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STRUCTURAL SAFETY ASSESSMENT OF SHAFT STEELWORK – A REVIEW

Shaft steelwork is a component of critical infrastructure in underground mines. It connects the mining areas to the surface and enables the transport of personnel, equipment, and raw materials. Its failure or malfunction poses a threat to people and causes economic losses. Shaft steelwork is an exceptional engineering structure exposed to dynamic loads from large masses moving at high speeds and is subject to intensive deterioration resulting from corrosion and geological or mining-induced deformations. These issues cause shaft steelwork to be subject to high structural safety requirements, design oversizing, demanding maintenance procedures, and costly replacement of corroded members. The importance and unique working conditions of shaft steelwork create practical design and maintenance problems that are of interest to engineers and scientists. This paper reviews publications on the structural safety of rigid shaft steelwork and summarises the range of research from the detection of guide rail failures through the assessment of load effects and guide resistance, to the evaluation of structural reliability. The effects of guide rail failures on guiding forces, models of the conveyance-steelwork interaction, the load-carrying capacity of shaft steelwork under advanced corrosion, and the probabilistic assessment of structural reliability are presented. Significant advances in understanding the mechanical behaviour of shaft steelwork and assessing its properties have been reported. This review summarises the current state of research on shaft steelwork structural safety and highlights key future development directions.

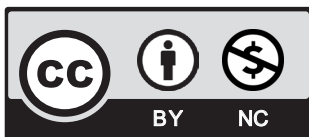
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1. Introduction

Reliable, safe, efficient, and fast transport are key factors in the efficient operation of mines. Shafts are the most important components in deep underground operations. They connect the mining fronts to the surface, provide ventilation, and transport mined raw materials, supplies, personnel, host pipes, and cables [1].

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Vertical shafts adopt two types of guiding of the hoisting conveyance: rope and rigid. Shaft conveyances move along tensioned steel ropes or steel beams anchored to the shaft lining, respectively. The extensive horizontal displacements of the conveyances guided along the ropes require large distances from the shaft lining and elements of the shaft infrastructure. This reduces the size of the conveyance and transport capacity [2]. Using rigid guides drastically reduces lateral movements, allowing massive skipping and high speeds. This makes rigid guiding the dominant guiding system in the industry.

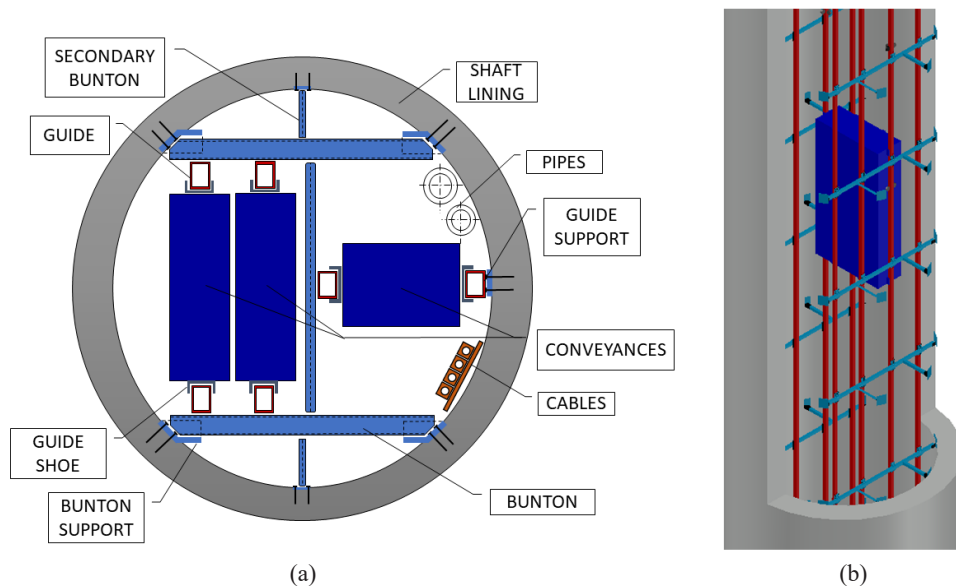


Fig. 1. (a) Simplified shaft cross-section and (b) three-dimensional view

Constraining the lateral displacements results in the induction of interaction forces between the conveyances and guide rails. Misalignments of the movement path resulting from mining and geological factors result in transversal movements of the conveyance and impact the guides [3]. The face and side components of the guiding forces have random values, directions, and application points.

Shaft steelworks are spatial steel structures comprising hot-rolled guides and buntons (Fig. 1). The load capacity depends on the implemented profile characteristics, spans, and connection types. A large reduction in member cross-sectional thickness is observed because mine environment conditions facilitate highly corrosive steel deterioration [4], which must be considered in the load capacity assessment of steelwork.

Assessing the load-carrying capacity of shaft steelworks is a complex engineering problem owing to the random nature of loads and the heterogeneity of corrosion phenomena. Industrial standards for shaft steelwork design involve multiple wide-ranging simplifications in terms of assessing the load effects and structural resistance. They are compensated for by arbitrarily high safety factors and oversizing. Scientific research conducted in recent years has shed new light on the problem of assessing and managing the structural safety of shaft steelwork.

2. Failures of the guide rails

Factors related to the shaft hoist operation and geological factors often lead to guide rail defects or damage, disruption of rectilinear movement, and the formation of strong interaction forces between the conveyances and the guide. Bruneau et al. [5,6] presented the degradation process of a shaft in a tectonic fault zone. They described the damage to the guide rails as a consequence of shaft lining deformation in the fault areas. They measured the rectilinearity of guide rails and determined the misalignment that occurs as a result of the movement of the rock mass in the fault zone [5]. Their research on the shaft led to the development of a numerical model for the shaft. Three-dimensional modelling of the rock mass and shaft was performed using the boundary element method. The model was used to predict the guide rail displacement rate [6].

Zhao et al. [7] studied the influence of non-mining ground subsidence on guide rails deformation. The model considers the impact of subsidence as a function of the bottom aquifer water head. A finite element model was built in the ANSYS environment to determine the relationships among the geological phenomena, shaft deformation, and guide rails. By determining such a relationship, conclusions about the condition of the entire shaft were drawn based on the measurements of the guide rail deformation. Zhao et al. [7] considered the possibility of failure of the connection between the main elements of a steelwork. The simulation showed that the guide rail deformations due to subsidence depend on the degree of preexisting damage to the shaft steelwork connection. The integral structure was highly resistant to further damage, and the amplitude of the lateral displacement was as low as 1 mm. In the case of a preexisting failure of the guide to the bunton connection, the amplitudes reached 6 mm, which might have resulted in high guiding forces.

Guide rails comprise thousands of meters of steel profiles located in mine shafts, where access for inspection is limited for technological reasons. This makes detailed measurements and inspections time-consuming and cost-intensive, which is why they are conducted at intervals of a few years. This necessitates developing methods for the rapid, inexpensive, and remote damage assessment of guide rails. Analysing the vibrations of guide rails under operating conditions could be one of these methods. Xingming et al. [8] proposed a dynamic model with two degrees of freedom to analyse hoisting conveyance passages through various types of guide rail failures. One of the conclusions of their research was that the amplitudes of acceleration for the same damage differed depending on the phase of the conveyance motion (acceleration, driving at a constant speed, and braking), which made damage detection even more difficult. Wu et al. [9] continued their work on guide rail damage detection by considering theoretical models and performing experiments on a physical model. However, effective damage detection based on vibration tests is difficult under shaft conditions. Various operating factors, including the mass of the conveyance, its velocities, and acceleration characteristics, make it a characteristic frequency-unknown problem. Wu et al. [9] used a novel analysis method combining a multiple time scale technique and a dynamic time warping algorithm, significantly improved the accuracy of guide rail damage detection, and established response patterns to bump- and gap-type faults (Fig. 2).

The fault-detection method exhibited very high sensitivities of 100%, 90.40%, and 84.53% for embossment-, bump-, and gap-type faults, respectively. Yao et al. [10] combined dynamic model studies and numerical simulations to determine the effect of guide rail failure on guiding forces. The modelling results were validated experimentally using a physical model. They also proposed a solution for reducing the dynamic effects of a hoisting rope using a tension equilibrators and magnetorheological dampers.

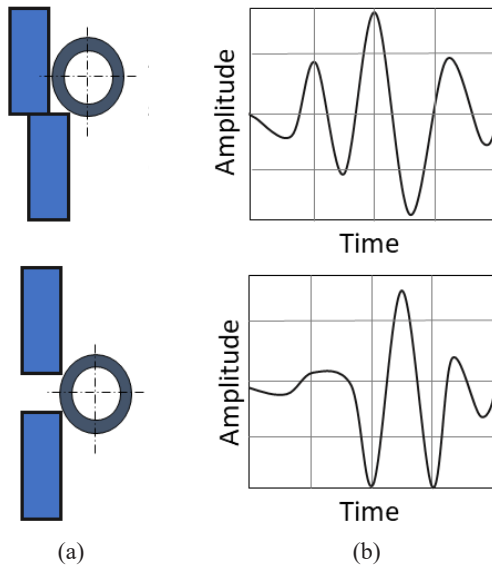


Fig. 2. (a) Common bump-type and gap-type guide rail failures and (b) the respective response patterns. Diagram based on [9]

Yao et al. [10] studied the important problem of the effect of guide rail failures on the forces in the hoisting rope. The problem of dynamic wire rope interactions is the subject of extensive research, e.g. [11-17], but is beyond the scope of this review.

In addition to the guide rails deformations, corrosion processes also damage shaft steelwork members (Fig. 3). As in the case of mechanical damage, assessing the corrosion phenomena through detailed maintenance inspection and ultrasonic wall thickness measurements is difficult in normal operating conditions of shaft hoist conveyance and is conducted at intervals of a few years [18].



Fig. 3. Corrosion in a mine shaft

Batko and Korbiel [19,20] made a noteworthy attempt to use operational modal analysis to assess the corrosion loss (CL) of guides. They numerically demonstrated that a uniform CL slightly affects the frequency of natural vibrations. The lack of a relationship between the examined feature and vibration frequency prompted them to analyse the impact of the CL on the system damping. An analysis of the obtained measurements showed a significant relationship between the global damping coefficient and the CL level [20]. They reported that analysing the damping coefficient allows the classification of guides that are likely to exhibit a high CL. Despite the existence of a physical relationship among the stiffness, mass matrix, and dynamic properties, failure detection based on modal analysis is complex and difficult to apply effectively, even for simple structures [21].

3. Guiding forces

Damage detection does not involve assessing the effect of guide rail failure as interaction forces between the conveyance and guides. The natural approach for estimating the guiding forces of a conveyance-steelwork system is to develop a dynamic model of the system [22]. A typical model comprises a rigid body with a mass and moment of inertia. The guiding system, depending on the design (sliding or rolling), comprises springs and viscous damper elements in various configurations (Fig. 4).

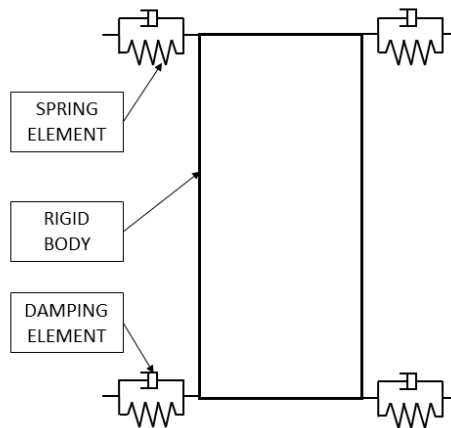


Fig. 4. Example of a simplified dynamic model of the conveyance-steelwork interaction. Diagram based on [8]

The model parameters are adjusted based on the assumptions made, characteristics of the tested conveyance-shaft steelwork system, and tested properties [23-25]. Heyns and Heyns [23] presented a force magnitude assessment based on the dynamic models of a conveyance-steelwork system. They proposed a 3D model of the skip using the mass and moment of inertia with six degrees of freedom. They modelled the interaction of the conveyance with guide rails using elastic constraints. Beam finite elements and buntons represented the guides and truss elements, respectively, with one degree of freedom. The data obtained from the model were compared with vibration measurement results, indicating high agreement. Wolny and Matachowski [26] and

Wolny [24,25] also presented dynamic skip-shaft steelwork models. The skip model comprised three masses corresponding to the top transom, the bottom transom, and the skip body, as well as a moment of inertia. The upper and lower masses were loaded using an elastic constraint with displacements corresponding to the misalignment of the guides. They determined the spectral density functions of the displacements based on actual measurements of the guide rails misalignment [26]. The dynamic model presented in [24,26] enabled determining the value of the forces resulting from the contact of the skip with the steelwork for various conveyance velocities in the shaft. This enabled selecting the optimal velocity owing to the forces generated. Deng et al. [22] and Yao et al. [27] established a dynamic model of the horizontal vibration of a mine-hoisting system. Using Simulink software, they simulated hoisting by different types of guide rail failures and calculated the transverse acceleration response at the centre of mass. The results obtained from the dynamic model were consistent with those of a simulation on a 3D virtual prototype developed in the Adams software. Validated models were used to study the effectiveness of magnetorheological dampers via advanced co-simulation using the Adams and Simulink environments.

The analysis of the guiding forces calculated based on the dynamic model was extended by analysing the stresses in the elements of the hoist conveyance [25]. Wolny and Matachowski [28] also attempted to estimate the guiding forces using a finite element skip model. They presented a 3D beam-and-shell model of a skip loaded with displacement applied to the top and bottom transoms. Using finite element simulations, they calculated the forces acting on the conveyance and the stresses in the loaded elements of the skip. They performed an in situ experiment to verify the numerical simulation. Observing the simulation and measurement results in terms of the guiding forces revealed considerable differences in the deformations and stresses. The authors attributed these differences to the inconsistency between the model developed based on the documentation of the conveyance and the actual conveyance, which could have its structural arrangement changed significantly during its assembly and operation.

Dynamic models require many simplifications and idealisations; therefore, these methods cannot yet be successfully implemented to guiding forces estimation. Extensive research has been conducted on the dynamics of conveyance-shaft steelwork systems in South Africa [29]. These results led to the development of a guiding force magnitude assessment method. This method assumes that the guiding force source is a slide of the conveyance along a curved track (Fig. 5). The stiffness of the steelwork and conveyance, effective mass, hoisting speed, and misalign-

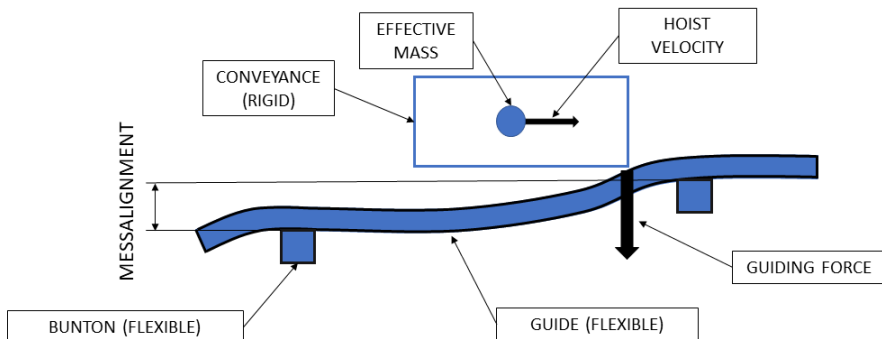


Fig. 5. Simplified model of conveyance and shaft steelwork interaction.
 Diagram based on [35]

ment magnitude affect the magnitude of the force. The results of the South African studies were implemented as national South Africa standards [30] and reproduced in Australia, New Zealand [31] and in the ISO series of standards [32]. Płachno [33,34] arrived at a similar conclusion. The drawback of this force estimation method is the assumption of continuous guide rail deformations, where extreme misalignment occurs between adjacent guides [9,10].

One of the conclusions from the accelerometer measurements was that the conveyance did not behave as a rigid body. This prompted research on the contribution of the conveyance mass to the guiding force. Research conducted in the Upper Silesian hard coal mines [36] initiated the development of methods for measuring the guiding forces [37]. Currently, four methods are approved for measuring guiding forces in Poland [38]. Two of them are based on the direct measurement of the guiding force by replacing one of the guiding shoes with a measuring system equipped with a dynamometer. The remaining two methods are accelerometer methods; therefore, the force measurement is indirect and uses physical principles. External experts periodically measure the actual guiding forces as part of obligatory inspections [18]. All methods show that the guiding forces are random with respect to the application point, magnitude, and direction, making the structural analysis of shaft steelwork difficult.

4. Load-carrying capacity

Shaft steelwork is operated in corrosive environmental conditions, comprising waterlogging, salinity, stray currents, or sulfur bacteria [39-43]. Shaft steelwork members operate with extremely high CL, which is not observed in other structures. The CL allowed by the regulations in Poland [18] is 50% of the nominal wall thickness of the cross-section. Fiołek et al. [44] presented studies on the load-carrying capacity of shaft guides as a function of uniform CL with reference to the Eurocode 3 (EC3) standards [45]. A series of FEM numerical tests were performed for the selected profile, which exhibited high compliance with the standard calculations.

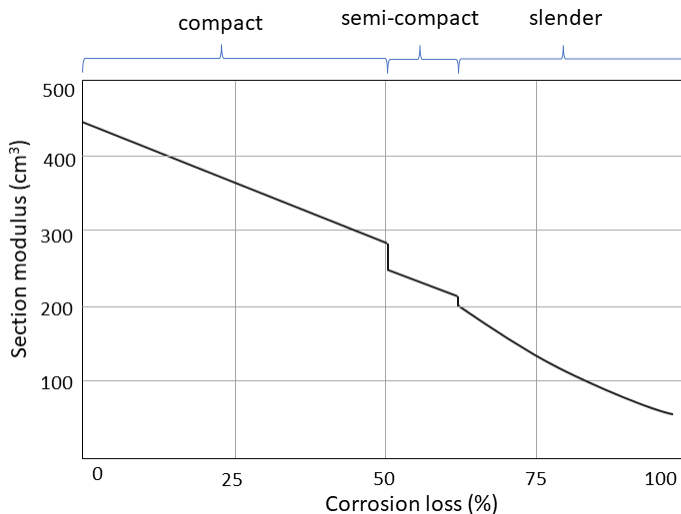


Fig. 6. Section modulus and CL relationship. Graph based on [44]

The standard calculations and numerical simulations showed a change in the profiles of resistance to local buckling with progressive CL. The load capacity decreased quantitatively, and the profile behaviour also changed qualitatively owing to progressive corrosion. For low deterioration, the cross-section was treated as compact (Classes 1 and 2 according to EC3), and the plastic section modulus governed the load capacity. The Class changed to 3 (semi-compact section) as corrosion progressed, and the elastic section modulus defined the load capacity. Finally, for a high CL, the hot-rolled section behaved as a thin-walled, slender section (Class 4), exposed to the loss of local stability in the elastic state. The effective section modulus defined the load capacity. Changes in the cross-section class were manifested in the diagram (Fig. 6) by discrete changes in the section modulus and load capacity. Laboratory tests (Fig. 7) performed on guides subjected to chemical etching to represent uniform CL [46] and naturally corroded guides [47] confirmed this particular change in the load capacity with the CL.



Fig. 7. Results of bending tests: (a) uniform, artificially corroded and (b) naturally corroded guide specimen

The results of the load-carrying capacity numerical simulations (Fig. 8) were consistent with the laboratory test results in the study by Fiołek and Jakubowski [46,47]. They proved the accuracy of the standard formulas for moment resistance assessment of highly corroded guides. However, it should be noted that the numerical models were consistent with the experiment in the entire CL range. By contrast, the standard formulas resulted in significant disagreements for extremely high wear (70% and more). Based on many FEM numerical simulations, Fiołek and

Jakubowski [47] showed that the influence of natural corrosion heterogeneity significantly affects the load-carrying capacity only for extremely corroded profiles, in which corrosion leads to wall perforation. Otherwise, corrosion can be accurately estimated based on the average wall thickness.

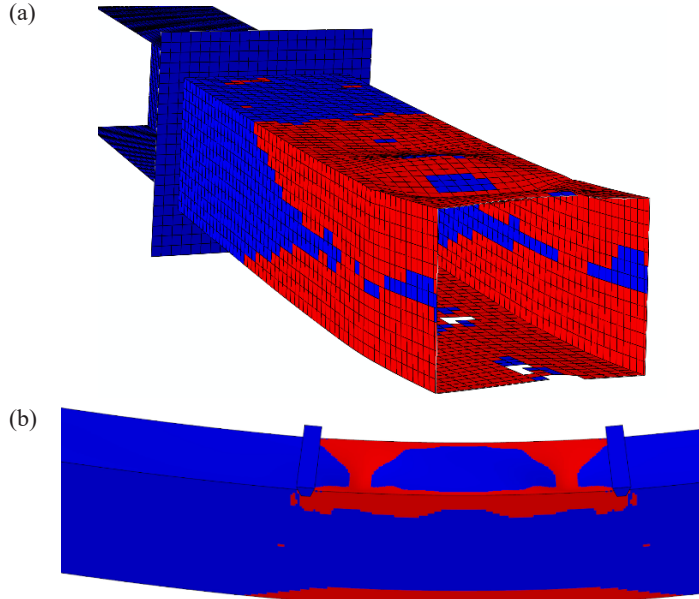
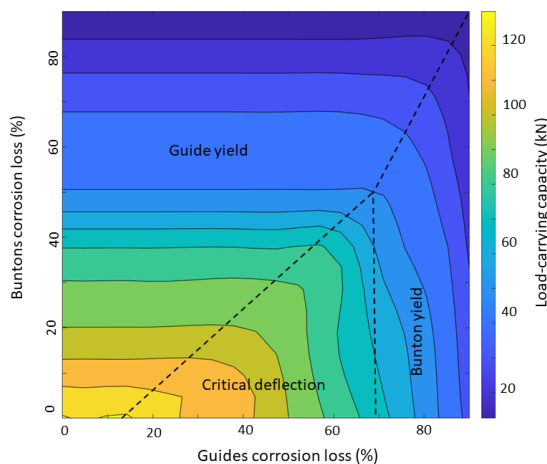


Fig. 8. Results of numerical simulation: (a) naturally corroded [47] and (b) uniformly corroded model [46]

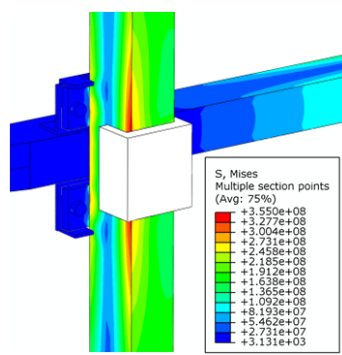
The main members, guides, and buntons of a structure determine its load-carrying capacity. Khan and Krige [35] conducted a load-carrying capacity analysis and forecasted further operation for two shafts in an advanced state of corrosive deterioration. Corrosion reduced the wall thickness and led to the loss of connection between the members. They considered various member failure scenarios in their study. By calculating the magnitude of the guiding forces [29,30], they considered a reduction in the stiffness of the structure owing to corrosion, which led to a reduction in the guiding forces. However, the lower stiffness of the steelwork increased the displacement, increasing the risk of derailment of the hoist conveyance. Stress and displacement conditions were considered to assess the structural safety of the shafts. Consequently, they presented recommendations for further operations and repairs.

The commonly observed differences in the degree of CL of the guides and buntons are related to different local exposures to corrosive agents and differences in steel grades or the consequence of repairs and replacements. Fiołek et al. [48] studied the impact of the CL of the guides and buntons on the load-carrying capacity and failure mode of a structure using numerical models. They demonstrated that the CL influenced the load capacity reduction and changed the failure mode of the steelwork. Tests were performed on a shaft steelwork numerical model. The bolted joints were represented directly by modelling the holes and bolts. The numerical model was validated against field tests in a hard coal mine shaft. With the force acting in the middle of the guide span, the load capacity decreased linearly with the CL of the guides, and the failure

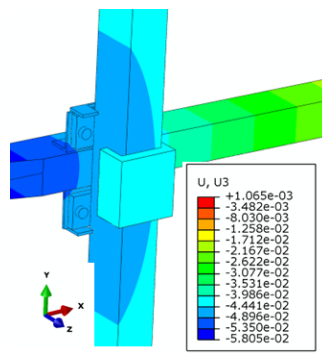
mode was yielding due to bending. However, when loaded at the connection between the guide and bunton, up to six different failure modes were observed depending on the degree of CL of the members and the direction of the force. Damage to the connection between the bunton and shaft lining owing to advanced corrosion occurring in this area was also considered a simulation variant [48]. Permissible deflection exceedance failure or plastic deformation failure was observed in the structure in which one of the joints was damaged. The results of the analyses are presented in the form of load capacity maps (Fig. 9).



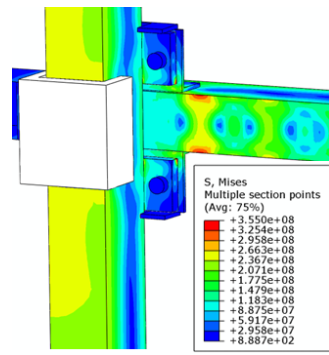
(a)



(b)



(c)



(d)

Fig. 9. Failure mode analysis of a structurally weakened steelwork [48]. (a) Load-carrying map. Failure modes: (b) guide yield, (c) critical deflection, (d) bunton yield. Figure based on [48]

5. Structural reliability

Industrial standards for shaft steelwork design and structural safety assessments involve multiple wide-ranging simplifications. They employ simple structural models of pinned, statically determinate beams, highly approximate load estimates, and load-carrying capacities compen-

sated with high safety margins, global safety coefficients [18], and partial coefficients [30-32]. Jakubowski and Fiolek [49,50] proposed a novel data-driven method for the structural reliability analysis of shaft steelworks. For this purpose, problems with the actual load effect and resistance assessments were re-examined.

The first step was developing a new method for assessing the actual load effect on the structure rather than its upper bound [49]. The structural model, load application point, and dynamic amplification factor (DAF) significantly affect the sectional force assessment. Field tests performed in shafts and numerical tests [51] indicate that the connection between the guide and buntion is semirigid. This affects the sectional force distribution in the guide. The DAF depends on the point of application of the force and the properties of the guide shoe (rolling or sliding) transmitting the guiding force from the skip to the steelwork. A series of dynamic FEM simulations provided the formulation of a polynomial DAF metamodel equivalent to a complex and time-consuming series of FEM simulations. Finally, numerical modelling, in situ testing, and structural analysis enabled the development of a model of load effects as a function of the force magnitude and its point of application. The probability distribution of the load effects (Fig. 10) was assessed [49]. Biaxial bending was considered.

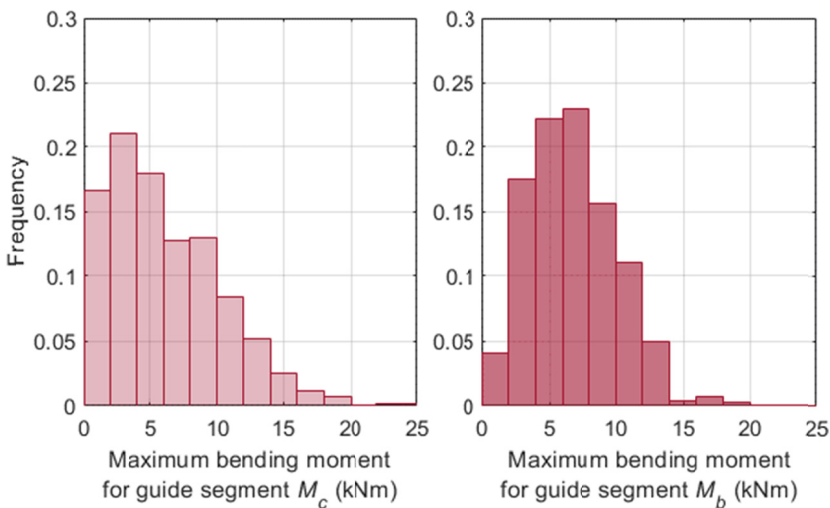


Fig. 10. Histograms of maximum bending moment owing to face (M_c) and side (M_b) forces [49]

The next step was a resistance analysis. The shaft guides primarily exhibited bending profiles. The properties of the steel and the actual geometric characteristics of the corroded guide cross-section determined the load capacity of the guide. Laboratory examination of the corrosion of guides dismantled from shafts enabled the development of a stochastic model for the corroded section modulus [49]. The resistance probability distribution was imputed by field measurements of the guide wall thickness in the shaft (Fig. 11) [49]. The resistance assessment considered the sensitivity to local buckling [44,46,47] and the uncertainty of the steel strength properties [52]. The load effects and resistance probability distributions enabled a probabilistic shaft steelwork reliability analysis.

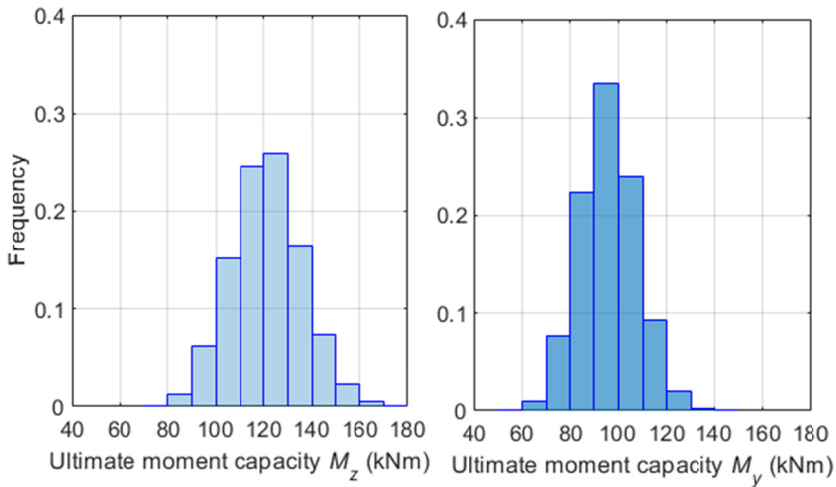


Fig. 11. Histograms of ultimate moment capacities about the strong and weak axes [49]

The developed analytical models of load effects and guides resistance supported by the maintenance field data on guiding forces and CL allowed for a structural reliability assessment in the assumed service time (Fig. 12). They also allowed for shaft steelwork fatigue analysis [53], which was previously not possible owing to the lack of methods for determining the stress range spectrum.

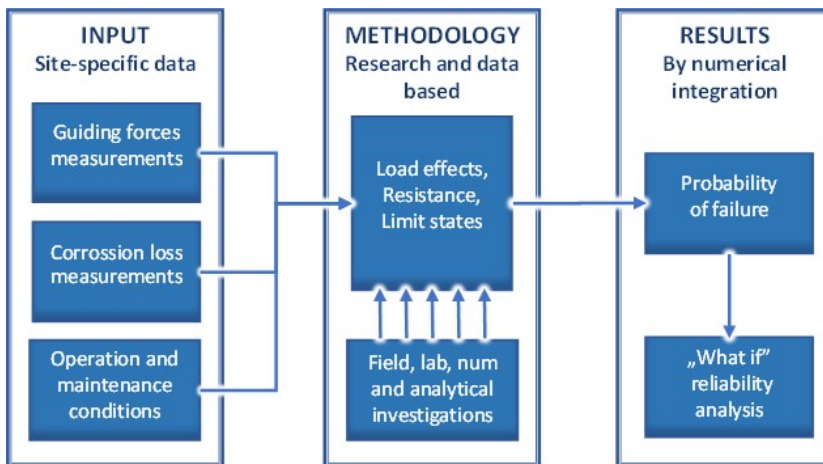


Fig. 12. Reliability analysis of underground shaft steelwork [42]

Jakubowski and Fiołek presented [50] an example of implementing a methodology to assess the reliability of shaft steelworks based on data from periodic maintenance inspections. They considered variants of different guide rails, corrosive deterioration levels, guiding force main-

tenance measurement results, and the type of guide shoe affecting the magnitude of the DAF. The failure probability (Fig. 13) was computed using numerical integration. The probabilistic method of assessing structural reliability demonstrated significant progress compared with the standard methods currently in use.

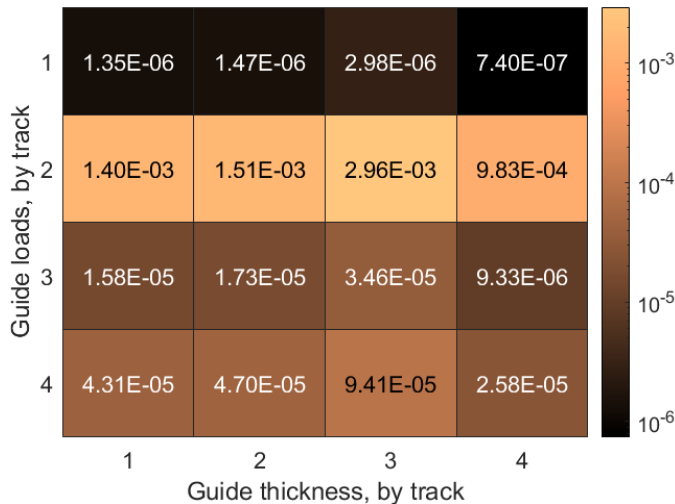


Fig. 13. Probability of ultimate failure for diverse guiding force and corrosion loss conditions [50]. Heatmap colours in a logarithmic scale

6. Conclusions

Owing to the critical role of shaft transport continuity and considerable repair costs, shaft steelworks require advanced field-testing techniques and sophisticated methods for structural safety assessment. This paper reviewed recent research publications on the rigid guiding of mine hoist conveyances and reported a wide range of research on guide rail damage detection, the determination of guiding forces and load capacity, and probabilistic reliability analysis. Significant progress has been made in understanding the mechanical behaviour of shaft steelworks and assessing their properties.

Guiding rail defects are the primary source of guiding forces that increase with the damage level. These defects result from geological processes [5-7], mining, and corrosion [19,20]. Analysing the vibrations recorded during the passage of the hoist conveyance can provide information about the condition of the guide rails; however, its results are not entirely clear or conclusive [8-10] and require further research. There is substantial demand for new testing methods for the rapid assessment of the CL level of steelwork members [19,20]. Despite the existence of physical dependencies between track misalignment and guiding forces, and many studies [23,26] conducted on dynamic models, empirical equations [30-32] or measurements [18] are used for the assessment of the magnitude of the guiding forces.

The authors' newest research on the load capacity of corroded structures enabled the identification of failure modes not previously considered [44,46,48]; thus, their accurate description

can reduce the uncertainty of load capacity estimation [47]. Field tests on the structural connection stiffness and shaft steelwork numerical model enabled the determination of the dynamic characteristics and DAF [51] as functions of the load application point position [50]. The research results, combined with routine maintenance tests and measurements performed on the shafts, enabled the estimating of the probability distribution functions of the load effect and structural resistance [49] and assessing structural reliability. Such knowledge enabled safety management throughout the life cycle of the shaft steelwork and optimal use of the potential of the structure while maintaining the required safety level [50].

Remote measurement technology and large-scale monitoring of shaft steelwork are expected to be introduced in the near future. Data from large-scale monitoring should enable further advancements in shaft steelwork structural reliability analysis.

This review provides relevant insights into the current state of research on shaft steelwork structural safety.

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