APPROACHES IN FORENSIC ENGINEERING OF EXCAVATING UNITS OPERATING ON OPEN PIT MINES OF SERBIA

Nebojša Gnjatović, University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia*
Milorad Pantelić, University of Kragujevac, Faculty of Technical Sciences, Svetog Save 65, 32000 Čačak, Serbia
Ivan Milenović, University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia
Aleksandar Stefanović, University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia
Srđan Bošnjak, University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia

Abstract: *Bucket wheel excavators (BWEs) are a backbone of any power industry that heavily relies on surface exploitation. As such, any failure, breakdown or collapse of the machine or its subsystems poses a serious drawback in the efficiency of an entire mining system, and is strongly reflected on costs in labour, finances, material and downtime, and is also a potential risk to the safety of workers. This, combined with lengthy lifetime of the machines operating in open cast mines of Serbia (measured in decades), places immense value on the avoidance of potentially hazardous problems during all stages of their lifespan, namely the design, manufacture and exploitation phases. Over the past decades, demand for the ever-increasing capacity and efficiency of BWEs has led to failures which may indicate a need for the reassessment of the calculation methods and guides. This paper presents few such cases, along with the discussion about causes, and suggests an approach to dynamic behaviour analysis based on reduced spatial dynamic models of BWEs which enable modal analysis and the analysis of a dynamic response for continuous variation of constructional parameters.*

Keywords: *bucket wheel excavator, dynamic analysis, forensic engineering*

INTRODUCTION

Bucket wheel excavators (BWEs) belong to the class of high performance machines and present the backbone of surface mining systems. In past decades, earthmovers, especially BWEs as continuous excavation machines, being the largest structures in earth based technology, have become progressively larger and their mechanisms more efficient. Their exploitation in harsh working conditions provides fertile ground for the occurrence of failures of their structures and substructures [1–6]. As stated in [7], the main reasons for the collapse of high-capacity earthmoving machines are 'designing-in' defects (design faults), 'manufacturing-in' defects (manufacturing faults), 'operating-in' defects (exploitation faults) and 'environment-in' defects (extreme environmental impacts). Failure of a machine is usually the consequence of a combination of previously mentioned negative effects.

Failures of the above-mentioned machines are always accompanied by high financial losses and, more importantly, represent a serious risk to the workers' safety and lives.

Permanent improvement of BWEs performances, especially their capacities, has not been adequately supported by calculation methods. This fact, combined with the age of excavators operating on open – cast mines of Serbia (more than half BWEs are in operation for more than 25 years, which was considered an economically optimal life by their manufacturers) draws a conclusion that it was practically impossible to carry out a detailed stress–strain analysis and the dynamic behavior analysis during their design.

**University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia*
ngnjatovic@mas.bg.ac.rs

Continuous soil excavation is a process of excessive dynamic character caused by repeatable bucket to soil interaction, unbalance of the bucket wheel and rotational components of belt conveyors and impacts by the stream of soil or soil fragments.

The extreme importance of the BWE dynamic behavior analysis is in the prevention of possible occurrence of resonance in the system. The said analysis is used as a basis for the analysis of the stress conditions in structural elements.

Modernization of excavating units realized in order to achieve better customization of the machine versus the operating conditions, and to avoid negative dynamic effects that cause failures of structural elements and prolonging the unnecessary downtime of the machine, is nowadays represented equally with the design and production of new units. During redesign and modernization procedures some of the constructional parameters with the most influence on the structural and dynamic behaviour of the BWE are being alternated. There are three major obstacles in the analysis of influence of any constructional parameter on the dynamic and consequently structural behavior of BWE: (a) extreme complexity of the dynamic system, (b) relatively small number of parameters which may be modified after the construction has been mounted and (c) limitations of the finite element method (FEM) which are reflected in the discreteness of the created models. The above-mentioned obstacles combined with the fact that current technical regulations do not account for dynamic behaviour of BWEs (instead, such problems are analyzed as quasi-static) emphasize the importance of development of new reduced dynamic models and methods for modal and dynamic response analysis in continuous domain of parameter variation.

DYNAMIC ANALYSIS - REDUCED SPATIAL DYNAMIC MODEL APPROACH

Analysis of the dynamic behavior demands a solution to the problems of creation of an adequate dynamic model of the machine and the creation of a model of the external load caused by influences of the work environment.

Prior to developing a reduced dynamic model of the BWE, basic parameters of the slewing superstructure (SS) must be carefully determined, since they largely determine the operation characteristics, reliability, and safety of a BWE. As stated in [8], the parameters may be classified into three main groups, those which determine the static stability, the strength and the dynamic behavior of the SS. The common denominators of all these parameters are the SS mass and its distribution along the structure. Deviations of the SS mass and the center of gravity (COG) position, inevitably appearing during the transformation from designed to the actual (produced) state of the structure, revealed by weighing, are compensated by adjusting the counterweight mass.

The afore-mentioned deviations are taken into account using the experimentally validated corrected 3D model developed by merging the results obtained from the superstructure 3D model and the weighing conducted after the completion of the erection process (the procedure is in detail presented in [8]). The 3D model developed in such a manner provides enough accuracy in determining the superstructure COG in the complete domain of the bucket wheel boom inclination angle, and enables accurate load analysis of vital parts of the superstructure.

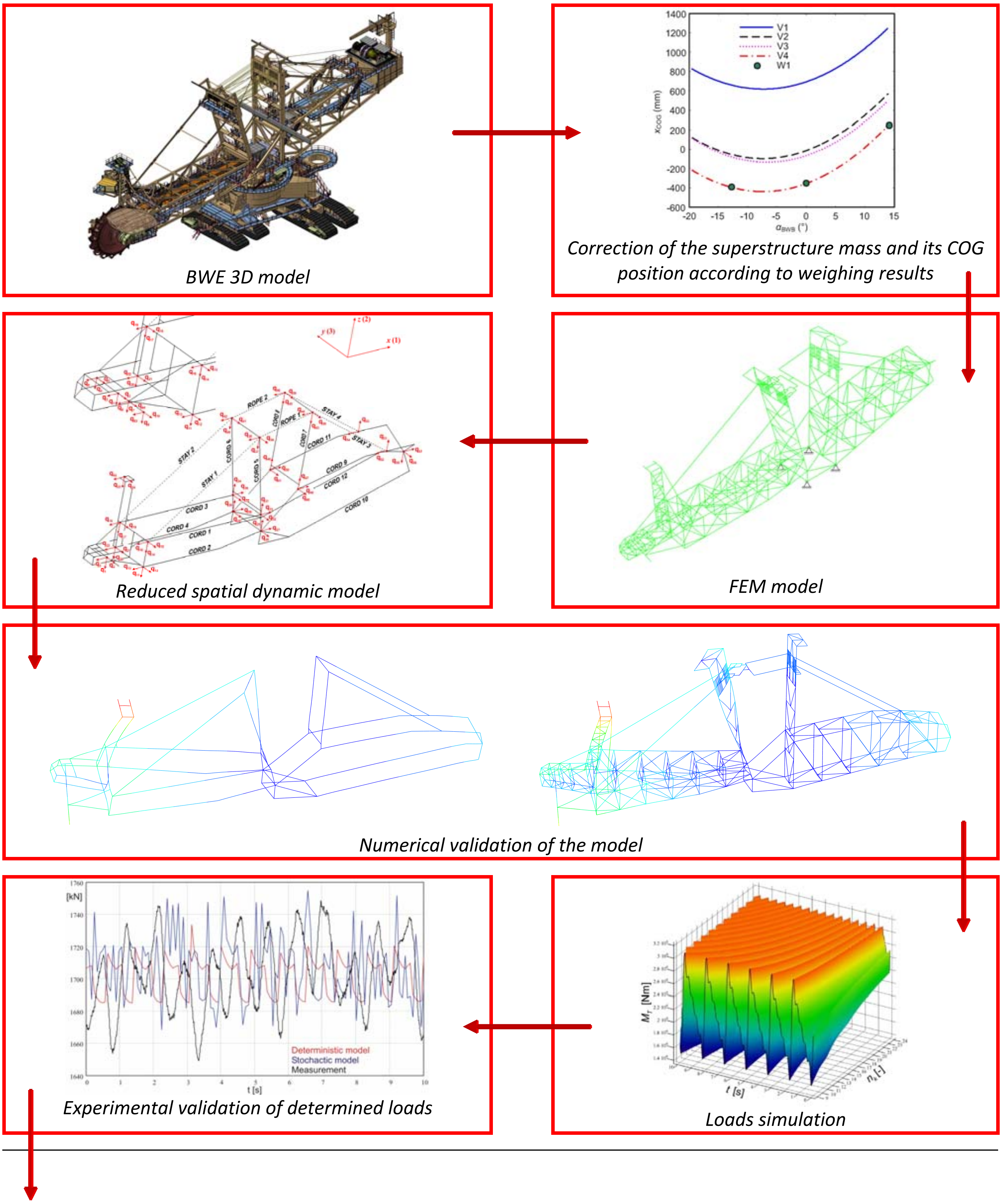
When the SS mass distribution is precisely determined, expressions for calculation of the kinetic energy of all superstructure subsystems are established considering chords of spatial truss structures as girders with continual mass distribution, and their dynamic deflection lines approximated by applying local linearization method presented in [9,10].

Spatial truss FE model of the superstructure, formed on the basis of the experimentally validated corrected 3D model, is used for determination of flexibility matrix coefficients in accordance with Clapeyron's theorem.

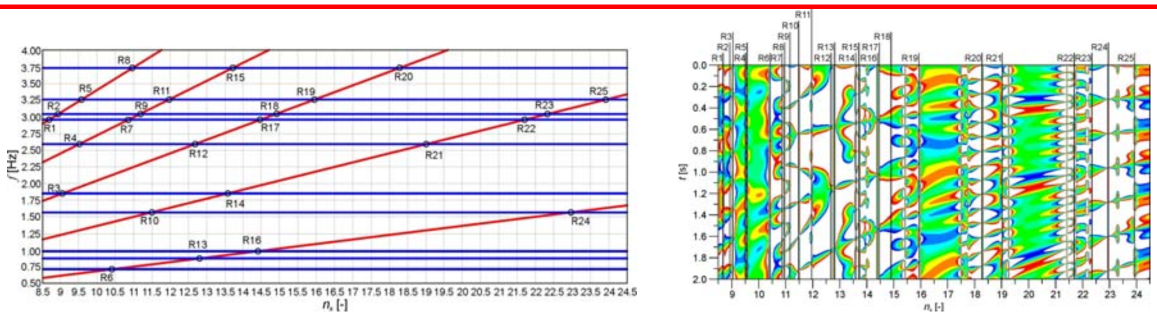
During the identification of the components of the resistance-to-excavation, according to the code DIN 22261-2, the effects of the bucket wheel eccentricity are neglected in relation to the system lines of the

*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
ngnjatovic@mas.bg.ac.rs

boom as well as the BW inclination relative to the vertical and horizontal plane. Therefore, based on the model containing the mentioned effects, the in-house software RADBAG has been developed [11], enabling to define the effect of resistance-to-excavation in any position of the bucket wheel boom. Credibility of the simulation model has been confirmed by measurement in real operating conditions [12]. Resistance- to-



*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
ngnjatovic@mas.bg.ac.rs



Modal analysis and analysis of response for continuous variation of constructional parameters

Picture 1. – Identification of the dynamic response

-excavation defined in such manner is used to establish the expression for virtual work of non-potential active loads from which the generalized non-potential forces of the system are obtained.

Key stages of the identification procedure of BWEs response to dynamic impacts, realized based on reduced spatial dynamic model approach, which enables modal analysis as well as analysis of the dynamic response in the continuous domain of constructional parameters variation, are presented in picture 1.

FORENSIC ENGINEERING AND REDESIGN

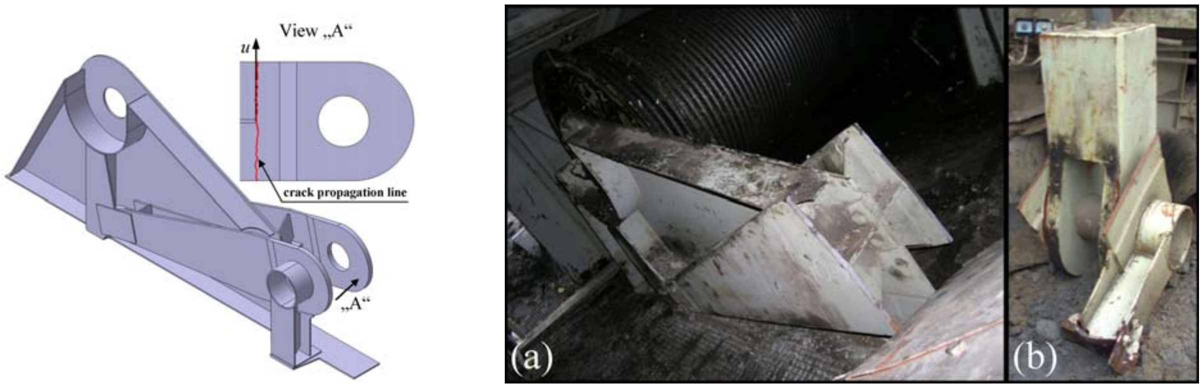
Although, as previously stated, failure of high performance machines such as bucket wheel excavators and their belonging substructures are usually a consequence of combination of negative effects, in the following section, examples of failures caused by typical 'designing-in', 'manufacturing-in' and 'environment-in' defects will be presented.

After a mere sixteen years of exploitation, a heavy accident caused a total collapse of the BWE SchRs 1760, picture 2, a machine with the highest theoretical capacity at that time (6100 m^3/h), operating on the overburden excavation on open pit mine "Kolubara". Revitalization process, which included the dismantling of the complete BWE structure, its transport to the erection site, repair and manufacturing of almost every part of the superstructure and putting it back to service, lasted for almost five years. Direct expenses in terms of material and labour were estimated to be around fifteen million Euros [13]. However, indirect losses, caused by the BWE's downtime substantially exceed revitalization costs.

Picture 2. – BWE SchRs 1760 before and after the collapse [14]

Damage diagnostics concluded that the straightforward cause of the BWE collapse was the failure of the end eye connection of the support of the right portal tie-rod, picture 3.

*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
nqnjatovic@mas.bq.ac.rs



Picture 3. – 3D model and the broken-down support of the right portal tie-rod [13]

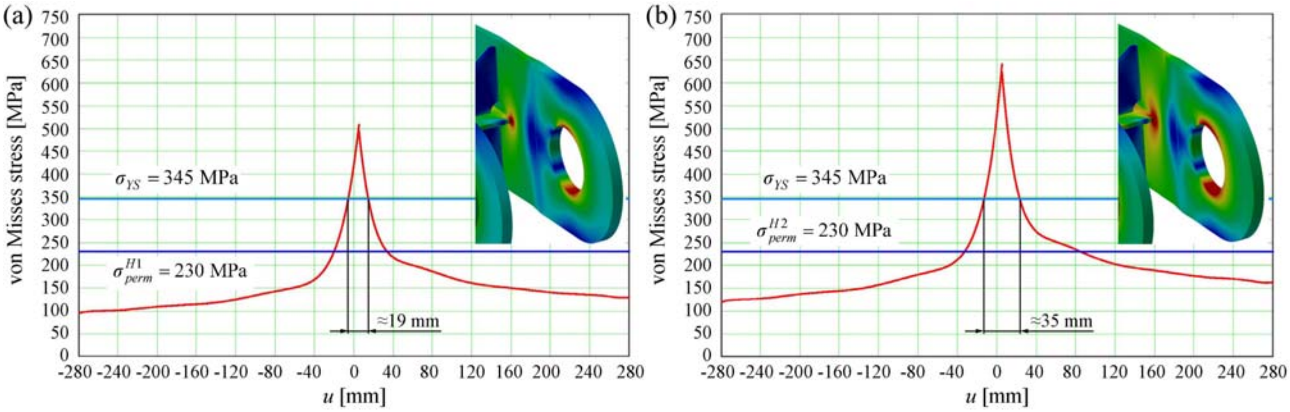
In order to detect the reason of the end eye connection failure it was necessary to calculate the stress state of the eye assembly. The load analysis and linear finite element analysis (LFEA), picture 4, of the support of the portal tie-rod were carried out for four referent load cases (LCs) prescribed by DIN 22261-2, according to which the construction was designed.

LFEA results point out that (a) due to the prompt incursion of the lengthwise supporting plate into the eye structure and the proximity of the location where the load is applied, the pronounced stress concentration occurs in the failure zone of the eye; (b) In all load cases maximum von Misses stresses are considerably greater than permissible stress values and the reserve of elasticity is also depleted and (c) the size of the high stress state zone (values higher than yield stress intensity) is expanding with the increase of load intensity from 19 mm for LC H1 up to 48 mm for LC HZS1, picture 4.

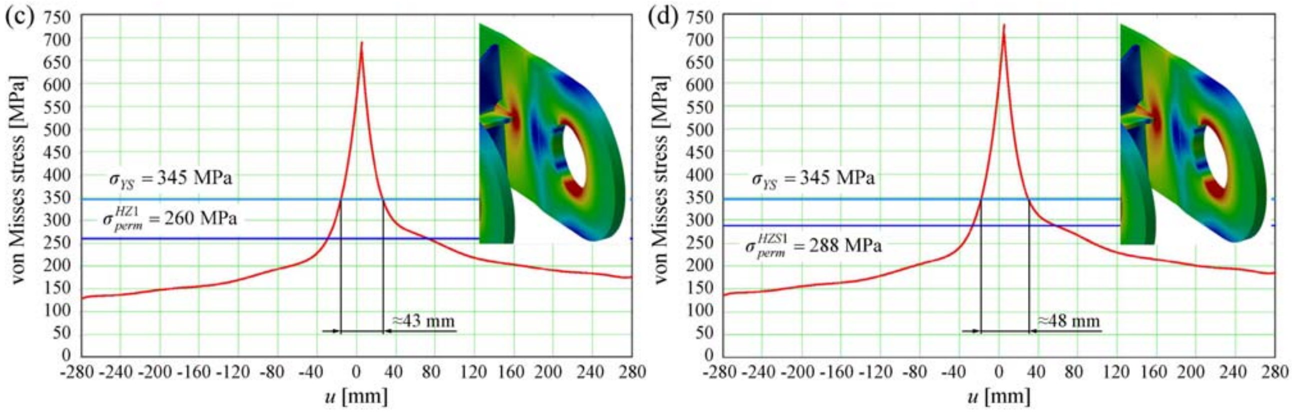
The high stress state of the designed support structure of portal tie-rods and dynamic character of loads are the principal reasons of the end eye connection failure and the BWE collapse.

After merely 1800 h of operation, cracks in the welded joints on the bucket wheel body of the BWE SRs 1300 were discovered. In order to prevent possible heavy damages to the machine, investigations are carried out to detect the causes of cracks occurrence.

LFEA, conducted on the basis of loads determined using the in-house developed software RADBAG, pointed out that the working stresses do not jeopardize the integrity of the respective structure, picture 5. This



*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
nqnjatovic@mas.bq.ac.rs

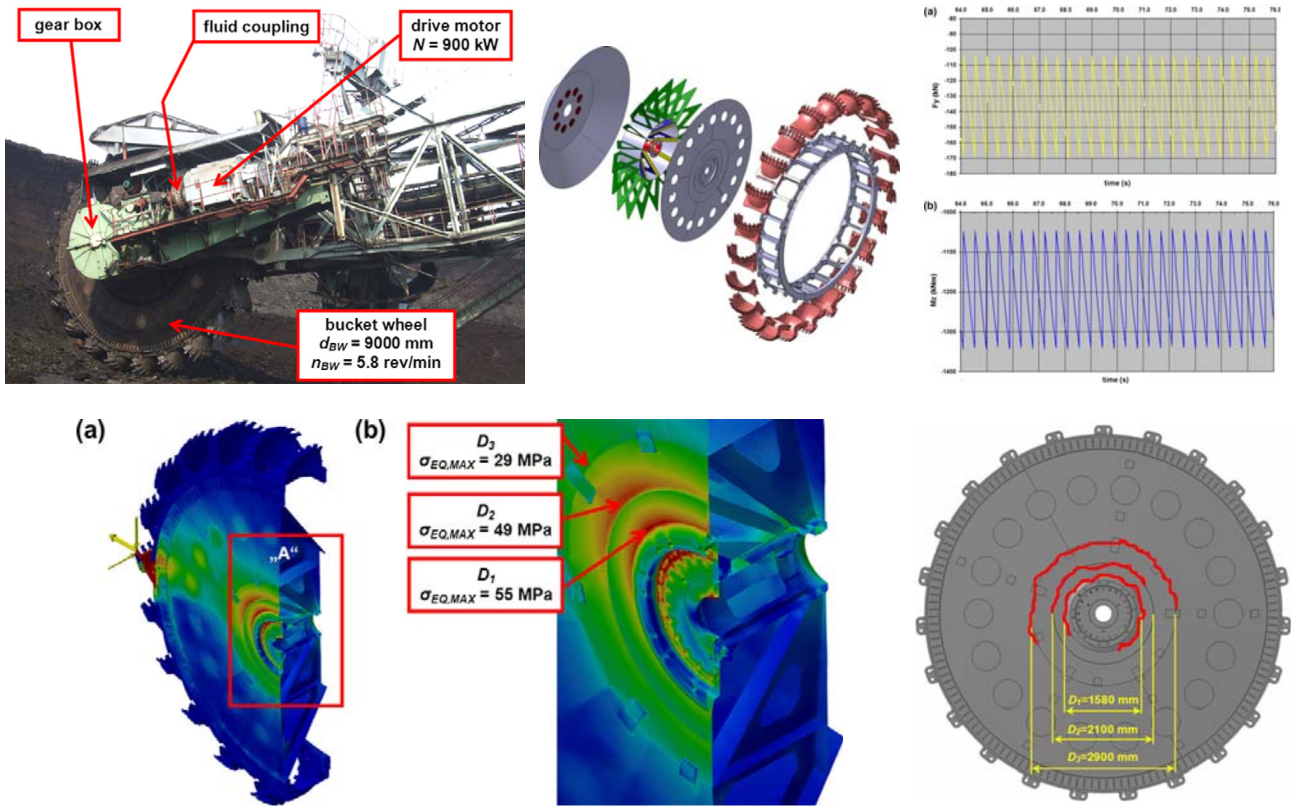


Picture 4. – Stress distribution along crack propagation line: (a) LC H1; (b) LC H2; (c) LC HZ1; (d) LC HZS1 [13]

conclusion is also confirmed by the results of the experimental stress analysis in real working conditions which is performed by the strain gauges methods [15].

Measurements of welding residual stresses are carried out by applying the centre hole drilling method. Experimental investigations defined the chemical composition, tensile properties, hardness, impact toughness, as well as the susceptibility to cracking [15].

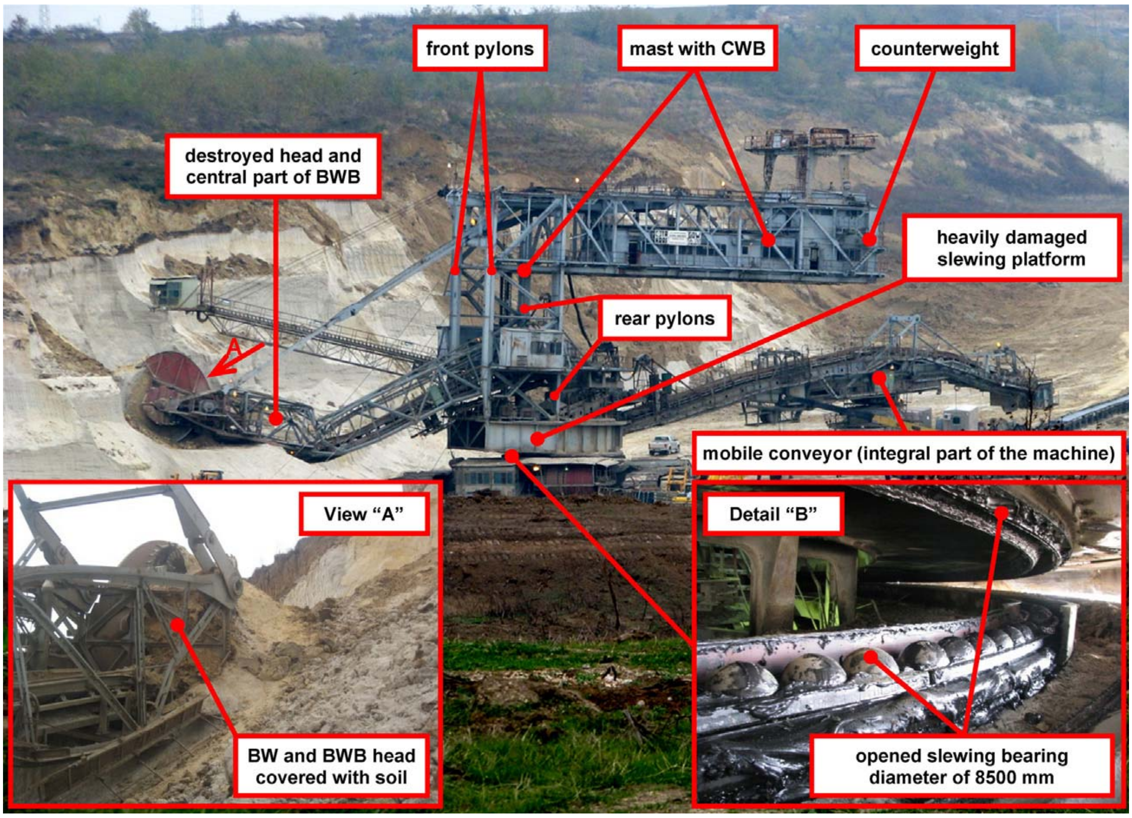
Experimental investigations have shown that welding residual stresses are high and occur primarily due to deviations from the specified welding technology. An insight into the technical documentation revealed that 25 mm thick ring plates were butt welded using a V-shaped instead of an X-shaped joint. Additionally, all thermal processes during welding were uncontrolled, which was indicated by much higher hardness measured in the heat-affected zone than in the parent metal and weld metal leading to lower plasticity and tendency for brittle fracture.



Picture 5. – Diagnostics of distribution of von Misses stresses in the cracks occurrence zones (red coloured areas on the bottom right picture) [15]

*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
nqnjatovic@mas.bq.ac.rs

Finally, on the basis of numerical-experimental analysis, the appearance of stress values, obtained as a combination of working (dynamic) and residual (static) stress, above the limit lines of the modified Goodman's curves was discovered [15].



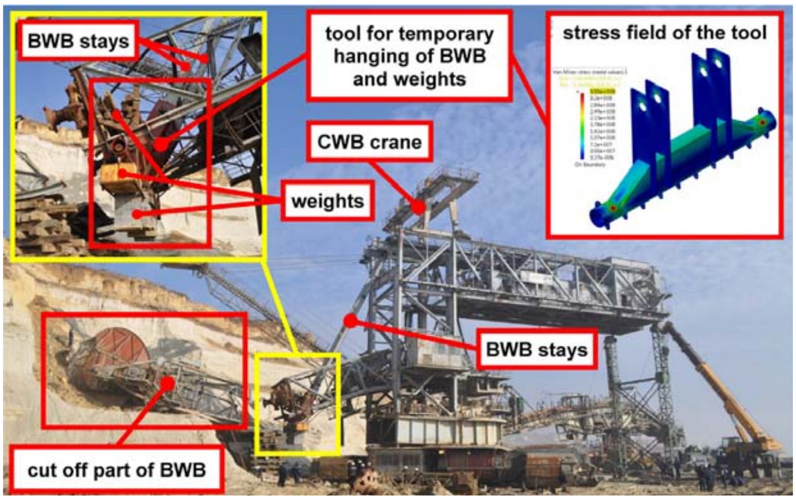
Picture 6. – BWE SRs 1200 after the accident [16]

BWEs are exposed to environmental impacts, predominantly those of the excavated soil. Apart from outstandingly dynamic and stochastic character of the loads caused by soil impacts in regular exploitation conditions, BWEs can also be subjected to extraordinary environmental impacts, such as slope failures, which inevitably lead to severe accidents. Rescue and reconstruction of a severely damaged BWE SRs 1200, picture 6, presented a number of extremely complex engineering challenges.

Visual examination, conducted after the temporary BWE stabilization, revealed the following: (a) bucket wheel boom (BWB) head and its central part have suffered severe damage followed by very pronounced plastic deformations of vital structural elements; (b) the damage degree of the BW with drive was so high that their repair was not possible; (c) the slewing platform also underwent serious damage.

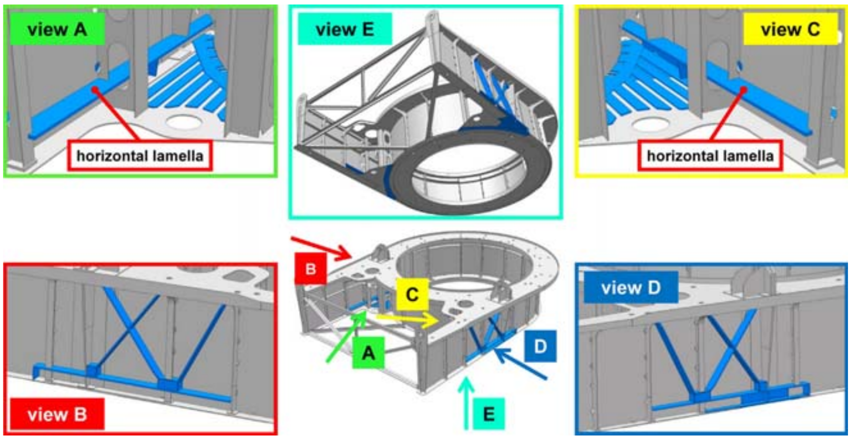
Rescue of the machine was achieved by cutting off the heavily-damaged BWB parts and its stays, picture 7. A tool for temporary hanging of the remaining BWB structure and set of weights (97 t) used to compensate the influence of the structural parts which have been cut off, was designed, manufactured and mounted [16]. Successful completion of the very delicate BWE rescue and balancing operation enabled the BWE to travel to the previously prepared temporary repair site.

*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
ngnjatovic@mas.bg.ac.rs



Picture 7. – BWE rescue and preparation for travel to the temporary repair site [16]

A new slew bearing, BWB structural parts and its stays as well as BW with drive had to be manufactured and mounted, but the decision has been made to redesign the revolving platform in field conditions, without dismantling the superstructure, drastically reducing the time required for the reconstruction works. The key idea of the slewing platform redesign was to realize favorable stiffness and loads distribution while eliminating geometrical stress concentrators. It was also necessary to remove structural parts that were seriously damaged during the long-term exploitation and breakdown, and install the newly designed elements in critical zones, picture 8.



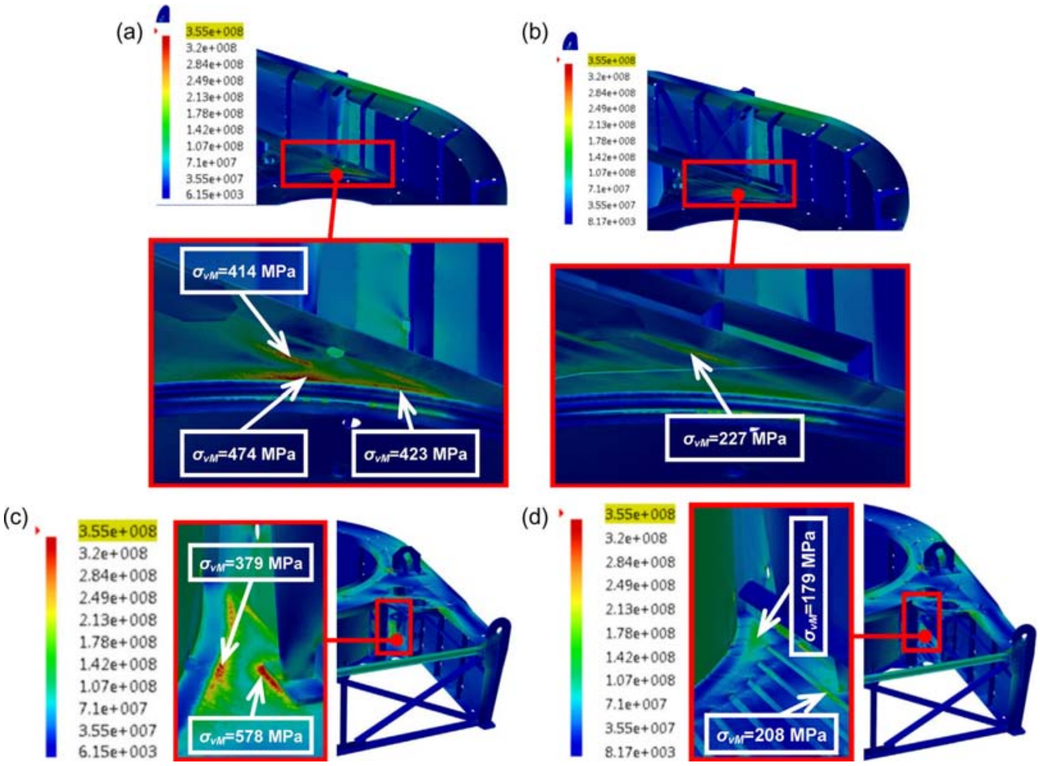
Picture 8. – The redesigned structure of the slewing platform (the newly built-in structural elements are shown in blue) [16]

Comparative stress analysis, conducted for the referent load case (in which the maximum value of the von Mises stress in the bottom plate of the original slewing platform is considerably higher than the permissible stress value in zones where cracks occurred during perennial exploitation) of both the original and redesigned solution revealed the following facts: (a) the maximum von Mises stress value on the bottom surface of the bottom plate is 2.1 times lower in the redesigned structure; (b) the maximum von Mises stress value on the upper surface of the bottom plate is 2.8 times lower in the redesigned structure, picture 9.

Reduction of the system downtime (and consequently drastic reduction of financial losses) was the prime motivation to restore the BWE to its working order in field conditions without dismantling the superstructure. This procedure imposed four engineering challenges: (1) temporary stabilization of the machine and returning the superstructure into the designed position; (2) cutting off the badly damaged parts of the machine, balancing the newly created superstructure configuration and BWE travel to the temporary repair site; (3) slewing platform redesign and (4) technology of the partial revitalization of the BWE [16].

**University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia*
nqnjatovic@mas.bq.ac.rs

Reliable and safe exploitation of the bucket wheel excavator was provided and its life prolonged with the reconstruction of the slewing platform as well as the installation of a newly manufactured bucket wheel with drive, the newly manufactured bucket wheel boom structural parts and a new slew bearing.



Picture 9. – Von Mises stress fields in critical zones of the slewing platform: (a and c) original structure design; (b and d) redesigned structure) [16]

CONCLUSION

Methods presented in this paper, namely the reduced spatial dynamic model approach to dynamic behavior analysis of BWEs, as extremely complex spatial dynamic systems, as well as the original procedures for analyzing sensitivity of the machine against continuous variation of basic parameters of the slewing superstructure [10,17] may have significant role not only during the design of new, but also during redesign, modernization and maintenance of old and obsolete machines intended for perennial exploitation in extremely harsh working conditions. The afore-mentioned approach and procedures should potentially fill in the existing gap between the design methods prescribed by current technical regulations and the methods for continuous monitoring of BWE structural responses in real operating conditions that are being developed and excessively used in last decade [18-24].

The age of the excavation units operating in open-cast mines of Serbia, and the already-mentioned fact that it was practically impossible to carry out a detailed stress–strain analysis and the dynamic behavior analysis during their design (stages/phases) emphasizes the necessity of their recalculation in order to determine the state of the most burdened structural components. Although the employment of such approach would not completely eliminate the occurrences of failures and collapses such as the examples presented in this paper, it would make them less likely, if only for the fact that designing-in faults would be much less frequent.

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**University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia*
ngnjatovic@mas.bg.ac.rs

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**University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia*
ngnjatovic@mas.bg.ac.rs

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*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade, Serbia
ngnjatovic@mas.bg.ac.rs