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Results of stress measurements on the guide rail supporting beams in a hoisting installation operated in the shaft Regis in relation to modelling data

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Abstract:

Presently the hoisting installation operated in the Wieliczka Salt Mine is mostly used for transporting visitors to the underground mine sections. It comprises two elevators which are able to effectively transport groups of up to 42 people during a single ride. Design objectives developed prior to its mounting at the shaft bottom and observations made by maintenance engineers clearly indicate that the guiding system in the shaft is very stiff and so deformations are in fact negligible. The components of the guiding system which have the highest stiffness are bunton beams, designed in accordance with pertinent regulations having relevance to hoisting installations.

To verify the rationale of implementing the stiff steelwork frame, the digital model of the steelwork frame was created and numerical procedures were applied, taking into account the maximal design loads and operational loads. Numerical results were validated through measurements of real stress values at selected components of the guiding system in the hoisting installation operated in the shaft "Regis', under variable operating conditions. The analysis of measurement data allows a preliminary evaluation of structural parameters of the car frame, highlighting the potential of reducing the mass of components selected to be optimised.

Keywords: measurements, mine hoist, FEM, stress, shaft steelwork

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1. Introduction

The full technical specification of the hoisting installation operated in the shaft “Regis” is provided in the article contributed to the KOMTECH 2021 conference materials [1]. The arrangement of two identical shaft-mounted elevators offers the lift capacity similar to that of the mine hoist operated in the shaft “Daniłowicz”. Besides, the energy demand is reduced (shaft “Regis”-0.08 kWh/person; shaft “Daniłowicz”- 0.11 kWh/person) and the operation and maintenance costs of the elevators, unlike the mine hoists, do not require extra staff as operators.

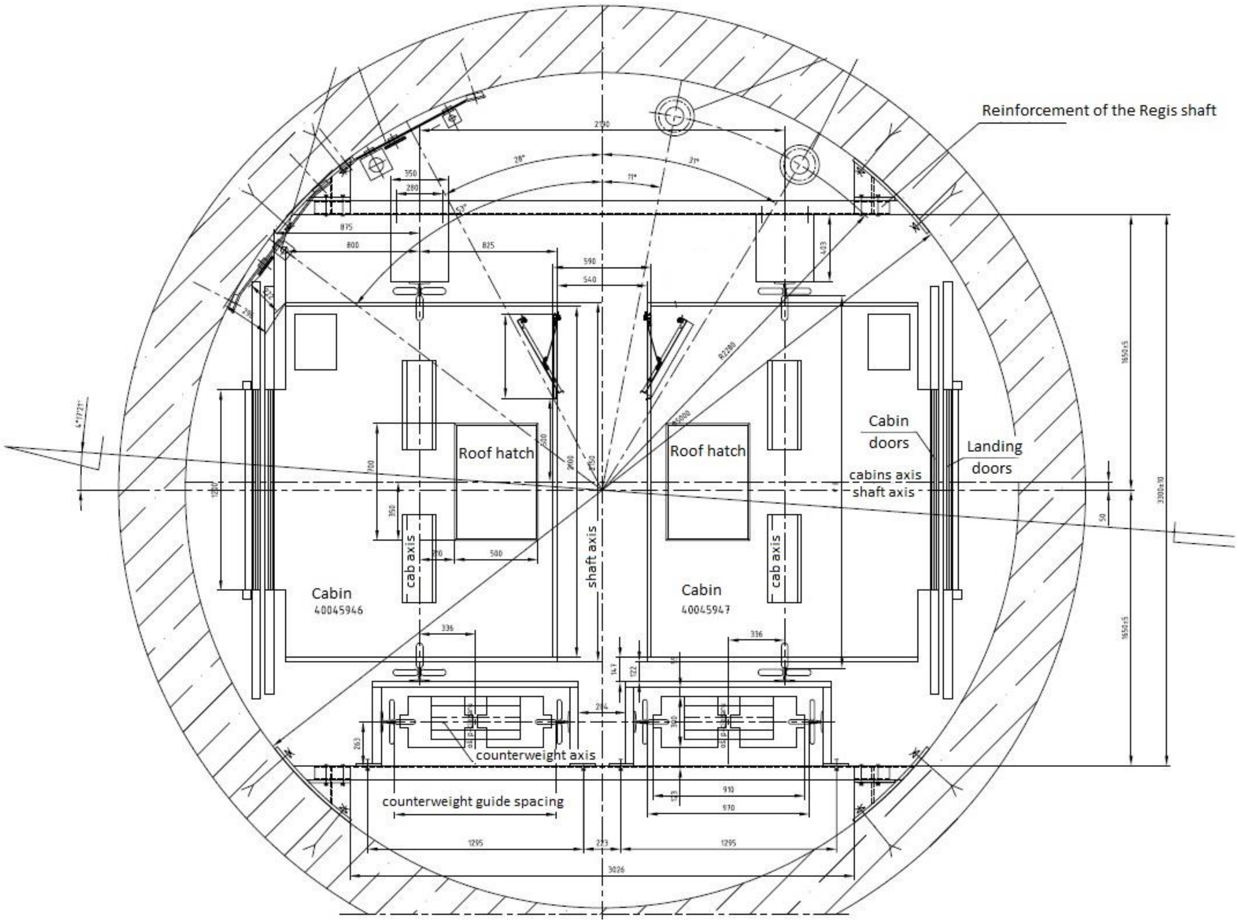

Fig. 1. Cross-section of the Regis shaft with wall-mounted equipment [2]

2. Analysis and modelling of buntons and supporting beams

Basing on the available engineering and technical specifications of the elevators and using the data from the inventory-taking in the shaft “Regis’, the 3D models were created of buntons and beams supporting T-guide rails T125x82x16B, machined. The modelled guiding system comprises a beam with symmetrical brackets used for mounting the column of guide rails upon which the elevator can travel.

Two variants were considered in the modelling and analysis. In the first variant the existing bunton structure is analysed, comprising a c-profile C 240 with the mass of 115 kg. The second variant considered was that of a modified bunton (with its mass reduced) in the form of a c-profile C120 weighing about 46 kg [3]. The static analysis was supported by Autodesk Nastran 2021 software. Fig. 2 shows a 3D model of the bunton in its east-side section with brackets for mounting the guide rails, and the system of maximal acting forces (design loads) due to the release of the catching device [4].

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The bunton was designed and fabricated from structural steel (a carbon steel), in the form of rolled c-profiles made of steel grade S355J2 (yield strength Re=355 MPa, tensile strength Rm= 470 MPa). According to endurance limits and fatigue stress data [5], [6], endurance limit for steel S355 is given as:

- Zgo- 170 MPa (endurance limit under cyclically repeated bending load).
- Zco- 130 MPa (endurance limit under cyclically repeated tensile load).
- Zso- 100 MPa (endurance limit under cyclic torsional load).

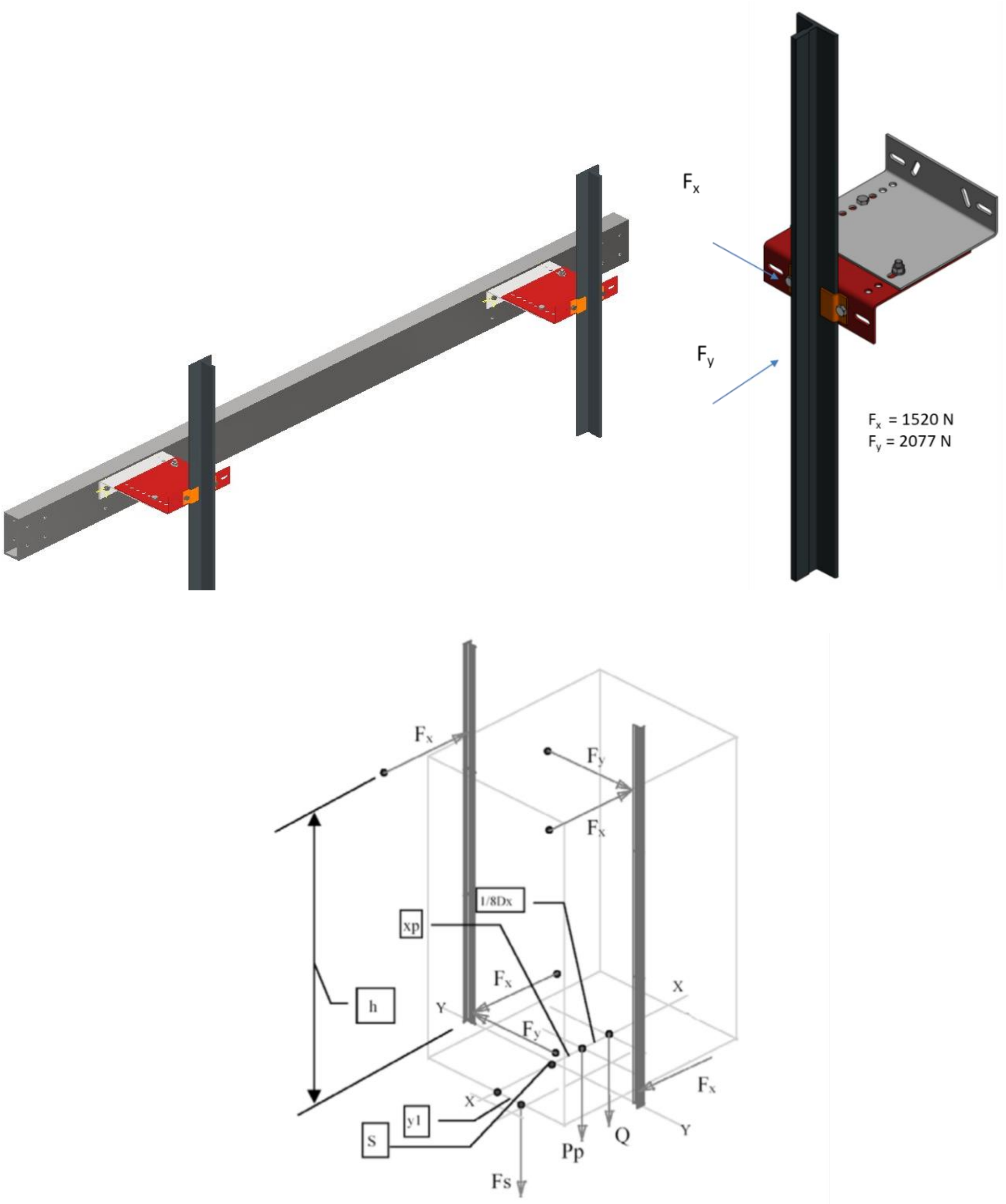

Fig. 2. 3D model of the guiding system with guide rail sections, with indicated loads [4]

3. FEM analysis of the original guiding system - design loads

Forces considered in the FEM analysis are the maximal horizontal design forces induced after the release of the catching device in the elevator. The adopted system of concentrated loads is shown in Fig. 2. The magnitude of two horizontal forces acting in the plane normal to the direction of the ride is taken to be: Fx=1520 N and Fy=2077 N. The support is modelled at the point the bunton is secured to the supporting beam (i.e. at endpoints).

The FEM mesh used in the calculations comprises 10-node parabolic tetrahedral finite elements:

- Number of finite elements: 1 097 107
- Number of nodes: 261 211

Static analysis of endurance strength reveals small displacements of the bunton beam, within the elastic regime.

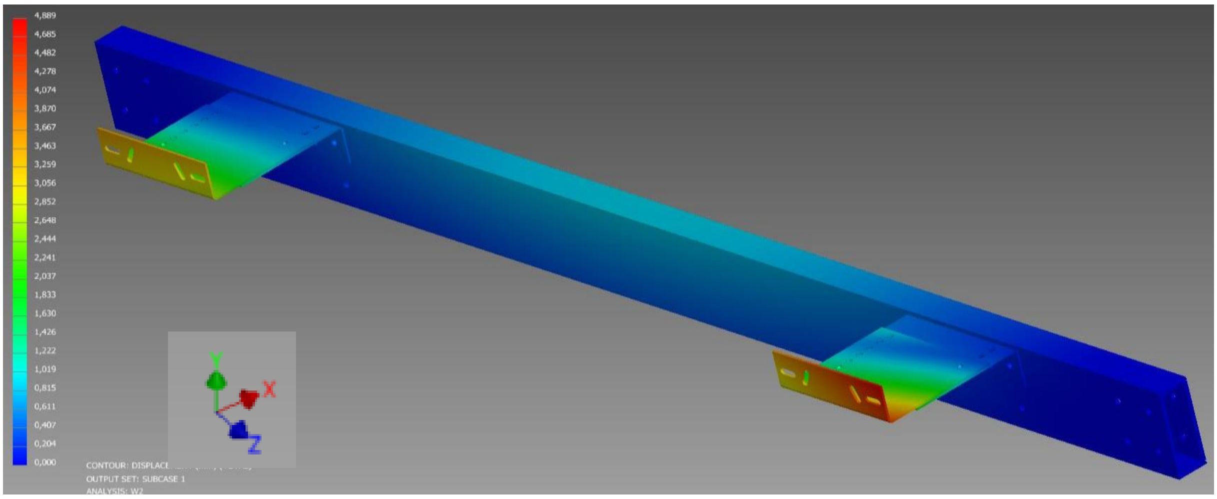

Fig. 3. Total displacement in millimeters of the bunton and supporting beam

In the central section of the bunton, on the upper part of the c-profile the displacement is observed of the order of 0.4-0.5 [mm] Displacements registered in vicinity of the supports and mounting brackets are less than 0.2 [mm], as shown in Fig 3. In most part the registered displacement is in the Y-axis. Maximal total displacement in the elastic range are observed on the brackets, at points where the guide rail is secured. The maximal total displacement of the bunton connection is about 4.9 [mm]. The length of the beam is 3,450 millimeters and the wheelbase of the supports is 2,190 millimeters. Even though supporting beam displacements are considerable, they do not adversely impact on the passenger safety. Actually, these modelled load levels are possible only in emergency conditions, for instance due to breaking of all hoisting ropes in the elevator installation. Displacements registered in the Z-axis are negligible, being of the order.

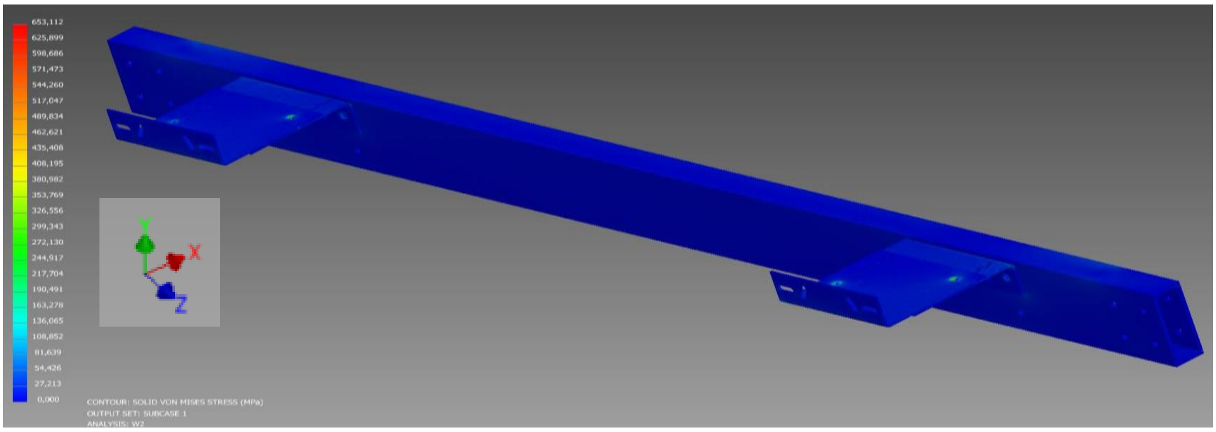

Fig. 4. Stress map: Equivalent stresses in bunton and supporting beam

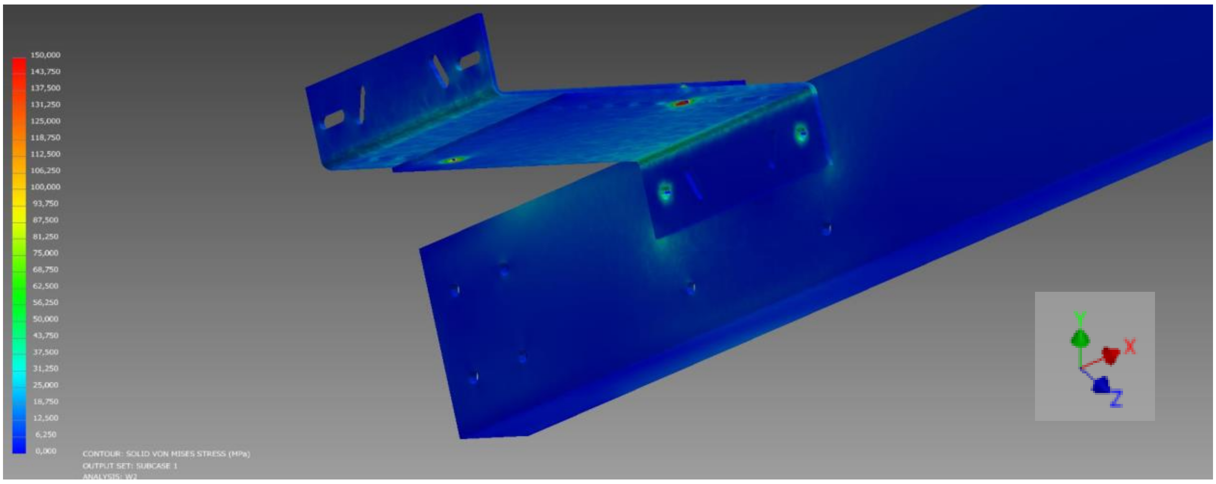

Fig. 5. Stress map: Equivalent stresses in bunton and supporting beam sections with indicates stress concentration zones - view from the car end

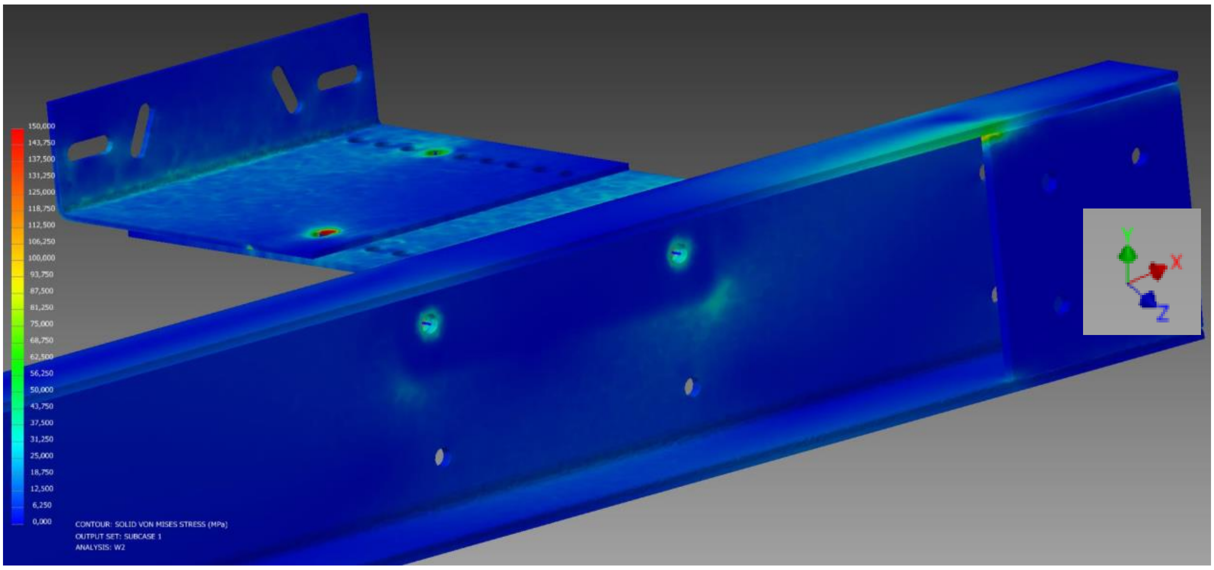

Fig. 6. Stress map: Equivalent stresses in bunton and supporting beam sections with indicates stress concentration zones - view from the shaft steelwork

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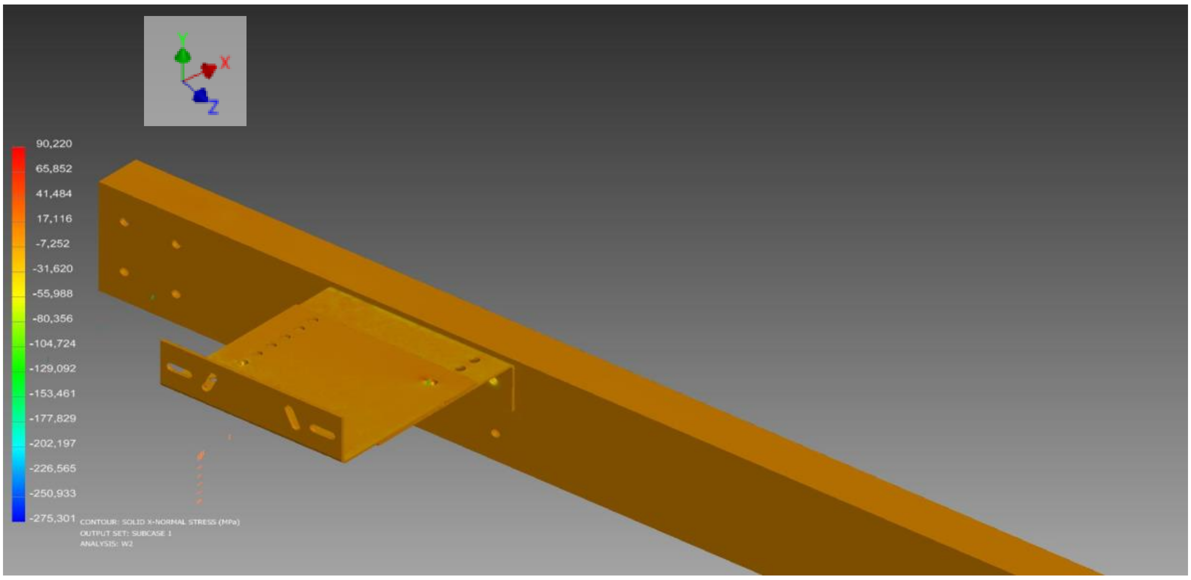
The analysis of equivalent stresses in a large part of the bunton and supporting beam surface shows the stress levels not exceeding 65 MPa (see Fig. 4, 5, 6). The revealed local stress concentration zones are attributable to surface pressure exerted in bolted connections. Equivalent stress concentration levels derived by the modelling procedure and shown in Fig. 5 and Fig. 6 do not exceed 150 MPa.

Bolted connections are modelled with the use of the module Bolt available in Autodesk Nastran 2021 software, the selected bolt material, the axial force and tightening torque are those of the 8.8 bolt. The analysis of the real system indicates that the solution adopted by the elevator manufacturers in order to distribute the surface pressure loads through the use of square - shaped or round washer pads is fully adequate. Resting on these assumptions, the stress increases resulting from surface pressure in bolted connections can be neglected in the modelling procedure.



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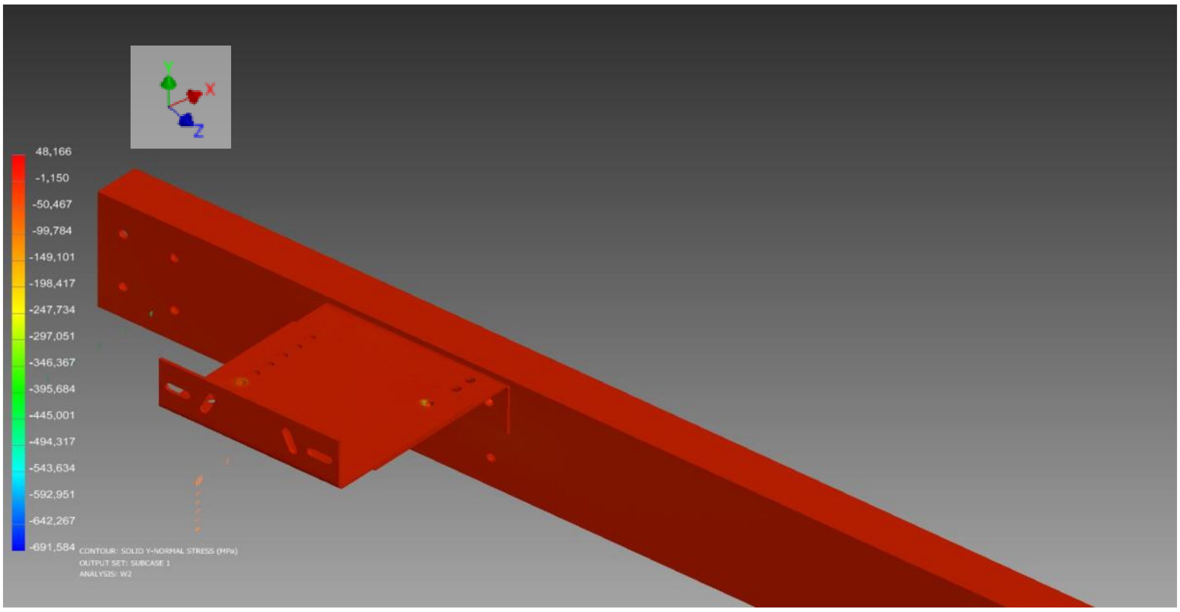

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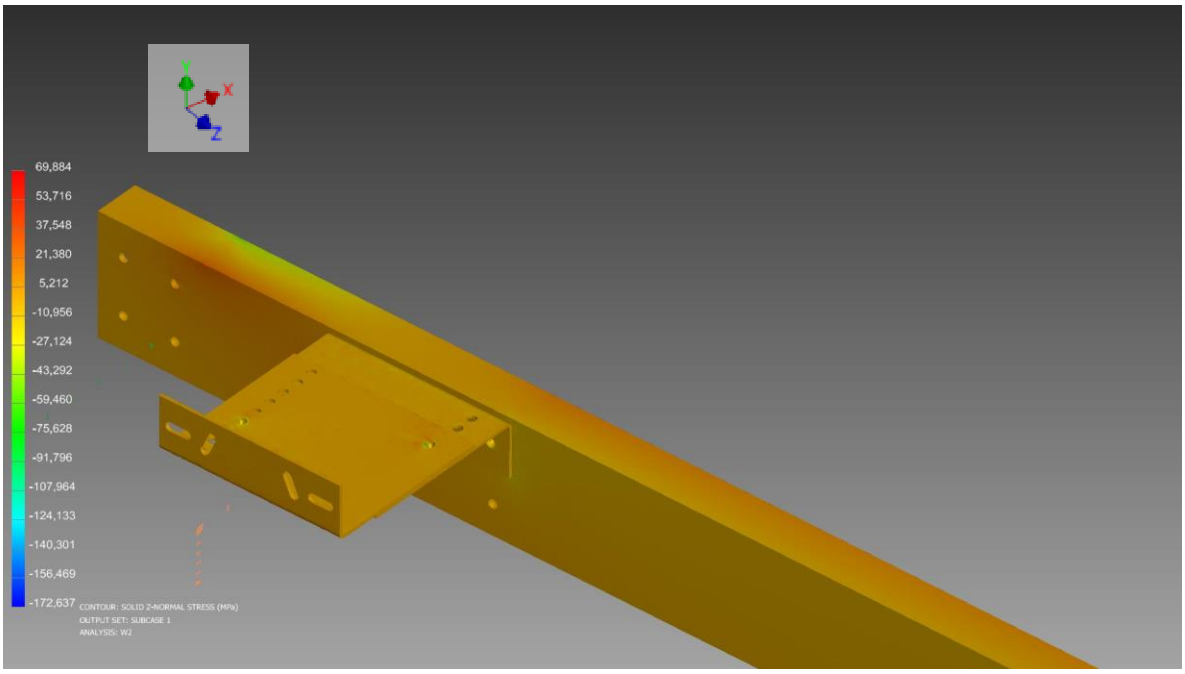

Fig. 7. Stress maps: a) normal stress in X axis, b) normal stress in Y axis, c) normal stress in Z-axis

Examination of stress distribution patterns on the larger fragment of the bunton reveals the normal stress in the X-axis (Fig. 7a) fluctuating in range from -50 MPa to 90 MPa. The largest values are stress concentrations registered next to openings in the supporting beam-bunton connection. The underlying causes of those local stress increases were highlighted in the previous section and will be duly taken into account. The analysis of respective normal stress distributions in Y- axis and Z-axis shows that their increment value should not exceed ± 60 MPa (Fig. 7b, 7c).

4. FEM analysis of the variant 2 (with reduced mass) - design loads

The underlying assumption was made that forces and loads acting on the guiding system with reduced mass are those highlighted in section 4.

The FEM mesh used in the modelling procedure comprises 10-node parabolic tetrahedral finite elements:

- Number of finite elements: 563 268
- Number of nodes: 152 327

The analysis of endurance strength of the modernised bunton with reduced mass reveals certain displacements in the elastic range, as shown in Fig. 8.

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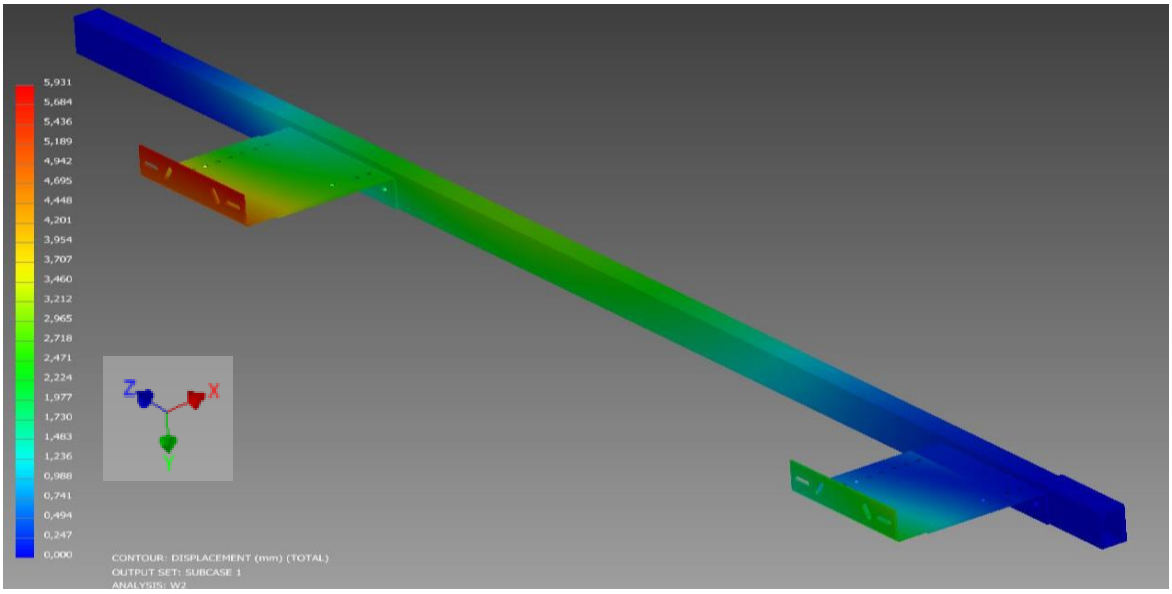

Fig. 8. Total displacements in milimeters of the bunton beam and supporting beam

The total displacement registered in the central section of the bunton, on the upper part of the c-profile, is of the order of 2.5 [mm]. Displacements registered in vicinity of the supporting beam and mounting brackets are less than 0.5 [mm], as shown in Fig. 8. In the largest part, the displacements are registered in the Y-axis. Maximal total displacement in the elastic range are observed on the brackets, at points where the guide rail is secured. The maximal total displacement of the bunton connection is about 5.9 [mm]. Displacements registered on the supporting beam are considerable, yet similar to the case highlighted in section 4, their mass is not subject to reduction, apparently their selection by the manufacturers selection was justified and correct. Displacements registered in the Z-axis are negligible, being of the order of 1/10000 of mm.

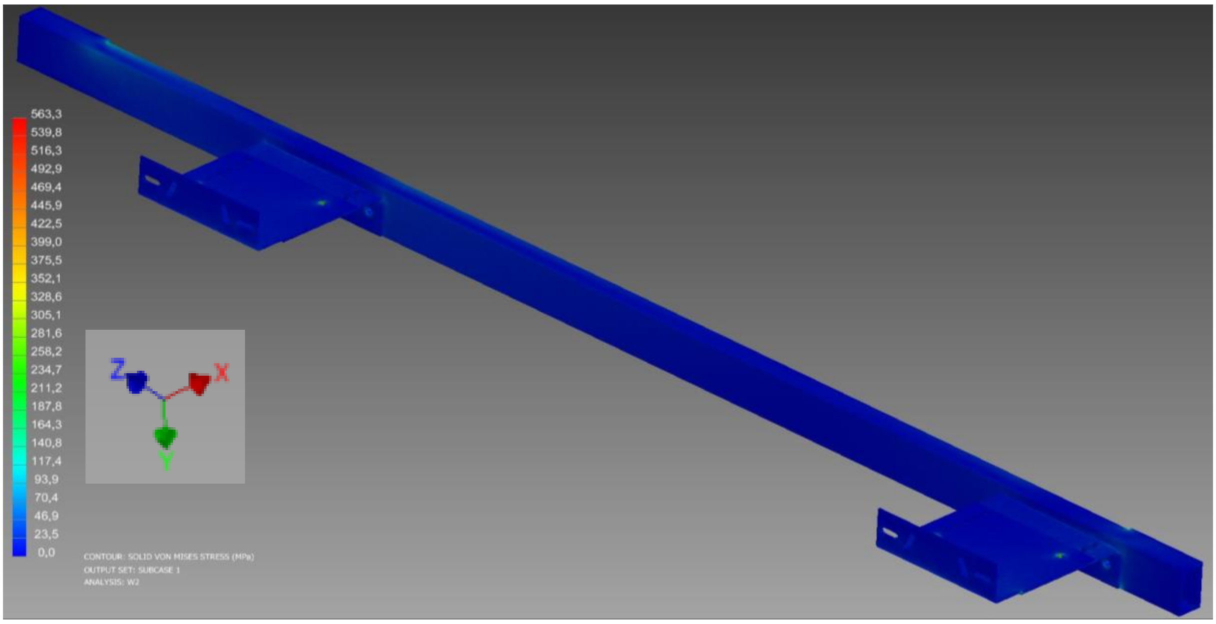

Fig. 9. Stress map: Equivalent stress in bunton and supporting beam

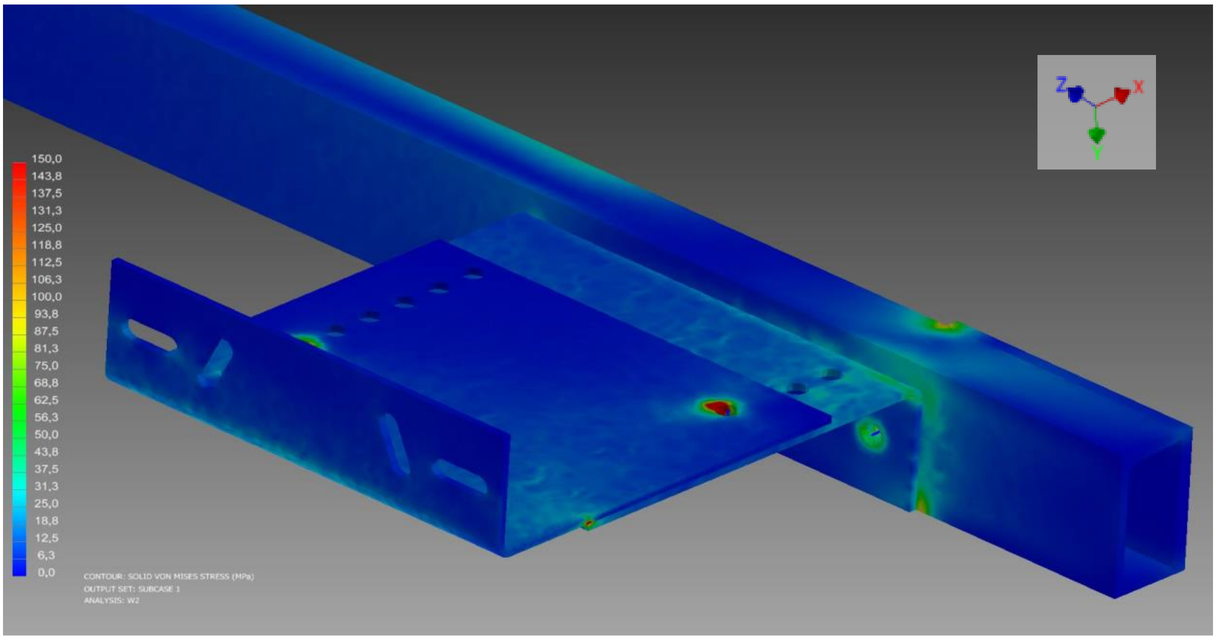

Fig. 10. Stress map: Equivalent stresses in bunton and supporting beam sections with indicates stress concentration zones - view from the car end

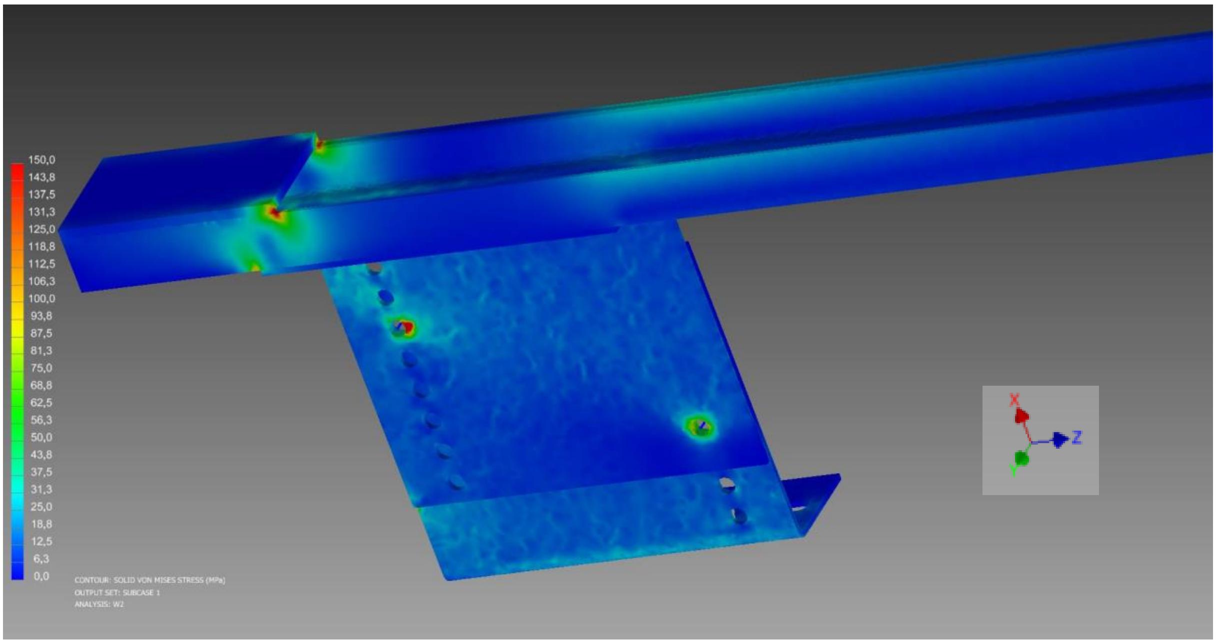

Fig. 11. Stress map: Equivalent stresses in bunton and supporting beam sections with indicates stress concentration zones - view from below

The analysis of equivalent stress distributions in this variant of the guiding system reveals the stress levels on the bunton and supporting beam not exceeding 85 MPa (see Fig. 9, 10, 11). Similar to the case highlighted in section 4, the revealed local stress concentration zones are attributable to surface pressure acting in bolted connections. Modelled equivalent stress concentrations, shown in Fig. 10 and 11, do not exceed 150 MPa.

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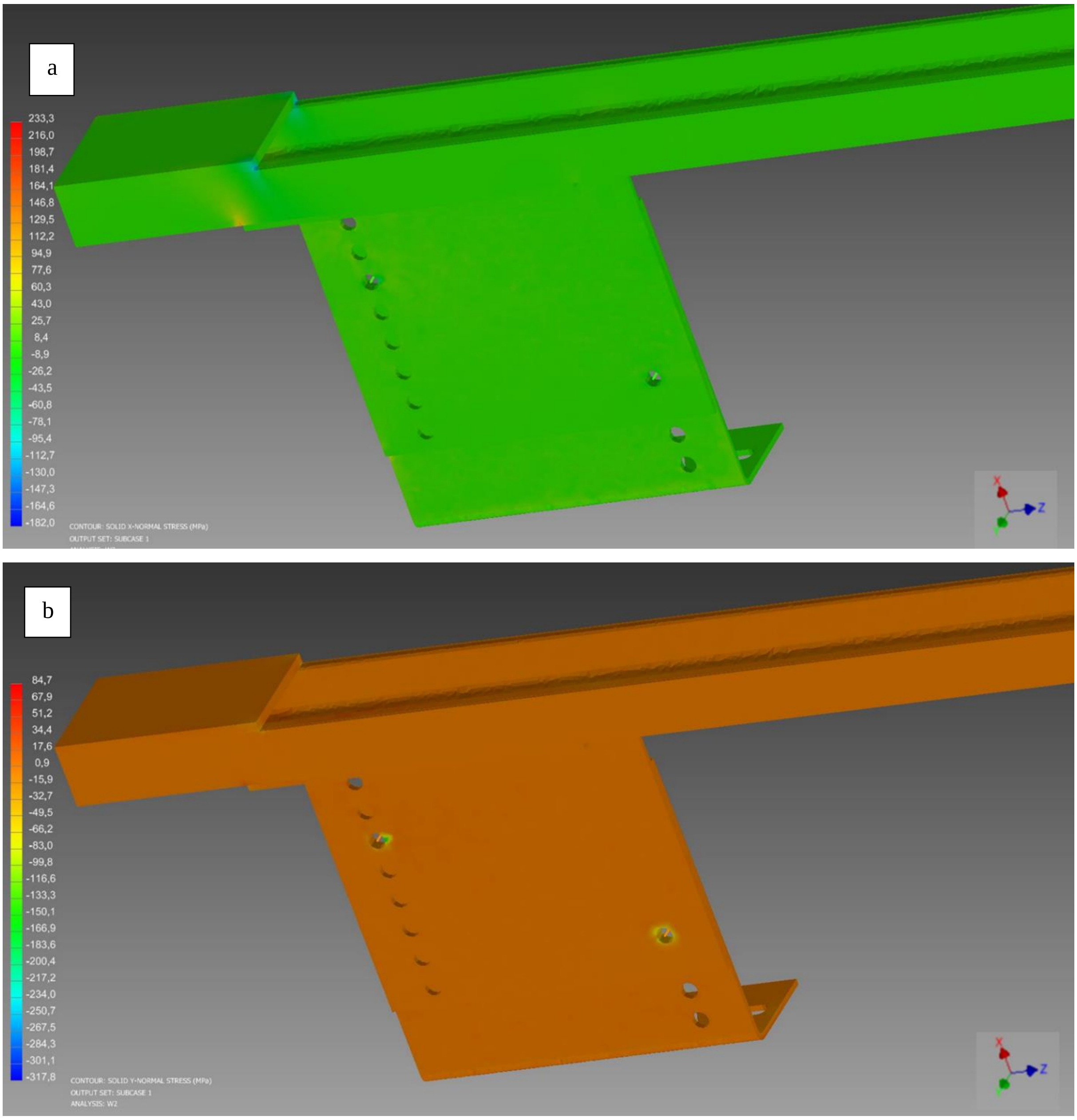

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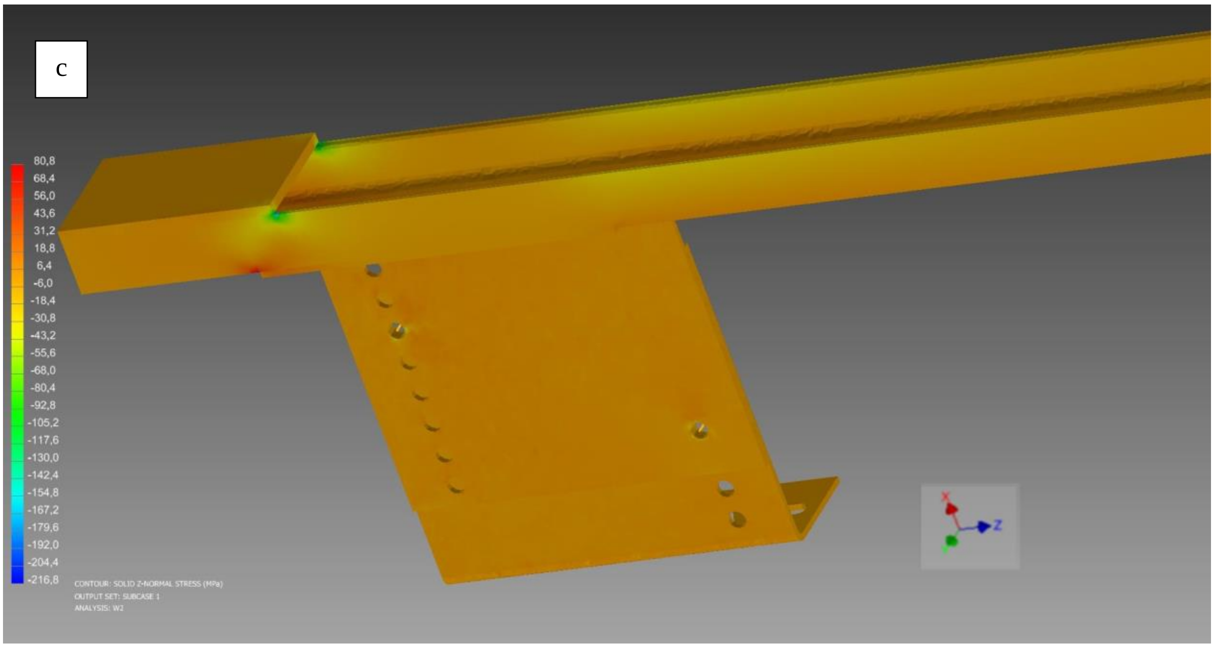

Fig. 12. Stress map: a) normal stress in X-axis b) normal stress in Y-axis c) normal stress in Z-axis

The normal stress in the X-axis (Fig. 12a) varies from -60 MPa to 95 MPa, the largest registered stress levels are at the stress concentration zones near the openings for bunton mounting brackets and at welded joints. The underlying causes of these local stress increases are highlighted in earlier sections. The distributions of normal stresses in the remaining two axes show that stress increments should not exceed ± 80 MPa (Fig. 12b, 12c).

5. Measurement set-up

To verify the stress levels obtained by numerical modelling of the elevator car guiding system, measurements were taken on a real object, i.e. the elevator operated in the shaft “Regis”. The location of strain gauge arrays on the supporting beam is shown in Fig. 13 and Fig. 14, the detailed description of the measurement set-up is given elsewhere (conference materials KOMTECH 2020 [7]. This particular location of strain gauges was selected because the supporting beam is the only components which does not exhibit excessive stiffness and therefore the results of strain measurements taken with these strain gauges should be regarded as reliable and quantifiable.

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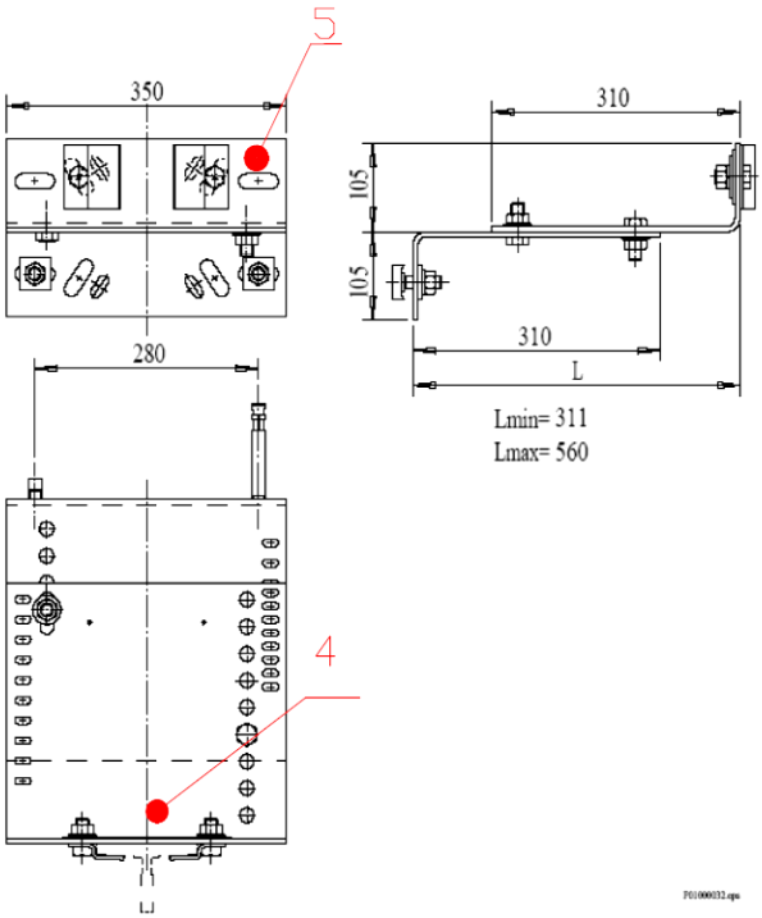

Fig. 13. Mounting bracket [7] with indicated location of arrays of 4 and 5 strain gauges

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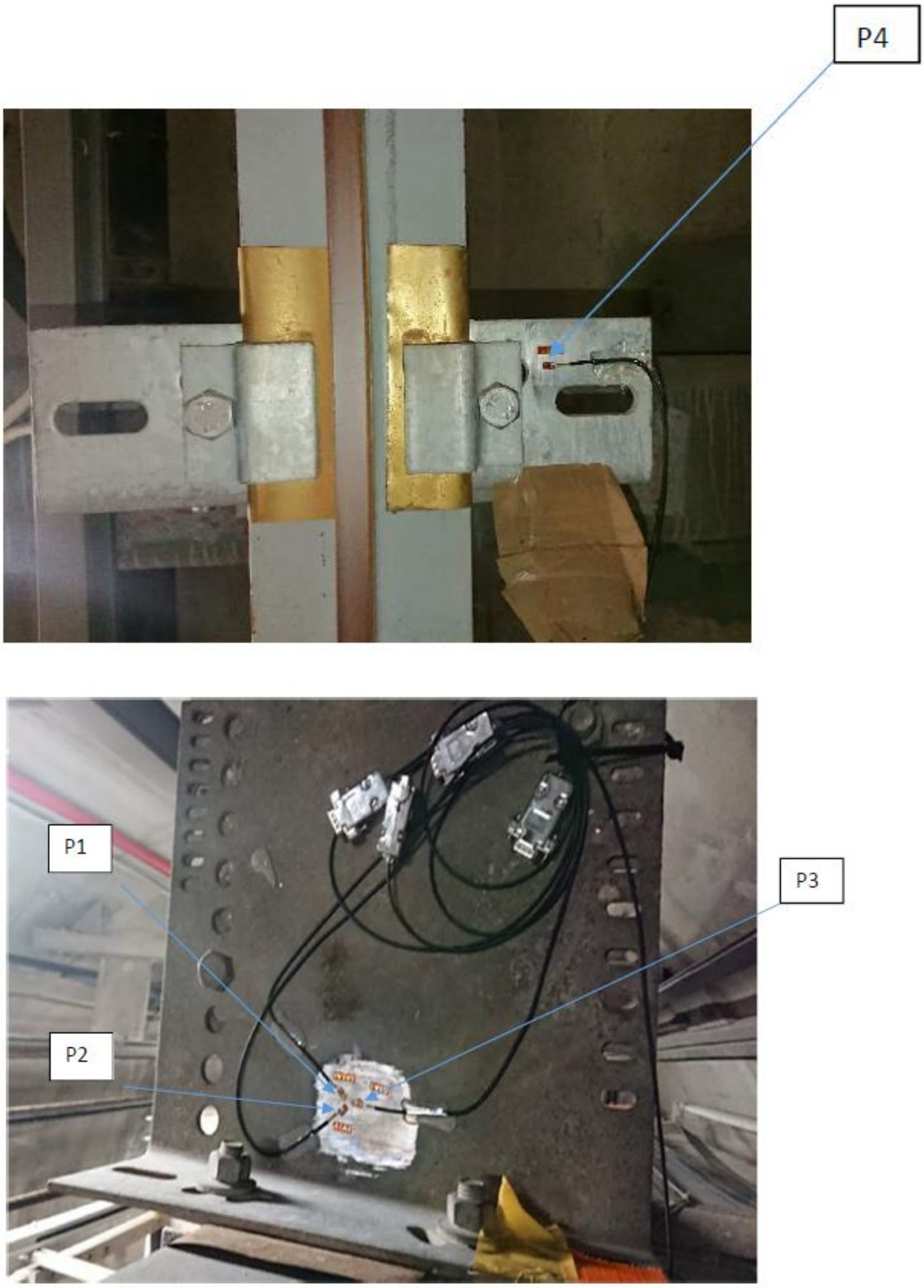

Fig. 14. Strain gauges and their designations

Respective designations of strain gauges attached to the supporting beam are given in Table 1.

Table 1. Designation of strain gauges on the supporting beam

Designation	Name	Location
P1	Strain gauge 1	Horizontal plane of the supporting beam (perpendicular to the direction of the car ride, see array 4, Fig. 13)
P2	Strain gauge 2	
P3	Strain gauge 3	
P4	Strain gauge 4	Horizontal plane of the supporting beam (the points where guide rails are secured, see array 5 in Fig. 13)

6. Results of measurements taken on the supporting beam

This section summarises the three most representative stages of the measurement procedure. Each stage shows distinctive features, representing the least favourable operating conditions in the elevator ride. In the first stage the elevator is travelling in the test mode at the speed limited to 0.3 m/s, with the possibility to stop the elevator immediately. The car was loaded with the maximal admissible load Q=1600 kg. Two cases were considered in the stress measurement procedure. In the first case the top roller linear guide carriage is interrupted during the downward ride near the beam section with the strain gauges. In the second case the car the roller linear guide carriage at the bottom is stopped near the analysed beam section during the upward ride. In this stage of the procedure, significant stress changes were registered in two situations only.

During the second stage of the procedure, the elevator travelled at the nominal speed of 4 m/s with full load Q=1600 kg.

During stage 3, the elevator travelled with full load, with an emergency braking and release of the catching device during the downward ride at the rated speed of 4 m/s. The loading conditions in this case are the worst possible, impacting on the structural elements of the guiding system and thus must be accounted for in design load calculations. The acting loads obtained by FEM modelling are highlighted in section 4.

Plots of stress changes registered by respective strain gauges at selected points on the supporting beam in the first stage of the measurement procedure are shown in Fig. 15, stress changes registered in Stage 2 and 3 are plotted in Fig. 16 and Fig. 17.

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Sample designation	Ride in inspection mode with rated speed GW down and DW up – decreasing when approaching the support			
006	[MPa]	Absolute, maximum value		
P1	P2	P3	P4	Comments
22	14	2	-4	GW
66	30	6	-28	DW

GW- roller linear guide carriage (TOP)

DW- roller linear guide carriage (BOTTOM)

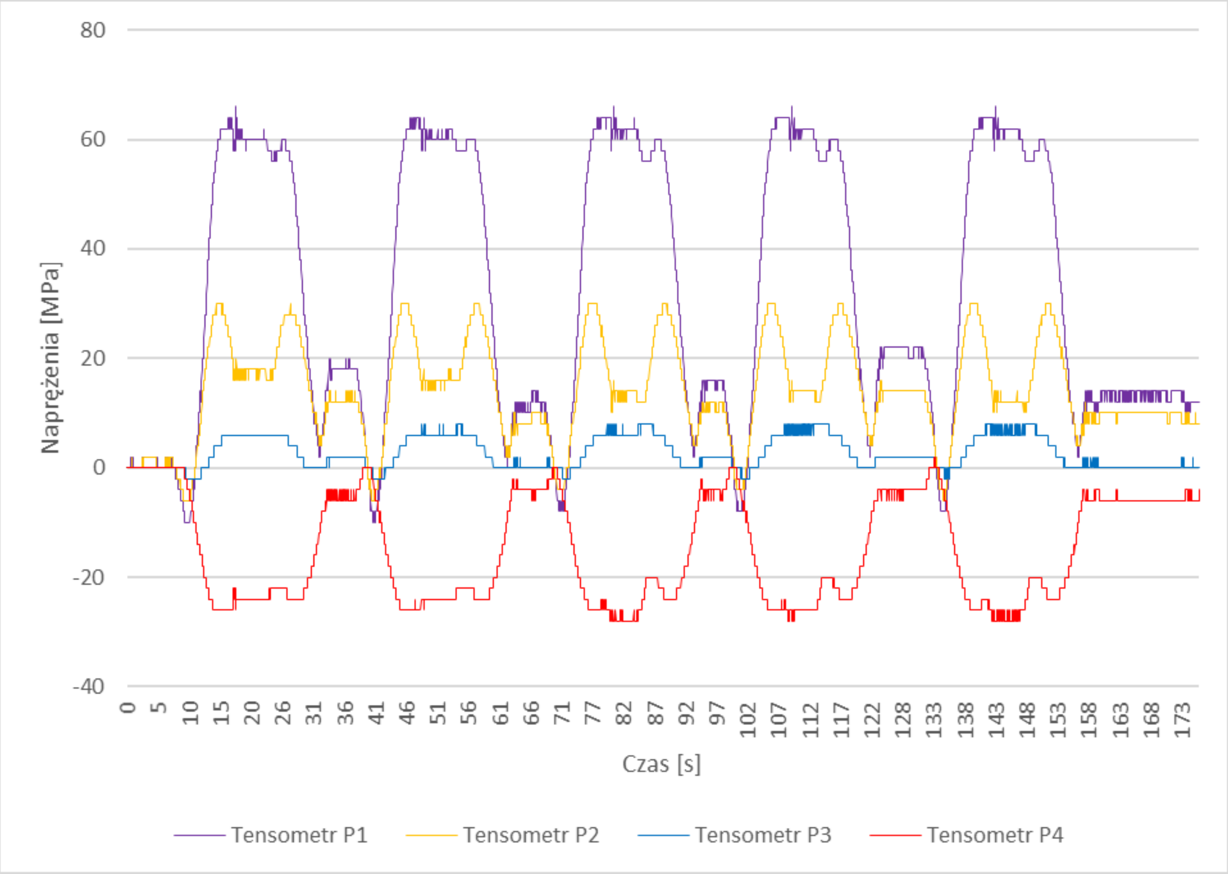

Fig. 15. Measurement results- Stage 1- inspection mode, V=0.3 m/s, Q=1600 kg

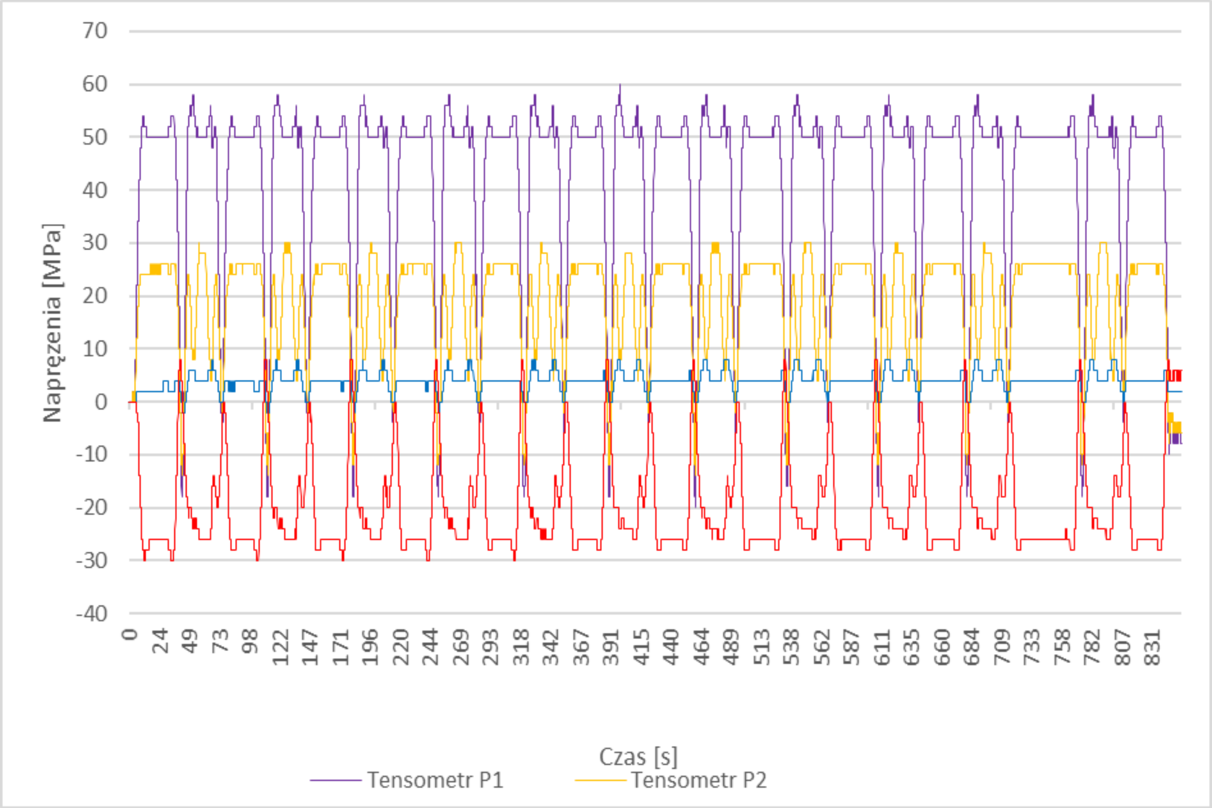

Fig. 16. Measurement results - Stage 2- 10 travels at nominal speed V=4 m/s, Q=1600 kg

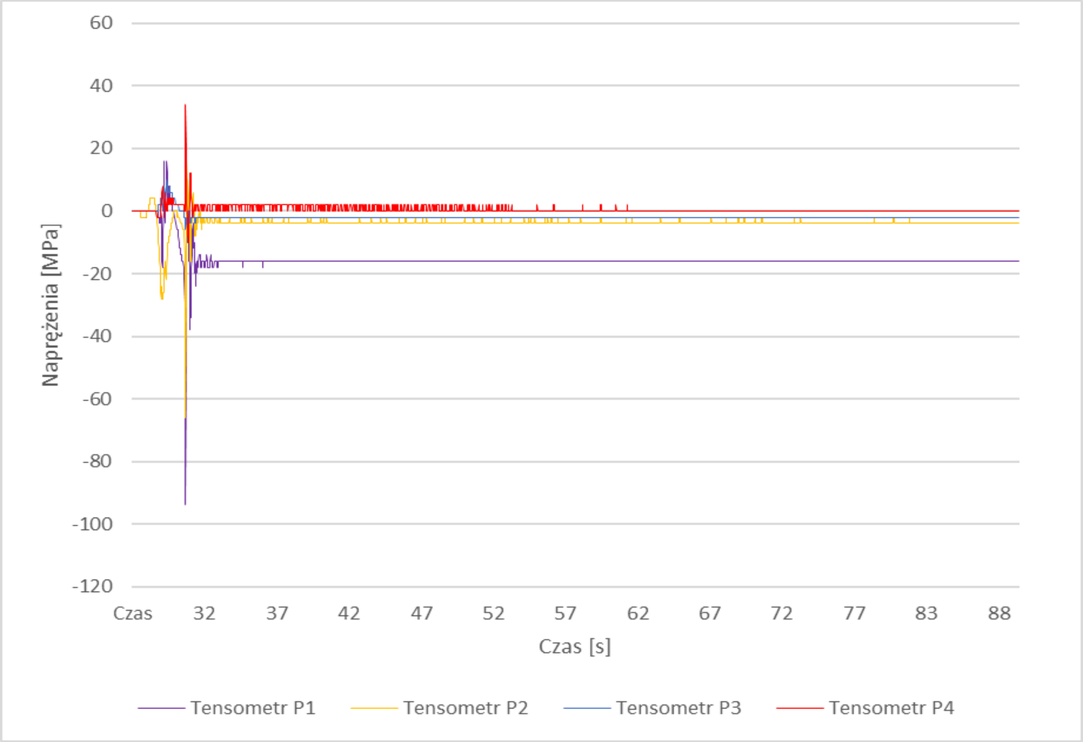

Fig. 17. Measurement results - Stage 3- triggering of the catching device, V=4 m/s, Q=1600 kg, downward ride

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The analysis of measurement data collected during three stages of the procedure clearly shows that real stress changes in structural elements of the elevator guide system are insignificant. The maximal stress changes were registered by strain gauge P1 in the first stage of the procedure (release of the catching device), amounting to 94 MPa (Fig. 17). Considering the specificity of the duty cycle of hoisting installations, the registered stress increments are associated with bending and torsion, their values approaching 60 MPa [1].

Summing up, the analysis of measurement results has confirmed that the elevator car guide system operates within a narrow limit of endurance strength range designed for the type of construction and material used, which is indicative of its high strength parameters. This fact has some implications relating to the mass of the entire guiding system. Application of numerical methods to evaluate the mass redundancy of its structural elements might lead to vast reduction of costs involved in construction of hoisting installations, at the same time maintaining the required safety levels.

7. Conclusions

Numerical analyses and measurements have demonstrated that stress increments due to bending and torsion of load bearing cross-profiles in structural elements of the elevator car guide system operated in the shaft “Regis” are insignificant in relation to the endurance limit of the material used. Stress increments registered under the duty loads are less than 60 MPa and during the emergency braking with the release of catching devices the stress should increase by no more than 94 MPa.

FEM modelling reveals that equivalent stresses in the large fragment of the load-bearing structure should not exceed 65 MPa for the existing system and 85 MPa for the modernised one (with its mass reduced). The enhanced stress concentration levels are found near the bolt connections. Local stress concentrations of up to 150 MPa obtained by FEM modelling are attributed to simplifications of the computational models and to surface pressure exerted by heads and nuts in bolted connections. In real conditions, this effect has been effectively eliminated through the application of square-shaped or round washer pads with large contact surface (Fig. 13). Fatigue endurance limits [5], [6] are not addressed in the study because measurement data fall well below the rated endurance limits for steel grade S355J2 (the material from which the bunton is made).

The analysis of measurement results from testing of the beam supporting the guide rails of the elevator operated in the shaft “Regis” followed by examination of modelling data reveals certain over dimensioning in the bunton design. This fact was verified and confirmed through modelling of the upgraded bunton (with its mass reduced), which satisfies the endurance strength criteria even though its cross-section area is smaller.

When planning new investments involving the installation of conventional mine hoists, the full endurance analysis of structural elements of the elevator guide system is fully merited. Moreover, the environmental conditions prevailing in the shaft have to be considered. One has to bear in mind that standards developed by maintenance engineers relating to air humidity and steelwork stability criteria are most rigorous and must be strictly obeyed during the entire service life of the installation. Every time a hoisting installation is to be implemented in the shaft, a full case-specific analysis of safety aspects is required and merited.

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