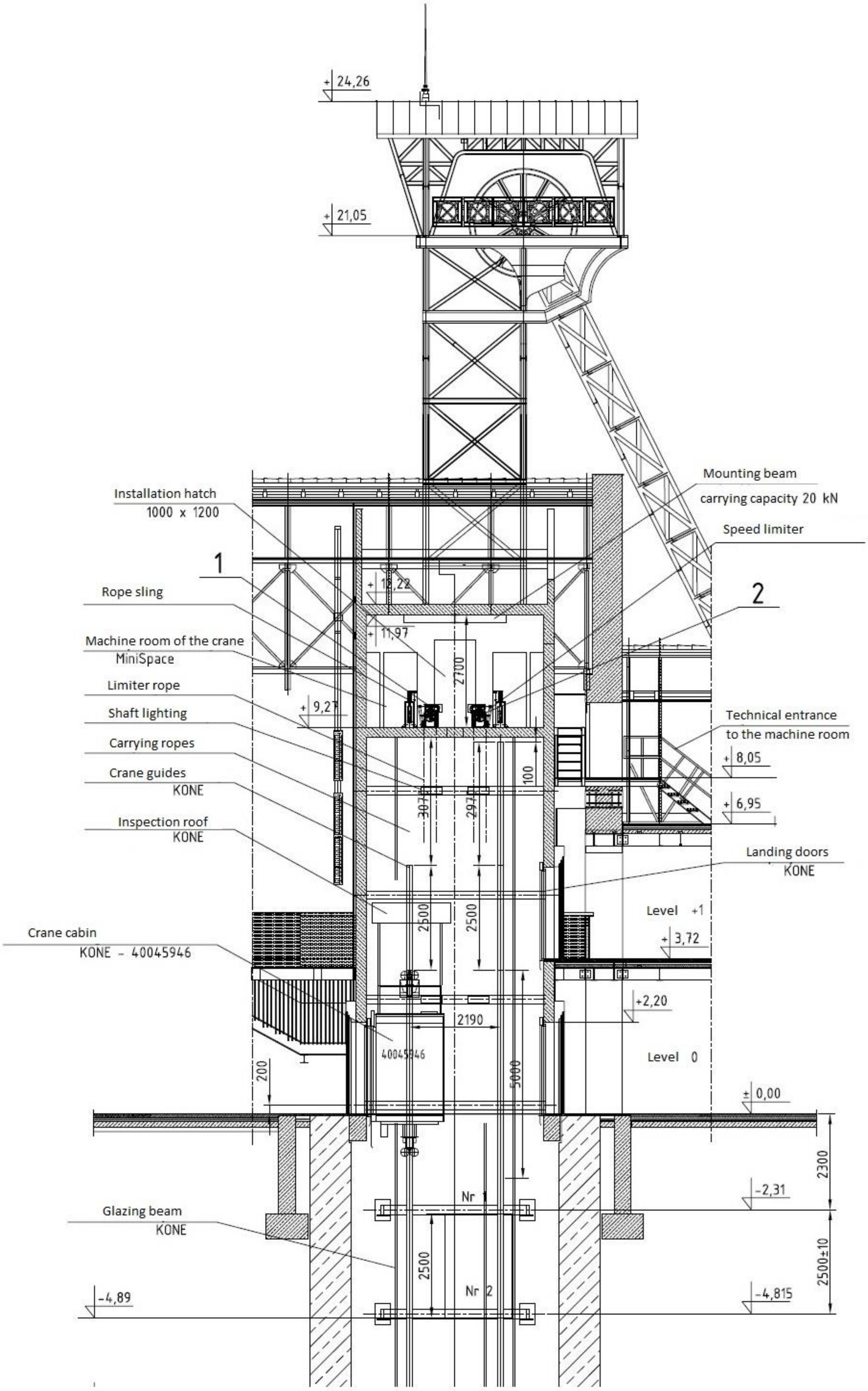

Fig. 5. Vertical section of shaft top facility and machine room [4]

2.2. Shaft steelwork

The shaft steelwork and wall-mounted equipment in the Regis Shaft are designed to support the guide bars to enable the slide-guiding of elevator cars and counterweights and to hold the station doors of KONE elevators for hoisting personnel and materials between the shaft bottom levels I, II, III.

The present positions of the elevator cars and counterweights and wall-mounted equipment within the shaft are shown in Fig. 5.

The critical components of the steelwork structure in the Regis Shaft between the pit bank level (+0.00 m) down to the level III (-127.65 m) are buntons spaced every 2.5 m, a safety deck on the shaft sump level (-132.12 m) with reversal stations for balance ropes provided with tension weights and devices used to keep the elevator car and counterweight overspeed governor ropes under tension, a control deck on the shaft sump level (an artificial shaft bottom) on the level -135.43 m.

Other components of the steelwork structure in the Regis Shaft include:

- chair mechanism on the pit bottom level I;
- shaft entry lock with the load-bearing structure on the level IIw,
- chair mechanism on the pit bottom level IIn;
- chair mechanism on the pit bottom level III;
- ladder compartment from level III to IV;

The diagram cross-section of the Regis shaft with wall-mounted equipment is shown in Fig. 6. The shaft with installed guide bars and other shaft fittings is shown in Fig. 4.

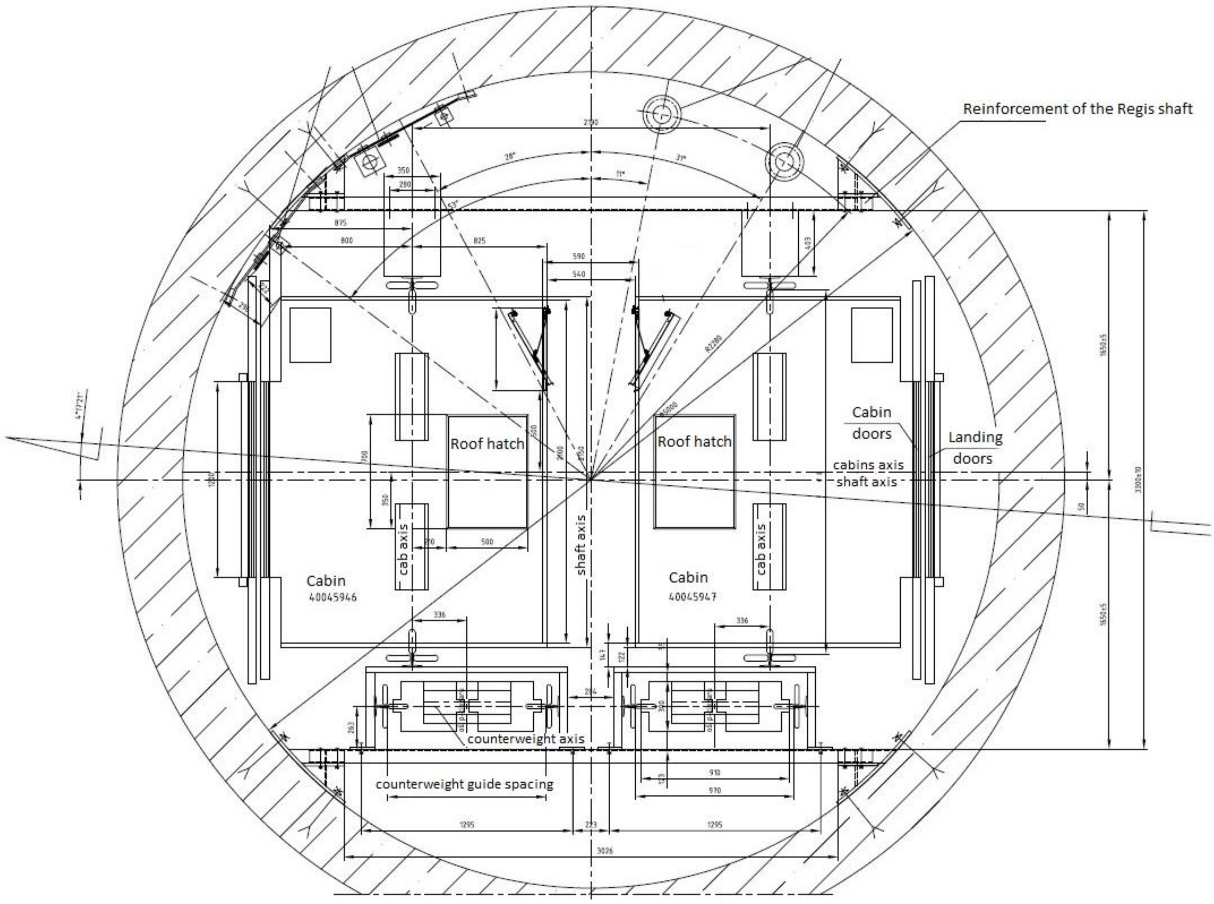

Fig. 6. Cross-section of the Regis Shaft with wall-mounted equipment [5]

2.3. Technique selection

In the course of research work the underlying assumptions relating to structural durability and endurance of the hoist frame and supporting beams in the Regis Shaft had to be verified. It was established that measurements with the use of electric resistance wire strain gauges would be the optimal technique for measuring stresses, displacements and deformations of the hoist frame structure or the supporting beams. Since the hoist mainframe and the guiding system are encased within a vertical pit alongside the elevator carrying the visitors and operated in the continuous mode, all laboratory methods of stress measurement had to be abandoned.

Obvious advantages of electric resistance strain gauges and feasibility of using a recorder equipped with a signal amplifier rendered this measurement set-up an optimal option for use in conditions prevailing in the Regis Shaft of the Wieliczka Salt Mine. An electric resistance strain gauge is firmly attached to the surface of the structure under testing with dedicated glue that is sufficiently elastic to allow an undisturbed operation of the strain gauge and an interaction with the surface under testing.

The measurement set-up, deployed in the shaft, was based on the CL460 recorder (model 1.51) designed to perform simultaneous high-precision measurements and recording of physical quantities to be converted into electrical signals with the use of strain gauges in the quarter-bridge configuration, current transducers with 4-20 mA output or potentiometer sensors [6]. Data analysis was supported by a dedicated software for recording and visualisation of signals. The device had 16 analogue channels to interconnect 16 adapters of strain gauges in the quarter-bridge configuration. Fig. 7 shows the position of analogue channel outputs. A resolution of measurements, conducted in the quarter-bridge configuration is 1μm/m, allowing infinitesimal stress changes to be registered.

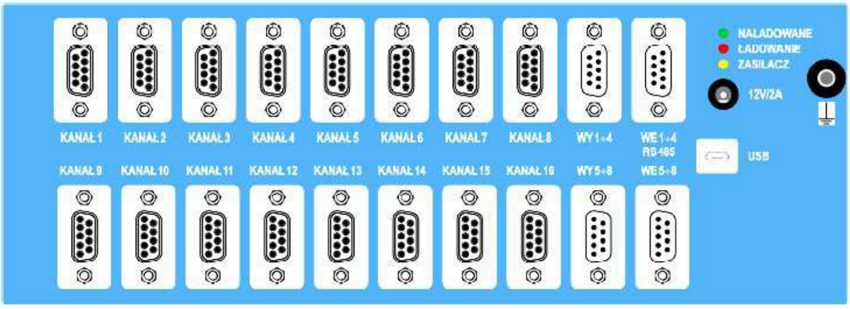

Fig. 7. Rear side of the CL460 recorder [7]

Measurements were taken with BCM strain gauges with the resistance 350.9 Ω and constant sensitivity 2.12+1%. The strain gauge in the quarter-bridge configuration was connected via a cable DY LIFYDY 4x0.04 mm^2. Adapters were directly connected to one of the 16 analogue channels equipped with RS-485 connectors, the present configuration of the strain gauge connection is shown in Fig 8.

The measurement set-up did not provide for compensation of the effects of temperature because the ambient temperature in the proximity of the hoisting installation remained stable, between 15 and 16°C.

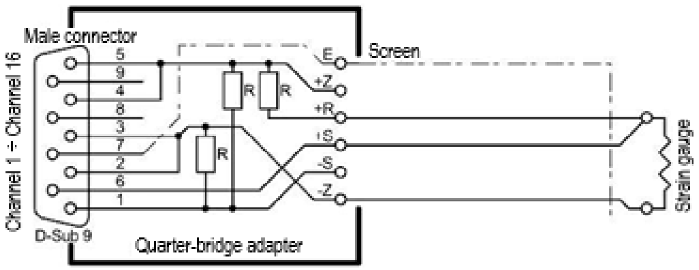

Fig. 8. Schematic diagram of the strain gauge connection to the quarter-bridge adapter [6]

2.4. Selection of measurement points

The elevator car frame is the CF25(TP) model complete with two rope sheaves. Preliminary FEM analyses revealed the critical points on the car frame where maximal stress concentrations should be anticipated. In the first place an array of strain gauges was attached to the roof beam in the elevator car frame (item 1 in Fig. 9). Three strain gauges fixed at this point are mounted at 120° in relation to each other. The second test point was located on the pull rod (item 2 Fig. 9), the third point on the car frame is located on the floor beam (item 3 Fig. 9). Designations of strain gauges mounted on the car frame are summarised in Table 1.

Table 1. Designations of strain gauges mounted on the car frame

Designation	Device	Position
P1	Strain gauge 1	Roof beam (item 1 Fig. 9)
P2	Strain gauge 2	
P3	Strain gauge 3	
P4	Strain gauge 4	Pull rod (item 2 Fig. 9)
P5	Strain gauge 5	Floor beam (item 3 Fig. 9)
P6	Strain gauge 6	
P7	Strain gauge 7	

Alongside strain measurements in the elevator car frame, measurements of increasing stresses on supporting beams were taken as well. In the tested elevator, there are two beams T125xB2x16B supporting the elevator car, made of material with the strength Rm=440 MPa. They support the guide bars and transmit loads onto the buntons whence they are directly transferred to the shaft lining. The supporting beams must be capable of bearing the maximum loads acting on the guide bars. Positions of selected control points on the supporting beam are shown in Fig. 10 and designations of mounted strain gauges are summarised in Table 2.

Table 2. Designations of strain gauges mounted on the supporting beam

Designation	Device	Position
Q1	Strain gauge 1	See Fig. 10, item 4
Q2	Strain gauge 2	
Q3	Strain gauge 3	
Q4	Strain gauge 4	See Fig. 10, item 5

Before the strain gauges were attached to the elevator car frame and to the supporting beams, the corrosion–protection coating had to be removed from their surface by polishing with silicon carbide sandpaper, grit range from 100÷400, to achieve as smooth and even surface as possible, free from corrosion pits and mechanical losses. All strain gauges, being attached at selected points, their leads were soldered to the quarter-bridge adapter. A view of strain gauges fixed at selected points on the car frame and supporting beam is shown in Fig. 11.

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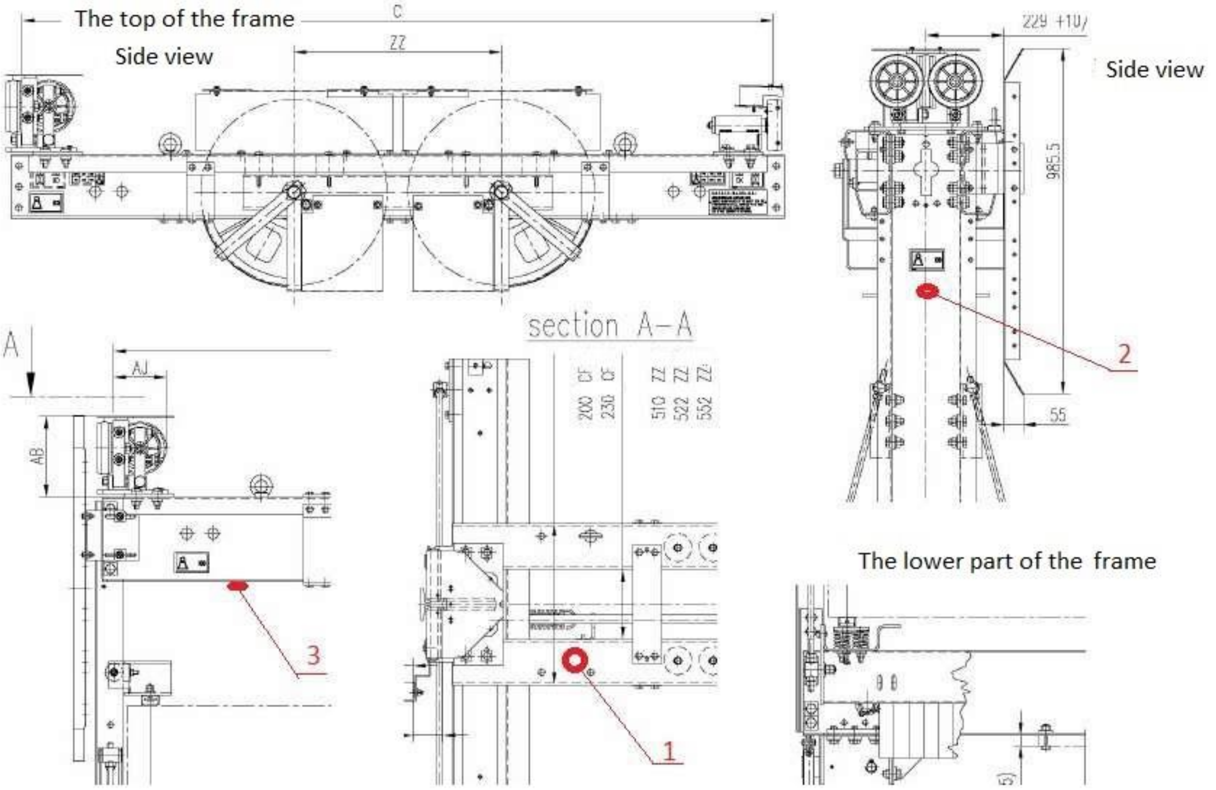

Fig. 9. Positions of control points on the frame of the elevator car (model CF25(TP) [3]

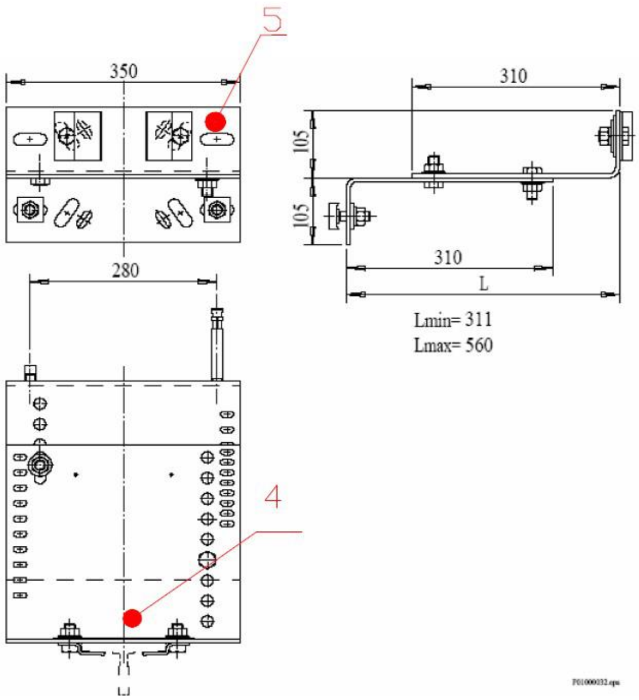

Fig. 10. Positions of control points on the east-end supporting beam [3]

Fig. 11. Strain gauges attached to the selected points on the car frame and east-end supporting beam [3]

3. Measurement results

An array of strain gauge was mounted on the car frame at points shown in Fig. 9 and anticipated stress increases were defined accordingly. The first place, where the strain gauges, were attached was the roof beam in the car frame (item 1 in Fig. 9), with three strain gauges designated as P1, P2, P3 mounted at 120° in relation to each other. A stress increase is anticipated at this point due to the action of the gravity force, the weight of the car frame with fittings and the rope self-weight load. The second measurement point has one strain gauge, designated as P4, mounted on the pull rod in the car frame (item 2 in Fig. 9). The third point is located on the floor beam in the car frame, where three strain gauges, designated as P5, P6, P7, were mounted at 120° in relation to each other (item 3 in Fig. 9).

Locations of measurement points on the supporting beam are shown in Fig. 10.

Measurement points, located on the supporting beam, are shown in Fig. 10. Strain gauge positions were defined in a similar way to those on the car frame, i.e. in terms of anticipated stress increases. On the supporting beam an array of three strain gauges were mounted at 120° in relation to each other at point 4 (see Fig. 10). At point 5 (Fig. 10) there is a single strain gauge mounted on the front surface of the support beam. A view of fully mounted and connected strain gauges is given in Fig. 11. It is anticipated that during the standard elevator operation the forces normal to the car frame might arise at this point and that the supporting beam might be subject to bending and torsion. Besides, the forces acting on the sides of guide shoes, which may cause the beam to bend in the opposite direction, might arise.

The first series of car frame tests were conducted during the ride at nominal speed. The standard hoisting speed during the normal operation was 4 m/s, with no load carried Q=0.0 kg. Fig. 12 plots the stress increase registered by individual strain gauges during the ride from the bank level station 1 down to the level – 135 m.

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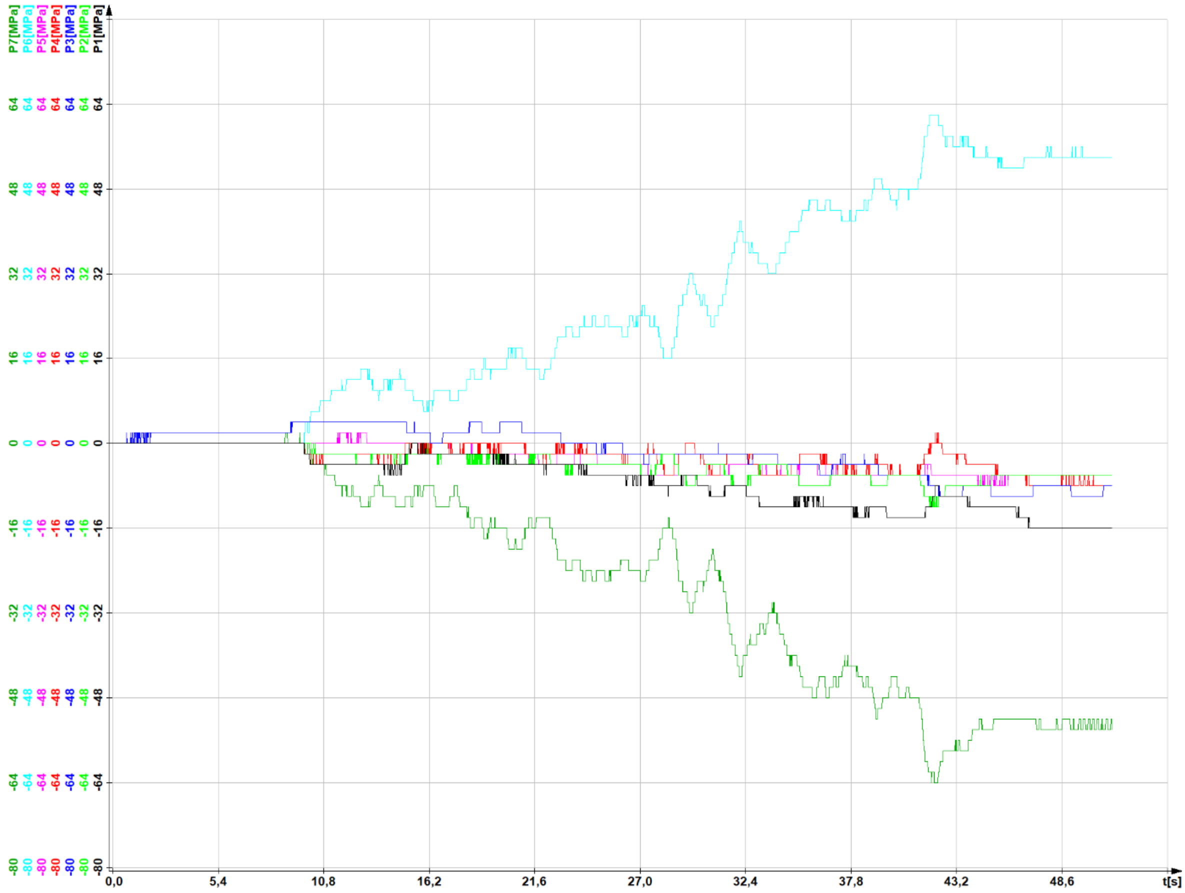

Fig. 12. Downward ride of the elevator car at 4 m/s, with no load [7]

During the first 9 seconds minor stress changes are registered by strain gauge 3, that is the time when the car doors and station doors are opened and closed. Afterwards, the elevator is started and the car begins to ride downward. Successively, with the metres travelled the stress tends to increase, which is registered by strain gauges P6 and P7. These stress increases result from the changes in loading due to the tail rope self-weight and the floor beam may experience slight bending and torsion. Forces and moments of forces that cause this effect are due to the changes of tail rope weight and tail rope motions. In the period from 43rd and 47th second, the car decelerates before reaching the bottom level station. Between the 47th and 49th second an opening of car doors occurs. The further part of the graph does not need to be considered because it reveals disturbances associated with the servicemen entering the car.

In the second series of tests, the elevator car travelled with the maximal load in the standard ride mode at 4 m/s, carrying the load of Q=1600 kg. Fig. 13 shows the results registered throughout 10 cycles of the car ride with the maximal values of operating parameters designed for this model of the elevator.

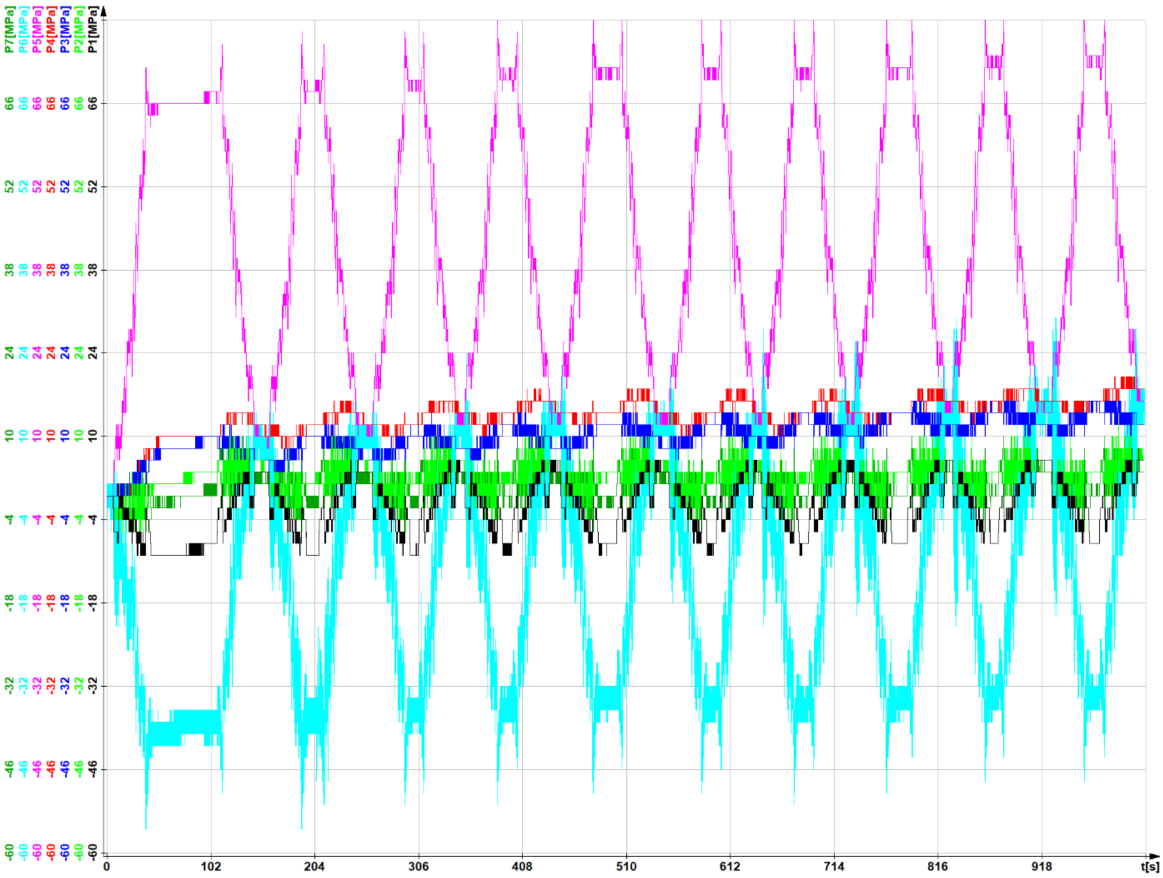

Fig. 13. 10 cycles of elevator car ride at v=4 m/s, with full load [7]

It is worthwhile mentioning that the maximal stress increases were registered again by strain gauges mounted on the floor beam, especially by P5 and P6, which is indicative of torsional moments arising due to tail rope self-weight load, and of the acting bending forces due to elevator car loads. The maximal stress increases tend to oscillate, fully revealing the impacts of the dynamic behaviour of the system. While the elevator stops, the stress tends to decrease until the momentary change of sign in the final stage of deceleration, which is readily apparent between the duty cycles, especially in readouts from strain gauge P6.

With regard to the supporting beam, measurements were taken during the elevator car ride at full speed v=4 m/s and with full load Q=1600 kg. Fig. 14 plots the results registered throughout 10 cycles of the car ride from the bank level station 1 (0.00 m) down to -135 m, with the maximal values of operating parameters designed for this model of the elevator. Apparently, stress variation patterns, registered by the strain gauge Q4 mounted on the front surface of the supporting beam, agree well with the made assumptions relating to the occurrence of forces acting perpendicularly to the shaft axis, causing the vertical plane of the support beam to bend. The maximal values of registered stress variations are about 28 MPa. On the horizontal plane of the supporting beam, where strain gauges Q1, Q2, Q3 are installed, the most significant stress changes were registered by strain gauge Q1 (around 50 MPa). This stress component gives rise to the beam torsion in the direction coinciding with the elevator ride and that is also in line with the underlying assumptions.

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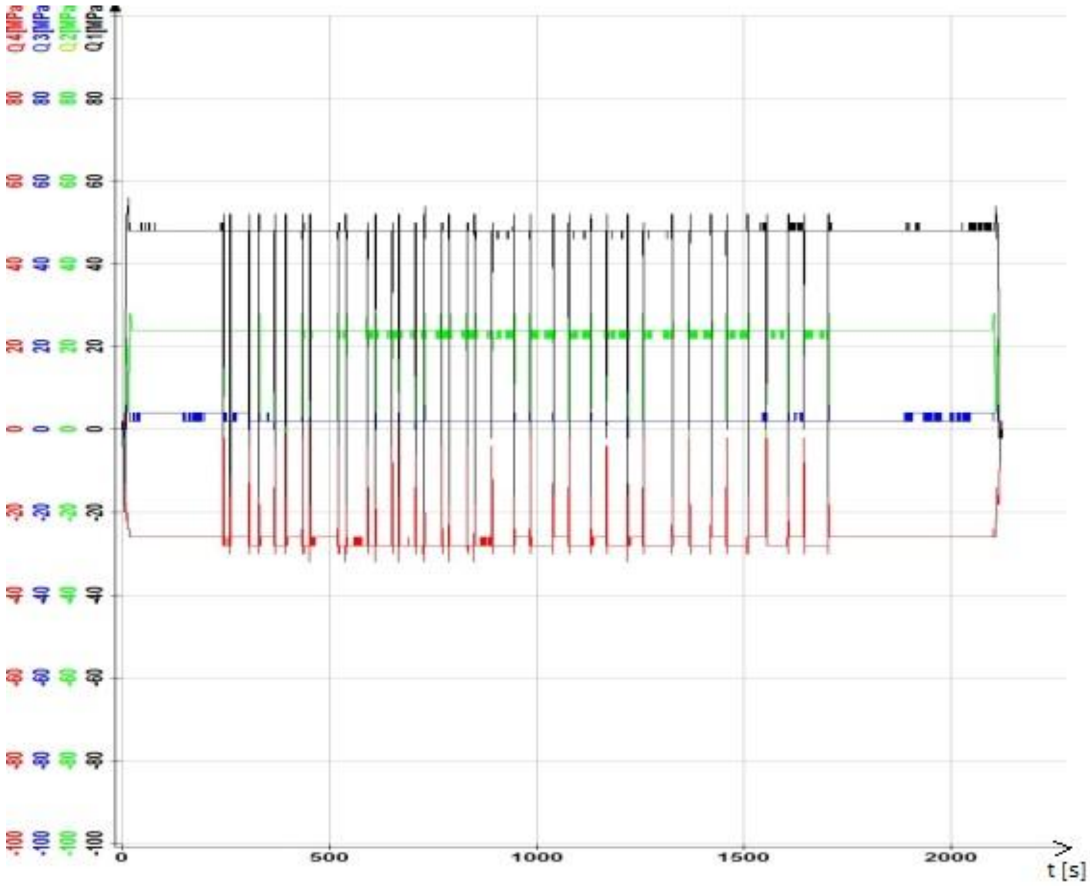

Fig. 14. 10 cycles of elevator car ride at v=4 m/s, with full load [7]

4. Conclusions

The analysis of measurement results reveals slightly increased stress levels in the examined structural components of the elevator installation. In most cases stress increases, registered in the car frame during the hoisting operation, should not exceed 60 MPa, whilst the stresses in the beam supporting the guide shoe rise by about 50 MPa, generating the bending and torsion effect.

Apparently, increased stress levels can also result from a misalignment of the guide string, and this parameter ought to be taken into account in structural integrity and fatigue endurance calculations. Considering the specifications of the car frame material and the fact that the supporting beam is made of carbon steel, grade S235JR (according to PN-EN 10025), with Re=235 MPa and Rm=340 MPa, it is reasonable to hypothesise that the examined car frame and supporting beam should operate well below the endurance limit, (see the S-N curve for the given steel grade).

To verify this hypothesis, computer-assisted model tests are required, based on the FEM approach in the linear range [8].

Should the stress components exceed the respective values Zgo=153 MPa, Zro=112 MPa, Zso=85 MPa, the full endurance analysis of the car frame and the supporting beam will be useful. In such a case the endurance analysis will help to determine the life of the tested system in relation to the number of repeated loading cycles.

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