Chapter 2
Main Problems Related to the Operation and Maintenance of Mega Machines

2.1 Introduction

There is a natural tendency to extend the operating time of machines, especially the complex and expensive ones, in order to minimize the costs of new investments and to avoid the downtime that is required to construct new machines. In the case of surface mining machines, this problem is much more tangible because giant earthmovers are the largest mobile machines built by man, which affects the cost and time needed to design and construct them. Moreover, in most mines, excavators are scheduled to operate until the mine is exhausted, which, in most cases, results in a natural need to extend the service life of the existing machine fleet.

Over time, this state of affairs increases the risk of failure in components and assemblies, which often causes long-term downtime for repairs or even dangerous accidents and disasters [1, 2], which, in turn, can result in the machine being removed from service or scrapped. Such events may be prevented by performing periodic inspections and tests on components of mega machines, especially in those subassemblies whose damage is dangerous for the entire machine [3]. The conducted research not only leads to useful conclusions related to their operation but also helps to expand knowledge on surface mining machines. By thoroughly analyzing new problems and issues related to the operation of surface mining machines, scientists, in collaboration with machine users, look for solutions to these new questions and thus expand the frontiers of knowledge. This primarily increases the safety of operation and extends the service life of mega machines.

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2.2 The Design of Surface Mining Machines

Safe operation and condition maintenance of surface mining machines requires excellent knowledge of their structure in terms of load-carrying structures and mechanical components, as well as of the control and power systems. The design of such machines is determined by the functions that are performed during the excavation of minerals, their transport and use in the production process, and their stacking or storage [4]. The following section covers the basic information on the structure of bucket-wheel and bucket-chain excavators and spreaders.

2.2.1 Bucket-Wheel Excavators

The general classification of bucket-wheel excavators is related to their size. According to this criterion, there are three basic groups of machines:

(a) Compact bucket-wheel excavators—these bucket-wheel excavators have a theoretical capacity of up to 5000 m^3/h and are the smallest, though in recent years there has been a tendency to construct larger machines of this type. They are characterized by a compact load-carrying structure and are equipped with hydraulic hoisting systems for the excavating and discharge booms. They are not equipped with a classic counterweight boom but the counterweight is located on the superstructure platform. The compact construction of such machines makes them suitable for operation in those areas of mines that are not easily accessible or in conditions where excavating is difficult due to the cutting resistance forces. They usually have a two-crawler undercarriage, which makes them easier to maneuver on the one hand, but limits their global stability on the other. Figures 2.1. and 2.2. show examples of different sizes of compact bucket-wheel excavators.

Fig. 2.1 KWK205L compact bucket-wheel excavator—designed by SKW Zgorzelec

Fig. 2.2 SRs(H) 1050.23/2.0 compact bucket-wheel excavator—designed by TAKRAF TENOVA (TAKRAF marketing materials)

(b) C-frame bucket-wheel excavators—mid-size bucket-wheel excavators with a theoretical capacity of up to 10,000 m^3/h (SchRs 4600.30), though the average theoretical capacity of such machines is approximately 5000 m^3/h. Their characteristic structural feature is the shape of the platform, pylons and the counterweight boom, which form the so-called C-frame. In contrast to compact excavators, these machines have a counterweight boom with a ballast permanently fixed to its end. The bucket-wheel boom is hoisted by means of a cable system with the main winch located on the counterweight boom. Some machines of this type (e.g., SRs 1200, SRs 2000), have an additional mast for the bucket-wheel boom, which is connected to the boom's head by means of a rigid tie rod. The cable-based boom hoisting system is located between the winch and the mast head. These machines are defined as mid-sized, which makes them suitable for operation in those areas of mines that are moderately difficult to reach. They can also operate in difficult excavating conditions in terms of cutting resistance forces but this requires a special design of their load-carrying structure and drive systems. One example is the KWK910L excavator designed by SKW Zgorzelec. The undercarriages of these machines are usually composed of three crawler tracks, or sometimes even four (SRs 1200), which makes them difficult to maneuver on the one hand, but provides good global stability on the other. Figures 2.3, 2.4, 2.5, 2.6 and 2.7 show examples of different sizes of C-frame bucket-wheel excavators.

(c) Large bucket-wheel excavators—these are the largest mobile bucket-wheel excavators with a theoretical capacity of up to 16,000 m^3/h. Their characteristic structural feature is that they have two main superstructure boom units: the excavating boom and mast interconnected by means of steel cables, and the counterweight boom unit, also with a mast, interconnected with similar steel cables. The two mentioned units are attached to the superstructure's slewing platform supported by a slewing bearing, which rests on an

Fig. 2.3 C-frame bucket-wheel excavator—BWE700L

Fig. 2.4 C-frame bucket-wheel excavator—BWE1400L

Fig. 2.5 C-frame bucket-wheel excavator—SRs 1200

Fig. 2.6 C-frame bucket-wheel excavator—SRs 2000

Fig. 2.7 C-frame bucket-wheel excavator—KWK910L

undercarriage portal frame and other elements of the tracked undercarriage. Moreover, these machines often have a ballast that can move along the counterweight boom depending on the positioning of the excavating boom. The tracked undercarriages have a three-point support design. However, the crawlers in individual supports are often multiplied in order to obtain the appropriate pressure of crawler pads on the ground. This is due to the fact that the mass of such excavators may exceed 10,000 tons. Figures 2.8 and 2.9 show examples of large bucket-wheel excavators.

2.2.2 Bucket-Chain Excavators

Multibucket chain excavators are used relatively rarely in operation due to their complicated structure and low excavating capacity. Nevertheless, they have one fundamental advantage over bucket-wheel excavators, namely a high range of excavation below the bench level in relation to the size of the machine. This is why they can be used in complex mining sites and in places where the pit face ends without the need to excessively enlarge the pit. These excavators are built in a similar fashion to bucket-wheel excavators in terms of their tracked undercarriage and counterweight and discharge booms. They are usually equipped with two bearings that control the slewing of the superstructure. Smaller machines have a

Fig. 2.8 Large bucket-wheel excavator—SchRs 4600

Fig. 2.9 Large bucket-wheel excavator—SchRs 4000

construction similar to that of compact bucket-wheel excavators. In such cases, a superstructure moment slewing bearing is used, whereas the counterweight is located on the superstructure platform. All bucket chain excavators are equipped

Fig. 2.10 Multibucket chain excavator—ERs710

with a chain composed of buckets connected by chain links. Such chain is mounted on a boom that consists of several segments, each with an independent hoisting cable system with winches mounted to the counterweight boom or to the superstructure platform. Such a construction makes it possible to excavate with the entire length of the chain boom, whose shape can be adjusted to the requirements of the digging technology. Examples of bucket chain excavators are shown in Figs. 2.10 and 2.11.

2.2.3 Spreaders

Conveyor spreaders are used in surface mines to pile the extracted overburden, which is collected on external or internal stockpiles at the surface mining site. External stockpiles are separated areas, usually near the surface mine, where overburden is stacked in stockpiles. Internal stockpiles are those parts of the mining site where extraction has been completed. Materials that are primarily stockpiled include overburden extracted by excavators or by-products of coal combustion in power plants, i.e. ash, which is usually transported from energy blocks by means of conveyor belts or, less frequently, by railway or trucks.

Fig. 2.11 Multibucket chain excavator—Rs560

Fig. 2.12 Spreader—A2RsB12500

Spreaders are similar in structure to excavators, but due to their function they are not equipped with an excavating unit. Instead, they have a discharge boom that piles the dredged material on stockpiles. The capacity of spreaders reaches up to 20,000 m^3/h of overburden. Examples of conveyor spreaders are shown in Figs. 2.12 and 2.13.

Fig. 2.13 Spreader—20000TPH

2.3 Main Mechanical and Structural Subassemblies of Surface Mining Machines and the Problems that Occur During Their Operation

The operational problems of surface mining machines can be grouped according to the functions carried out in individual stages of the mining process, in the case of excavators, and the spreading process, in the case of spreaders. The following section describes the main mechanical and structural subassemblies of bucket-wheel excavators and spreaders, in which operational problems occur. The main focus is on those structural and mechanical components that are subject to degradation processes and determine the machine's uptime and operational safety.

Excavating unit

This consists of the following elements, which are prone to operational problems:

- Bucket-wheel drive gear—this is subject to damage that is typical for spur gears, i.e. damage to the teeth, bearings, axles and shafts. Damage also occurs to the housing of gears due to their large size in this type of machines. Additionally, fractures can occur in moment beams whose function is to transfer the moment resulting from the cutting force to the load-carrying structure of the bucket-wheel boom. The problem of gear degradation can be improved significantly by using properly operating torque limiting couplings [5] (excluding hydraulic couplings, as these are not torque limiting couplings for impact loads), provided that correct and invariable coupling settings are maintained, which is also very important in the case of double or triple gear drives. Examples of damage to bucket-wheel drive gears are shown in Fig. 2.14.

- Bucket wheel shaft or axle—damage to this element is relatively rare. It is mostly prone to ultimate failure resulting from extreme overloads or to damage during disassembly in areas where loads are transferred, e.g., press fit between the drive gear and the shaft. Examples of damage to bucket-wheel shafts are shown in Fig. 2.15.
- Bucket wheel—this is mostly subject to fatigue damage, mainly around the wheel hub (attachment of the wheel to the shaft or axle), and at points where buckets are attached. Damage to this element of the excavating unit are relatively frequent. Examples of damage to bucket wheels are shown in Fig. 2.16.
- Cutting elements: buckets—these are mostly subject to the process of natural abrasive wear resulting from the excavation process [6]. In addition, there are

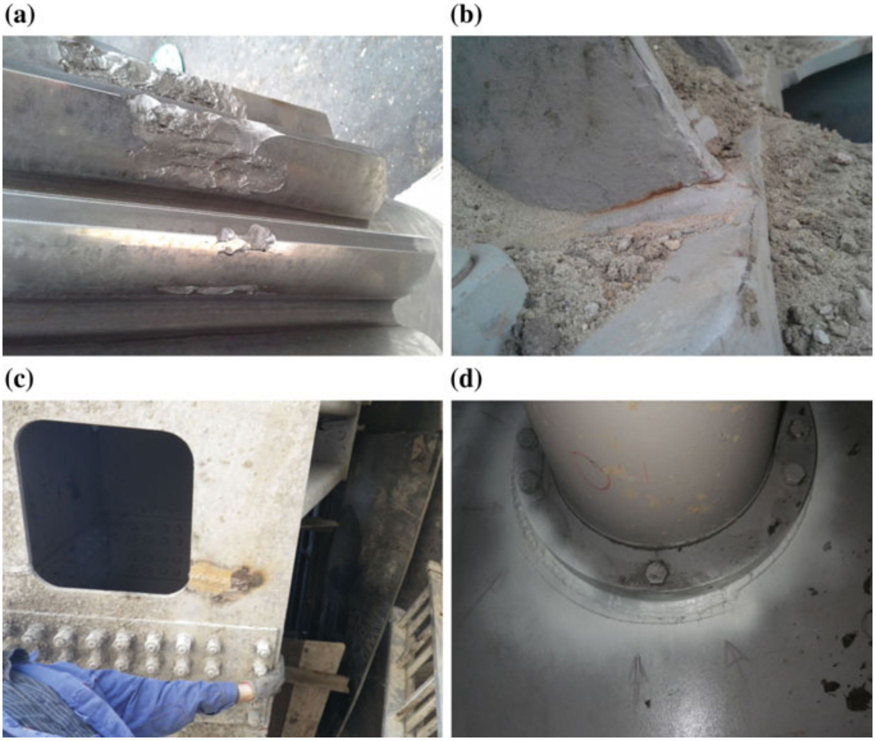

Fig. 2.14 Damaged elements of the bucket wheel drive gear in surface mining machines: **a** damage to spur gears of the drive gear in SRs 2000 excavators; **b** fractures on the housing of the gearbox in the SchRs 4000 excavator; **c**, **d** damage to the moment beam and its mount in the bucket-wheel drive gear on the SRs 1800 excavator

Fig. 2.15 Damage to the bucket-wheel drive shaft in the KWK 1200M excavator

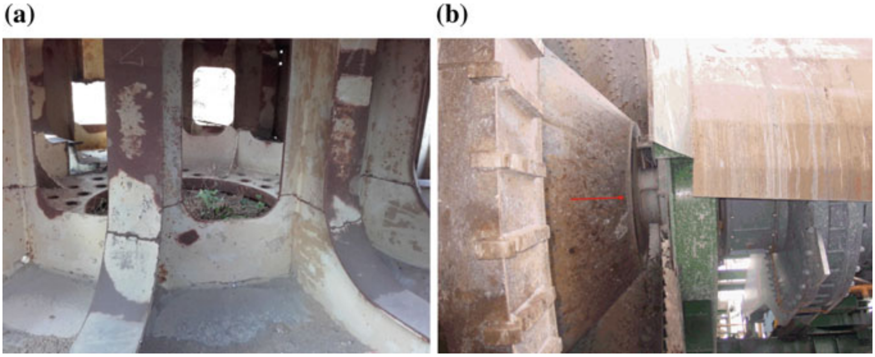

Fig. 2.16 Damaged areas of bucket wheels in excavators: **a** SchRs 4600 and **b** KWK 1200M

numerous cases of ultimate failure caused by dynamic overloads generated when a bucket strikes non-mineable material. Cases involving fatigue damage are rather rare since buckets are designed mainly for impact loads and operate for a short time before they are replaced and regenerated. Examples of the typical processes of wear and ultimate failure to buckets are shown in Fig. 2.17.

Superstructure slewing system

The superstructure slewing system consists of the following elements, which are subject to operational problems:

- Superstructure slewing drive gear—this is subject to damage typical for spur gears, which is further enhanced by the instability of loads generated during operation. This problem mainly pertains to excavators, whereas in the case of spreaders such a phenomenon is practically non-existent. In the case of excavators, the main load acting on the superstructure slewing gear drive is the lateral force generated during excavation. This is a time-varying load that is random in character and involves dynamic events that occur when the

Fig. 2.17 Wear and damage process of buckets

excavation unit is overloaded. This happens when a bucket strikes non-mineable material. Such drives are also subject to failures of their torque limiting couplings, whose purpose is to limit the force transmitted to the drive gear. When the machine operates under difficult and variable excavating conditions, the number of switching cycles of torque limiters can be sufficiently large to accelerate its degradation. Another practical problem involves ensuring proper adjustment of settings depending on the coupling type (friction, powder etc.) and the invariability of these values over time. There have been numerous cases involving problems in ensuring the same settings for individual or multiple drives (usually two or four superstructure slewing drives).

- Superstructure slewing ring—superstructure rotation drive is transmitted from the drive gear through a pinion onto the superstructure slewing ring. The problems that occur are typical of spur gears, especially in the case of excavators, which operate in more severe conditions than spreaders. An additional problem in the case of excavators can be damage to the elements that connect the slewing ring with the portal. These are usually connected by means of bolted connections, which are subject to loosening and, occasionally, cracking. This results from the heavy loads generated when overload occurs and the bucket-wheel drive is switched off, which in turn causes momentary overloads to the superstructure rotation drive system.

- The superstructure slewing bearing and slewing wheel support—the rotation of surface mining machines is carried out primarily through large slewing bearings or, less commonly, especially in older machines, through a slewing wheel support with a system of bogies, a raceway and bogie wheels [7]. In the case of slewing bearings, the main and numerous problems are associated with accelerated wear of the rolling elements and the raceway. In the case of the so-called hard raceways, wear mainly occurs as a result of pitting (less frequently, fretting) and the rapid degradation that follows, whereas in the case of the so-called soft raceways, wear is the result of plastic deformations and the "settling" of the bearing. Examples of damage to superstructure slewing bearings are shown in Fig. 2.18.
- Damage to superstructure slewing wheel supports of surface mining machines occur in the bearing joints of individual bogies and are caused by an uneven distribution of force on the bogie wheels. Other damage that typically occurs involves pitting of the raceway and wheels. These types of structural joints also generate damage to their supporting structures resulting from the lack of alignment in the transfer of loads between the bogie wheel and the raceway. As a result, the raceway and the top flange of the supporting structure experiences

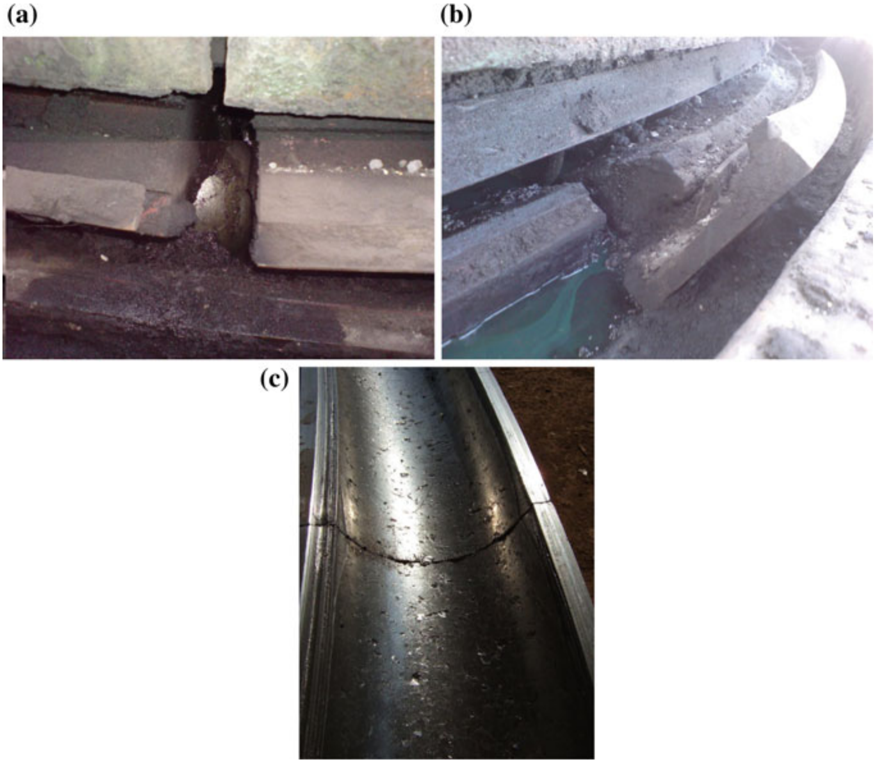

Fig. 2.18 Damage to the superstructure slewing bearing of surface mining machines: **a**, **b** plastic deformation of the bottom raceway; **c** pitting

local bending, which in consequence may lead to fatigue fractures. Examples of such phenomena are depicted in Fig. 2.19.

Undercarriage drive system

The undercarriage drive system consists of the following elements, which are subject to operational problems:

- Drive gear—this is subject to wear processes typical of spur gears, which, due to the intermittent character of operation, are not very intensive. Other problems include those related to the transmission of power to the drive wheel of the crawler track. The drive shaft transmits high torque and is subject to overloads resulting from the uneven surface on which the machine travels. Such a situation can cause damage to the shaft or to the connection with the output shaft of the drive gear. Another common problem in the operation of drive systems is the wear of drive wheels in the chain of the crawler track in the area where torque is transferred to the pad, as well as damage to this area in the form of fractures. Examples of damage to this system are shown in Fig. 2.20.

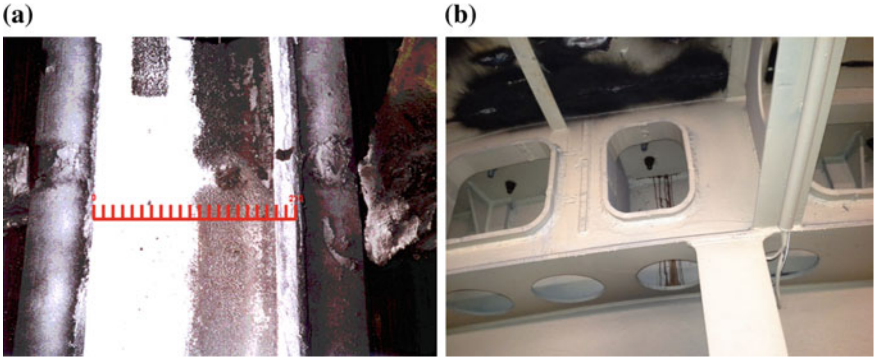

Fig. 2.19 Slewing wheel support of a bucket-wheel excavator: **a** lack of alignment in the contact between the bogie wheels and the raceway; **b** fatigue cracks in the slewing wheel support

Fig. 2.20 Examples of damage to the drive trains of tracked undercarriages

- Crawler crossbeam, multi-bogie-system—these are subject to typical fatigue processes, which involve fatigue cracks in high stress zones, such as axle bearings and tensile zones in the bottom sections of bogies. In terms of mechanical damage, bogies undergo damage resulting from overloads or material faults [8]. Examples of damage to these elements are shown in Fig. 2.21.
- Crawler pads—these are mainly subject to damage in the form of cracks in the area where subsequent pads are linked, resulting from torsional and bending loads acting on the links of individual pads. Additionally, although less frequently, cracks occur in load-carrying areas of pads on which wheels travel. Examples of damage to these elements are shown in Fig. 2.22.

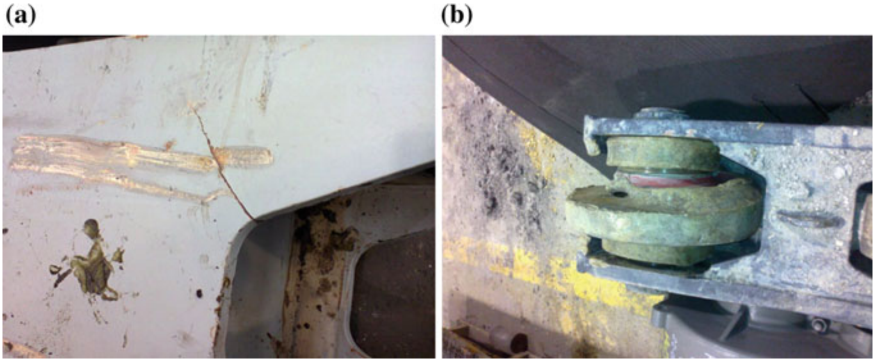

Fig. 2.21 Examples of damage: **a** fractures of the lower flange of a spreader's bogie; **b** damaged bogie wheel in the undercarriage of a bucket-wheel excavator

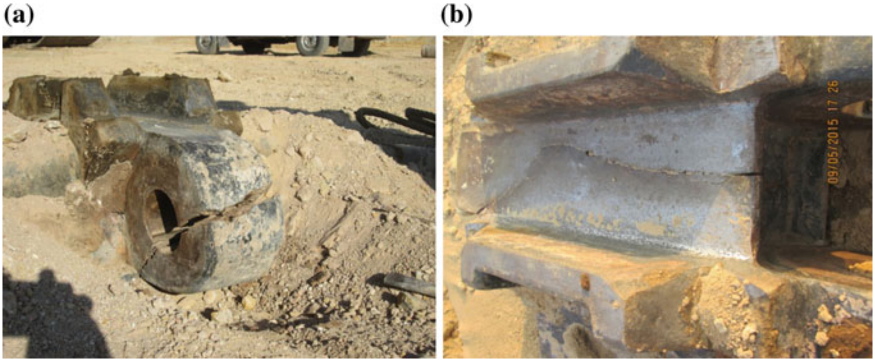

Fig. 2.22 Examples of damage: **a** fracture of the crawler pad link; **b** damaged raceway of a crawler link

Tracked undercarriage steering system

This consists of the following elements, which are subject to operational problems:

- Actuator or steering shaft—the most popular three-point support system for surface mining machines comprises a fixed crawler unit and two steerable crawler units whose turn is controlled by a hydraulic actuator or a steering shaft attached to the end of the drawbar in steerable vehicles. During operation, this system is prone to problems typical for hydraulic systems, i.e. leaks resulting from accelerated wear caused by difficult working conditions in working levels in the mine. Damage also occurs to attachments of actuators and steering shafts to the undercarriage portal frame, which are caused by substantial loads transferred through this area, especially if the machine is operating on rough and wet ground. In winter, additional loads can be generated by the tracked undercarriage freezing to the ground.
- Steering and non-steering frames in the tracked undercarriage system—the load-carrying elements of the steering system also function as supports for the entire machine and, in addition to horizontal torsional forces, they also transfer vertical forces [9]. Damage to these elements appear in the areas of the greatest bending moments and shear forces, i.e. in the attachments of axles/half-axles in track frames, in the eyes of attachments between drawbars and the undercarriage portal frame, or in the areas of section changes and structural or technological notches. Damage also occurs to the above-mentioned half-axles of track frames. Nearly all of the damage to these elements is typically related to fatigue. Examples of damage are shown in Fig. 2.23.

Belt conveyors

The belt conveyor system of surface mining machines consists of the following main subassemblies, which are subject to operational problems:

- Belt conveyor drive system—this consists of single or, less frequently, double spur gears powered by electric motors. The gearbox is mounted on the shaft of the conveyor's drive drum, whereas its frame is supported like a typical moment beam on the other side by a supporting structure. During operation, this system is subject to damage typical of spur gears, resulting from natural wear processes. An additional factor that contributes to gear damage are start-up and stop overloads when the boom with the belt conveyor is tilted. This causes an additional dynamic surplus, which, in the case of lacking or incorrect coupling and/or brake adjustments, may even lead to shear damage to the system. There is also damage within the drive drum in the form of damage to the rigid connection between the gear and the drum shaft, as well as damage to the drum itself in the form of fractures in the connection between the side wall of the drum and the shaft. Fractures also occur in the drum shell, which are exacerbated by the pendulum-like cyclic bending of the drum unit with a very high number of cycles. Nearly all of the damage to these elements is typically related to fatigue. Examples are shown in Fig. 2.24.

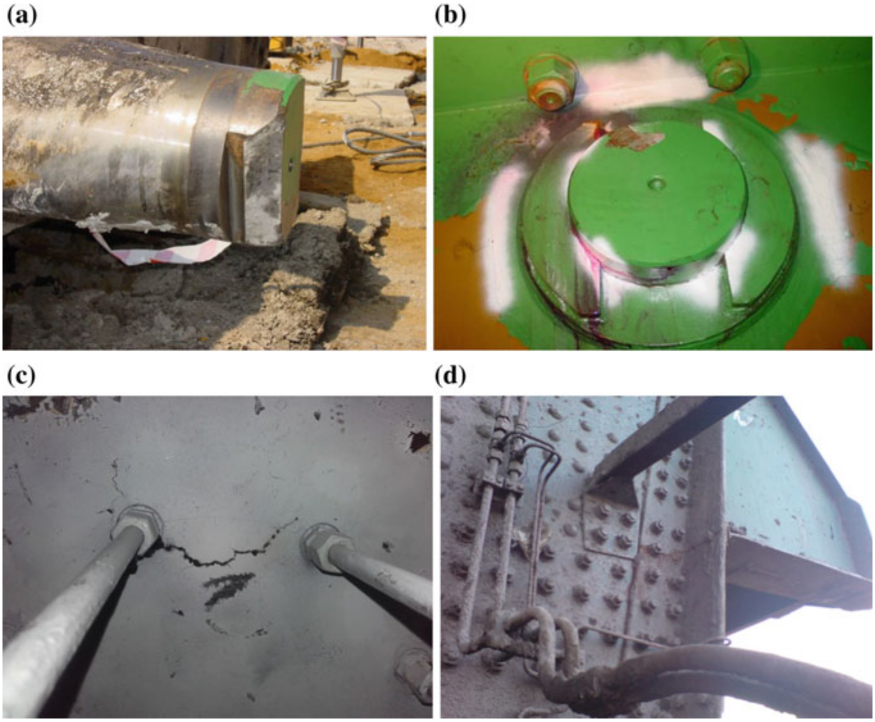

Fig. 2.23 Examples of damage: **a** damaged end of crawler frame half-axle; **b** end of the half-axle before damage; **c** fracture of the spherical cup of the supporting ball in the frame support of a spreader’s tracked undercarriage; **d** fracture in the attachment area of the excavator’s non-steering frame

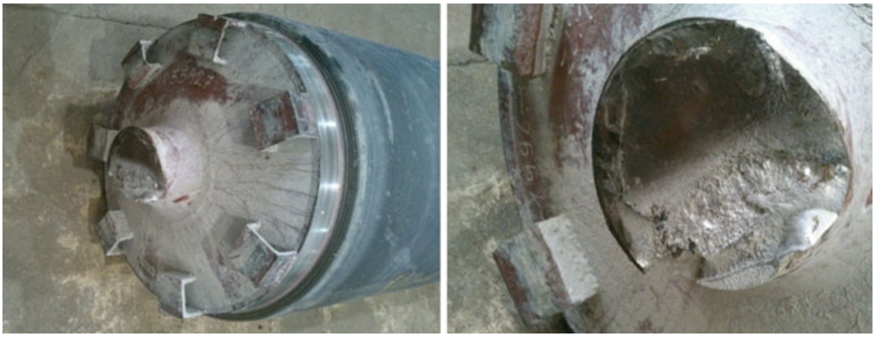

Fig. 2.24 Examples of damages—fracture of the drive drum of a bucket-wheel excavator’s belt conveyor

- System of belts and rollers—consists of a belt and the supporting rollers. At the points of transition between conveyors, there is an increased number of rollers, whose function is to absorb some of the energy generated by the falling material. In such areas, the belt most often gets damaged in the form of rips, cuts, punctures or fractures. The dynamics of the phenomenon also cause damage to the rollers and their mounts as well as to the supporting structure. Similar damage to rollers occurs along the entire length of the belt conveyors, but is less severe. The heterogeneity of the transported material, especially the overburden cut by excavators, in the form of chunks, and sometimes large stones, accelerates the process of wear and the frequency of damage to the conveyor belt systems of surface mining machines. Examples are shown in Fig. 2.25.

Load-carrying systems of steel structures in surface mining machines

The load-carrying structures of surface mining machines consist of the following main elements, which are subject to numerous operational problems:

- System of load-carrying structures of booms:
  - Bucket-wheel boom—this load-carrying structure experiences the highest effort in terms of strength of materials. It is subject to direct impact of

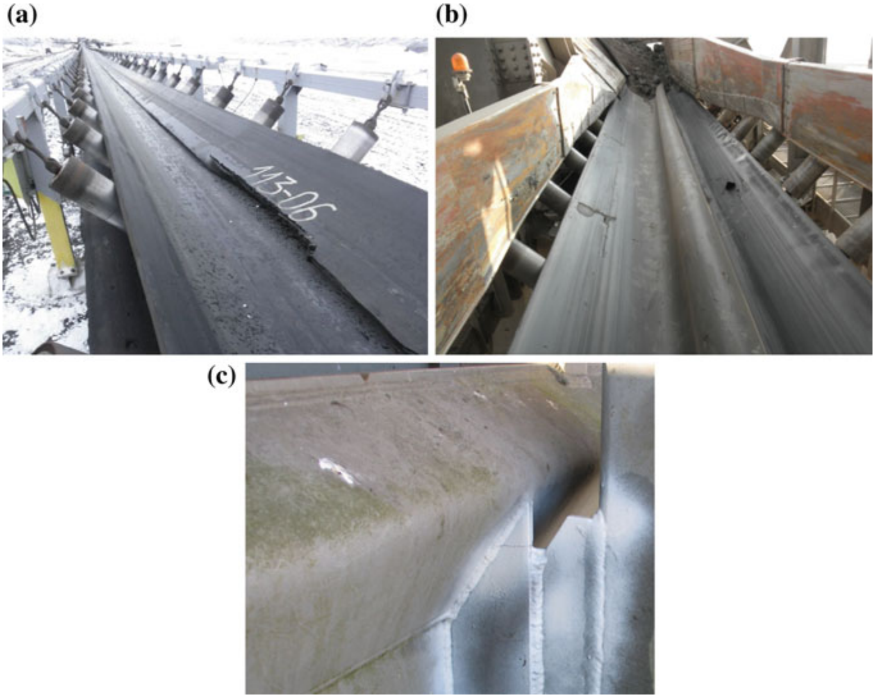

Fig. 2.25 Examples of damage: **a**, **b** damage to conveyor belts; **c** damage to elements that support the rollers

variable cutting forces, i.e. the digging and side forces. The dynamic phenomena that accompany such forces, i.e. overloads to the excavation unit, intensify the damage that mainly takes the form of fatigue cracks in welded joints or in the native material, in geometric notches. Most of the damage is located on the boom head and in the points where it is attached to the excavator platform, where large values of bending moments occur. Damage also appears in the truss joints of the boom's horizontal and vertical sections. Shear damage may also occur to beams and structural joints when the boom collides with external obstacles. Examples of damage to excavating booms of bucket-wheel excavator are shown in Fig. 2.26.

- Feeding and discharge booms—these are elements of both excavators and spreaders. Main loads to these systems are generated by the overburden, the tilt of the machine and the dynamic horizontal and vertical loads that occur mostly during excavator or spreader travel [10] [11]. Damage occurs rarely and mainly takes the form of fatigue cracks in welded joints or in the native material, in the vicinity of geometric notches. Damaged areas are difficult to determine due to their small number.

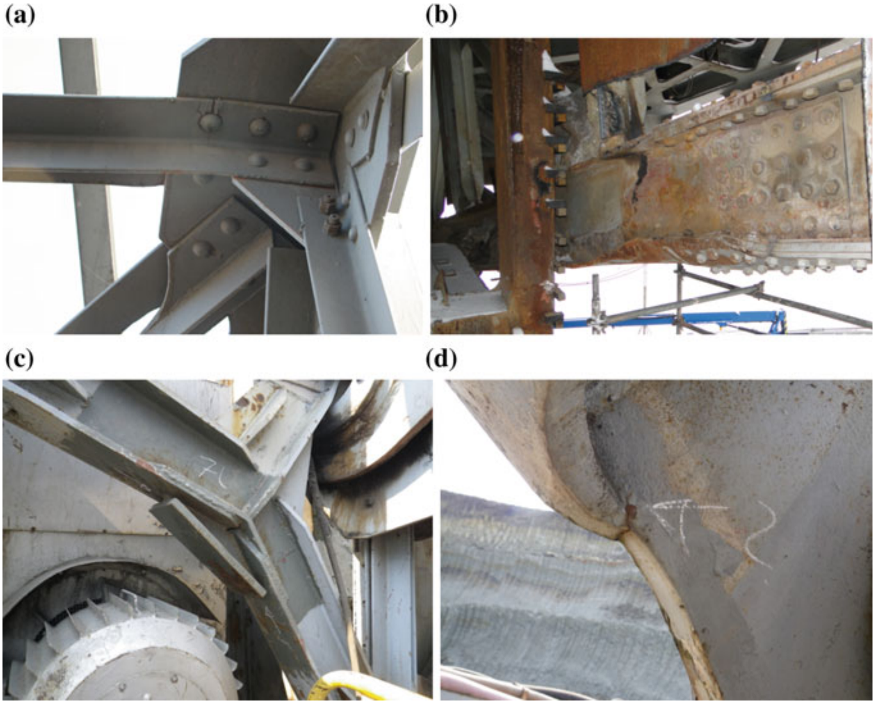

Fig. 2.26 Examples of damage to the bucket-wheel boom: **a** deformation and fracture of structural joint; **b** ultimate failure to the horizontal beam of the boom, near the bucket wheel; **c** fracture of the joint near the attachment of the torque beam of the bucket-wheel drive, **d** fracture in the eye reinforcement of the boom attachment

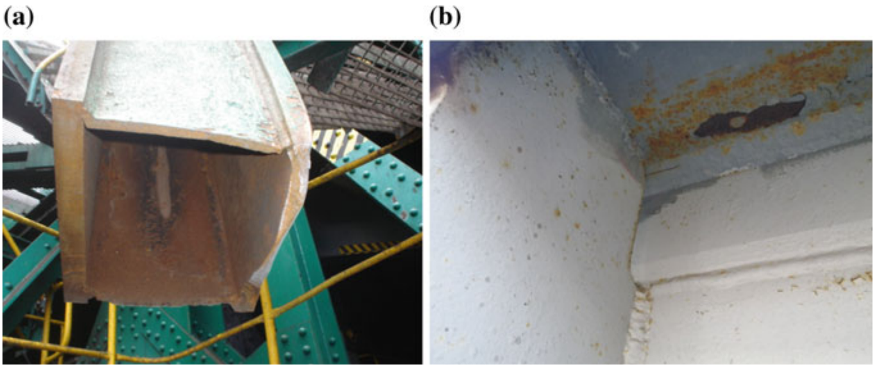

Fig. 2.27 Examples of damage to counterweight booms: **a** fatigue cracks of the counterweight boom tie rod [13]; **b** fracture of the top girder of the main counterweight boom on a bucket-wheel excavator

- Counterweight boom—this is an element of both excavators and spreaders. It provides stability and, by means of a winch that is attached to it, it performs the hoisting function of the excavating and discharge booms. Main loads are generated by the tilt of the machine and the dynamic horizontal and vertical loads that occur mostly during excavator or spreader travel or during digging of the excavator. Damage mainly takes the form of fatigue cracks in welded joints or in the native material, in geometric notches [12, 13]. Damage occurs in the joints of vertical and horizontal bracing and in suspension systems. Examples of damage to counterweight booms are shown in Fig. 2.27.

- Masts—these are elements that function as support for the booms of surface mining machines. Depending on the type of the machine, there can be single or double masts. Main loads to these systems are generated by the tilt of the machine and the dynamic horizontal and vertical loads that occur mostly during excavator or spreader travel. Damage occurs rarely and mainly takes the form of fatigue cracks in welded joints or in the native material, in geometric notches. Damaged areas are difficult to determine due to their small number.
- Pylon—this central part of surface mining machines is supported by the superstructure platform, to which the excavating and counterweight booms are attached in medium-sized and compact bucket-wheel excavators. In this case, it is most often a plate girder. In the case of spreaders, pylons typically take the form of 3D frames attached to the superstructure platform and are connected to the counterweight boom. Attached to them are discharge booms and masts. Damage mainly takes the form of fatigue cracks in welded joints or in the native material, in geometric notches. Damaged areas include the connections with the superstructure platform, structural joints of the plate girder and the frame. Damage also occurs near the connection with the counterweight boom. Examples of damages to pylons are shown in Fig. 2.28.

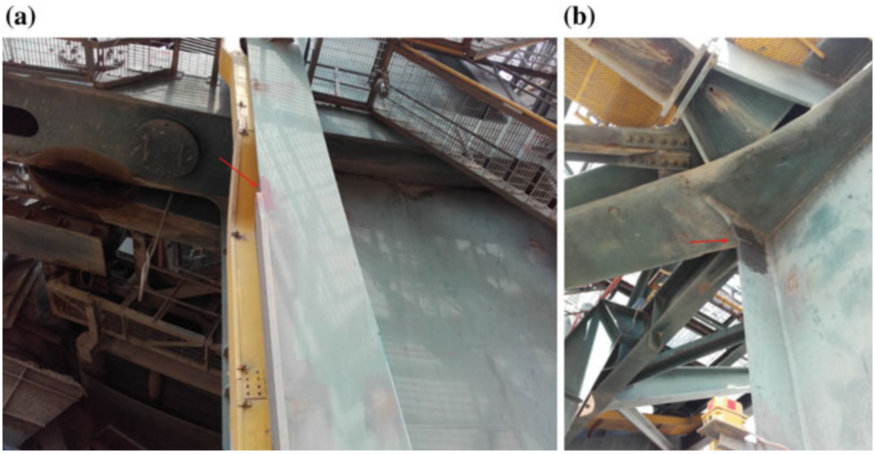

Fig. 2.28 Examples of damage to pylons of surface mining machines: **a** damage to the vertical pillar of the pylon; **b** fracture in the structural joint

- Slewing platform—the superstructure slewing system of surface mining machines, which supports other elements of the superstructure. It is supported in its lower part by a slewing bearing or slewing wheel support, and then by the undercarriage portal frame. Usually, it has the form of a plate girder connected to the pylon in the case of medium-sized and small machines. In the case of large machines, it supports the excavating and counterweight booms. Damage to the slewing platform primarily consists of fatigue cracks in welded joints and the native material located mainly near the connection with the pylon or with the booms. Fractures also occur in the attachment of the superstructure slew bearing or slewing wheel support bogies. Examples of damage to slewing platforms are shown in Fig. 2.29.
- Undercarriage portal frame—this is a load-carrying structure that supports the rotating part of the superstructure in surface mining machines, by means of a slew bearing or a slewing wheel support. It is usually a plate girder supported at the bottom by crawler units. Damage to girders is located mainly near the joint of superstructure rotation, as well as in the connection between the ring and the supports, which typically form a triangle. Damage also occurs around the connection with crawler units. In most cases, damage is related to fatigue, both in the case of welds and the native material. Examples of damage are shown in Fig. 2.30.

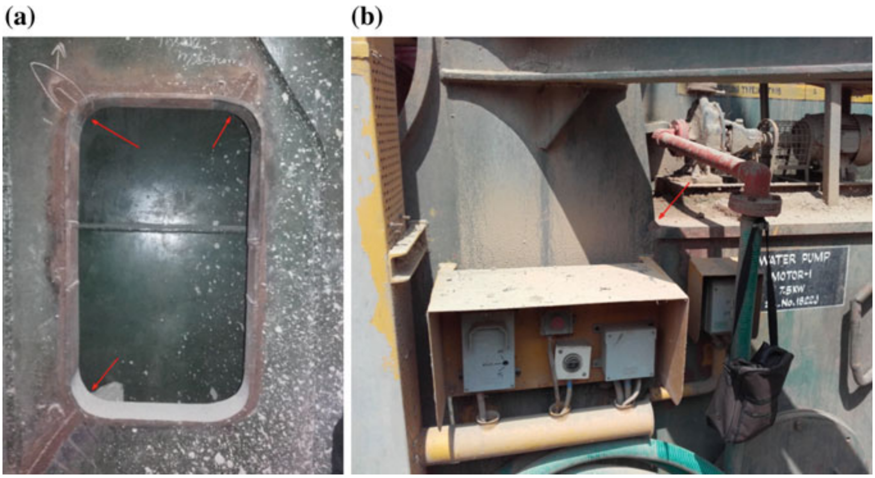

Fig. 2.29 Examples of damage to slewing platforms of surface mining machines: **a** fractures in the platform diaphragm; **b** fracture in the connection between the pylon and the slewing platform

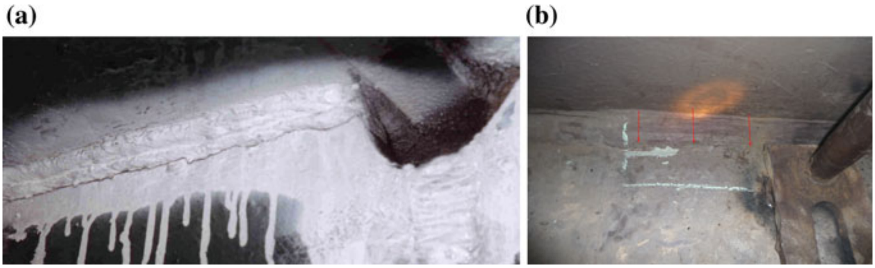

Fig. 2.30 Examples of damage to the undercarriage portal frame of surface mining machines: **a** fracture of the reinforcing rib in the connection between the web and the *top* flange of the frame; **b** fracture of the vertical diaphragm in the welded joint

2.4 Main Phenomena During the Operation of Surface Mining Machines

The phenomena that generate operational loads to surface mining machines also determine the frequency and character of their potential damage. Such phenomena can be generally divided as follows:

- Those that occur during excavation (digging forces, dynamic phenomena, loads in kinematic nodes),
- Those that occur during operational movements (primarily during machine travel).

Their influence on the individual elements of surface mining machines is different and depends on the range and intensity of interactions. The following section discusses the individual loads generated during the operation of surface mining machines.

Loads generated during excavation

The two main forces acting on the load-carrying structure of bucket-wheel and bucket-chain excavators during operation are as follows:

- Digging force U: this acts on the cutting edges of the bucket wheel tangentially to the wheel, with its orientation resulting from the direction of wheel rotation and from the value that is mainly the result of the amount of power transferred to the wheel shaft by the installed drive system, consisting of an engine and a drive gear,
- Side force S: this acts on the cutting edges of the bucket wheel in the horizontal plane and perpendicularly to the plane of the bucket wheel, with its orientation resulting from the current direction of excavation and from the value that is mainly the result of the amount of power expended by the relevant mechanism to rotate the machine in the horizontal plane.

Calculations of external loads acting on the bucket-wheel excavator [3] can be performed by means of two different methods. The first is related to the use of standards that define loads based on the power of drives and overload factors [14]. This is the typical approach applied in the design of surface mining machines. The power of the drive, on the other hand, is determined on the basis of the total value of the impact of the material being excavated on the unit, i.e. the total cutting resistance *F*. In general, this value consists not only of the resistance associated with the breaking of the structure and separation of the material from the deposit, generally called cutting resistance F_{s}; but also of the resistance associated with friction of the extracted material against the walls of the unit, called friction resistance F_{t}; the resistance associated with horizontal movement of the extracted material by means of the mechanism, called movement resistance F_{p}; the resistance associated with filling the container with extracted material, called filling resistance F_{n}; or the resistance associated with lifting the dredged material within the tool, called lifting resistance F_{H}. Thus the total resistance can be generally presented in the following form [3]:

$$F_u = F_{\mathrm{s}} + F_{\mathrm{p}} + F_{\mathrm{t}} + F_{\mathrm{n}} + F_{\mathrm{H}} + F_{\mathrm{odp}} \tag{2.1}$$

where:

F_{s}—cutting force,
F_{p}—movement resistance force,
F_{t}—friction resistance force,
F_{n}—filling resistance force,
F_{H}—material lifting force,
F_{odp}—ground resistance force.

It should be noted that not every excavation process includes all of these resistance forces and that their share in the total resistance also varies. However, it has been determined that in the case of joint rock and consolidated dry material, the 70–90% cutting forces are predominant, whereas in the case of unconsolidated and loose materials, it is the friction and filling resistance or horizontal or vertical movement resistance that are predominant.

The second method for determining the forces that occur during operation is based on measurements of the actual excavation loads [3]. This approach is particularly desirable in technical condition assessment and in the prediction of the service life of existing machines, as it allows the actual load data to be taken into consideration when calculating residual life. This method employs dedicated and calibrated monitoring systems, usually based on strain gauge sensors.

A comparison of cutting forces obtained by means of the first and the second approach leads to the following conclusions:

- The average loads measured in normal operating conditions are consistent with the values calculated on the basis of standards,
- The measured maximum loads that occur, especially during impact phenomena when the bucket wheel of the excavator suddenly stops, are several times larger than the values calculated using the standards. Such phenomena occur during excavation of overburden with non-mineable formations, such as rocks or stones, which is shown in the examples in Figs. 2.31 and 2.32.

Fig. 2.31 Overburden with non-mineable formations in a surface mine

Fig. 2.32 Broken bucket corner of a bucket-wheel excavator after a collision with a boulder

Loads occurring during operational movements

The operational movements of surface mining machines, i.e. travelling over the working level and all movements of the individual booms, as well as rotation of the superstructure, generate dynamic loads that affect the load-carrying structures of these machines. Experimental tests confirm that machine travel plays the most important part in the generation of dynamic phenomena. Such operational movement excites broadband vibrations of the entire machine and its individual elements. In such cases, global and local vibrations are excited. The values of these loads are established in standards as dynamic factors. They are also diversified depending on the type and element of the surface mining machine (Tables 2.1 and 2.2).

The values of dynamic loads can also be measured on actual machines. This is carried out by means of data monitoring systems with acceleration sensors located on the machine under test. Through this procedure, time traces and amplitude-frequency spectra of vibration acceleration values are obtained, which then serve as the basis for calculating the actual dynamic factors acting on individual elements of surface mining machines. The vibration sensor installed on the mast of a SRs-2000 excavator is shown in Fig. 2.33.

Examples of time traces registered during the operation of a bucket-wheel excavator are shown in Fig. 2.34 and its spectrum is shown in Fig. 2.35.

Table 2.1 Values of dynamic factors according to DIN-22261 [14]

Machine type	Machine element	Dynamic effects factors		
		Vertical D_V	Transverse D_Q	Longitudinal D_L
Bucket wheel excavator	Bucket-wheel boom	1/10	1/60	0
	Tower or central structure with counterweight boom	1/25	1/30	0
Bucket-chain excavator	Bucket-chain boom with cable supports	1/7	1/30	0
	Main support frame in the hoisting area of the chain boom	1/10	1/30	0
	Central structure	1/30	0	0
	Counterweight boom	1/20	1/50	0
Crawler-mounted spreaders	Discharge boom	1/10	1/10	0
	Tower—central part	0	0	0
Crawler-mounted machines	Counterweight boom	1/20	1/15	0
	Connecting bridges	1/20	1/10	1/15
	Cabs for operators	1/2	1/2	1/2

Table 2.2 Values of dynamic factors AS-4324.1 [15]

Machine	Machine part	Dynamic effects factors		
		Vertical	Horizontal	
			Transverse	Longitudinal
All rail mounted machines	Without digging element	1/10	1/30	1/30
	With digging element	1/8	1/30	1/30
Crawler-mounted machines and equipment with mechanical or hydraulic lifting feet	Bucket wheel boom	1/5	1/30	1/30
	Discharge boom	1/5	1/10	1/30
	Counterweight boom	1/5	1/15	1/30
	Tower or central structure	1/5	1/30	1/30
	Connecting bridges	1/5	1/10	1/15
All machines	Cabs for operators	1/2	1/2	1/2

2.5 Disadvantages of Traditional Methods of Dimensioning Surface Mining Machines

Long-term studies of surface mining machines, including both numerical methods and experimental tests, based on conditioning and data monitoring systems that use vibration sensors and strain gauges, make it possible to assess and identify the disadvantages of traditional dimensioning methods for this type of machine. This assessment addresses two main issues:

Fig. 2.33 Vibration sensor installed on the mast of a SRs-2000 excavator

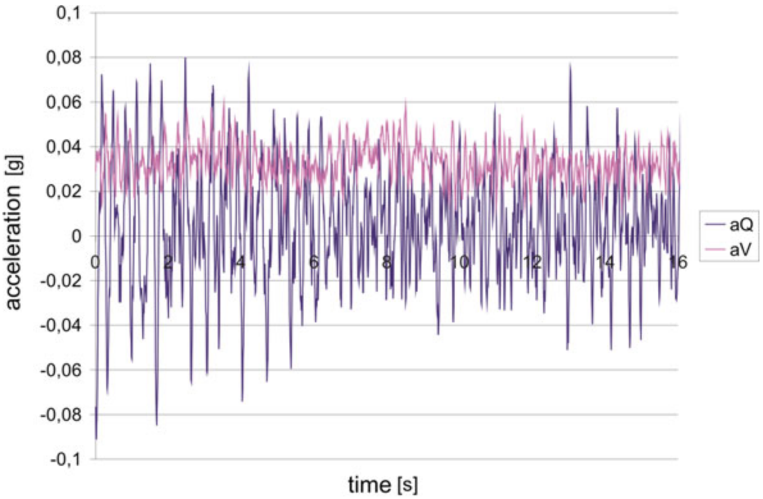

Fig. 2.34 Examples of time traces of horizontal (aQ) and vertical (aV) vibration accelerations measured on the SchRs 4600 excavator

- The incorporation of proper values of operational loads in calculations,
- The accuracy of determination of strength parameters of load-carrying structures in calculations.

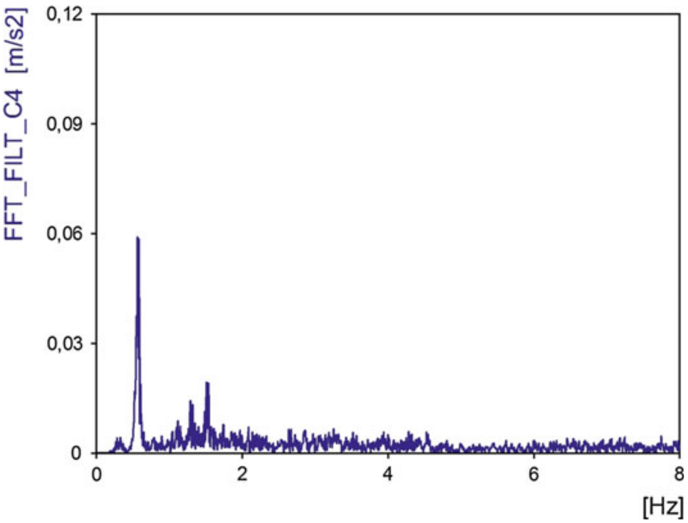

Fig. 2.35 Amplitude-frequency spectrum of vibration accelerations measured on the SchRs 4600 excavator

With respect to operational loads, several years of research into surface mining machines has led to an important conclusion that, in many cases, the standard approach to designing surface mining machines in which vibrations are accounted for by means of factors that increase constant loads, results in an underestimation of such loads and therefore in an incorrect estimation of durability. This situation pertains to, among others, excavating units of surface mining machines, especially those that strip overburden, in whose case the loads are determined by variable cutting resistances and dynamic phenomena generated by non-mineable formations in the material being excavated. During operation, excavating units frequently experience overloads that are not included in standard fatigue calculations and that may significantly influence the pace of the wear process. Figure 2.36 shows an example of a time trace of the digging force registered on a bucket-wheel excavator

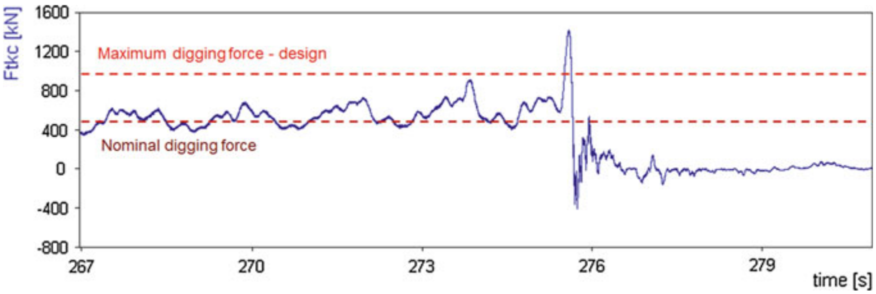

Fig. 2.36 Overload to the excavating unit and load values permitted by design

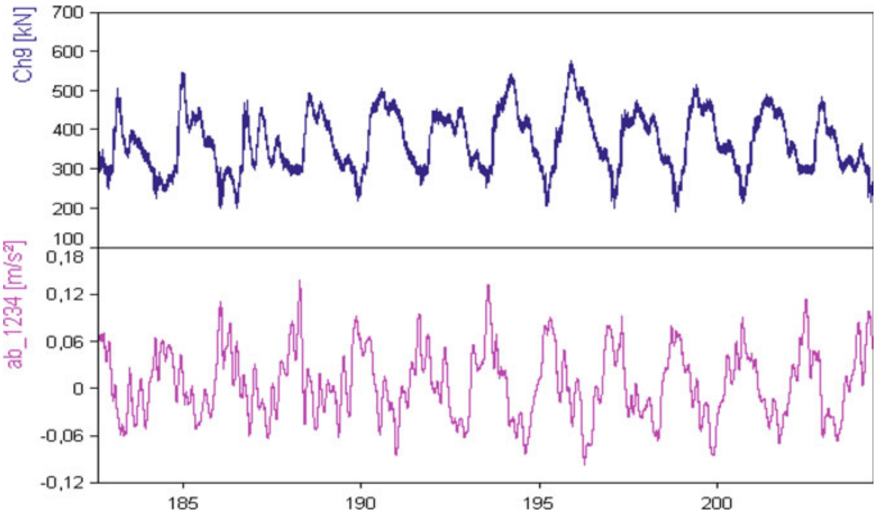

Fig. 2.37 Time-trace of changes in the digging force (*top chart*) and a similar time-trace of vertical vibrations of the excavating boom

with the indicated overload to the unit. Figure 2.36 also indicates the maximum load value permitted by the design, which is much lower than the actual value.

Figure 2.37 shows a similar time-trace of the dynamic effects that occur during excavation of the bucket-wheel excavator. There is a visible impact of vertical vibrations of the bucket-wheel boom on the value of the digging force U. These vibrations cause an additional amplitude of the cutting force, whose value is approximately 50% of the nominal force. This obviously affects the load to the load-carrying structure of the excavator and decreases its service life. These phenomena, however, are not included in traditional or standard-based methods of dimensioning surface mining machines.

Dynamic phenomena in the form of vibrations of surface mining machines and their individual components occur continuously throughout their service life. Vibration amplitudes described in the dimensioning standards for surface mining machines by dynamic factors are often underestimated in relation to the actual measured values. This has a direct influence on the underestimation of such loads in the process of fatigue development of load-carrying structures and thus can lead to fatigue damage.

Experience resulting from tests carried out so far on surface mining machines has led to the following conclusions:

- In many cases, the values of dynamic loads that act on load-carrying structures of surface mining machines exceed the values set or calculated on the basis of relevant standards.

- There is a correlation between the structure type of surface mining machines (e.g., C-frame, compact and large machine) and the nature and level of global and local vibrations.
- The effect of dynamic loads on the the decrease in durability is the greatest for counterweight and discharge booms. Subsequent elements of the bucket-wheel excavator's load-carrying structure towards the bucket-wheel boom are also subject to dynamic loads, but their influence on the generation of effort and fatigue damage decreases.
- With the increase in size of bucket-wheel excavators, the multiple of the overload factor in the bucket-wheel drivetrain decreases. Similarly, excavators with lower capacities and mass generate larger overload values that affect the that result in the decrease the durability.

The accuracy in calculations of strength parameters of load-carrying structures directly influences the quality of all calculations related to the development of load-carrying structures of surface mining machines. This primarily pertains to calculations related to ultimate and fatigue strength. Dimensioning standards for surface mining machines are based on analytic or numeric calculations but they use simplified models (beam or rod models). This approach necessitates increasing the values of partial safety factors. By doing so, an appropriate reserve resulting from the estimation of the level of stress in structural nodes can be taken into consideration in computations. This results in machine designs that are not optimal (heavy), but may also lead to a faulty design of load-carrying structures and result in their damage. What could help in such situations is the use of detailed shell or solid numerical models that represent the geometric characteristics of structural nodes and thus allow for a much more accurate determination of their stress state. There is a tendency to increase the accuracy of calculations and the designs of load-carrying structures, including those of surface mining machines, which improves the quality of these processes.

Given the above information, it seems justified to thoroughly update standard guidelines for designing surface mining machines. Such changes must be made both to the aspects regarding the determination of operational loads, as well as the adjustment of standard levels of safety factors and calculation methods to the currently used tools in this regard. It is also important to subject crawler undercarriages of surface mining machines to dimensioning requirements in terms of fatigue. Current guidelines only include calculations related to ultimate and buckling strength, which is a serious error in the DIN-22261 standard [14].

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