‘Design-in’ Faults - the Reason for Serious Drawbacks in High Capacity Bucket Wheel Excavator Exploitation

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This paper describes the failure analysis results of undercarriage and superstructure vital subassemblies, which led to periodical stoppage and eventually total collapse of the bucket wheel excavator (BWE) SchRs 1760, once the machine with the highest theoretical capacity operating on the overburden excavation in open pit mine “Kolubara” - Serbia. It is conclusive that the main cause of two wheel bogie structural failure, described as case 1, is its insufficient strength during the action of lateral forces which are dominantly applied during the BWE curve travel. Case 2 analyses the support structure of portal tie-rods failure which was the consequence of superposition of the negative effects caused by inadequate shaping and dimensioning of the support assembly for given load conditions, as well as influences of defects of the metal weld structure. Both of the described failures are caused by the design-in faults.

Keywords: Bucket wheel excavator, Failure analysis, Finite element analysis

1. INTRODUCTION

Bucket wheel excavator (BWE) SchRs 1760, Fig. 1, was put into exploitation during the year 1989. At that time it was the machine with the highest theoretical capacity of 6100 m^3/h operating on the overburden excavation on open pit mine “Kolubara” – Serbia.

Figure 1: BWE Sch Rs 1760

Ever since the beginning, the exploitation of this BWE was followed by frequent breakdowns of its crawler travelling mechanisms vital subassemblies, especially crawler chain links [1] and two wheel bogies (TWB), Fig. 2. During three years period, from 2001 to 2003, fifty-one two wheel bogie bodies and forty-nine track wheel axles with nuts were manufactured and substituted [2].

Complex substitution procedure, which is done on site in extremely harsh working conditions consists of hole digging (4m length, 3m with and 0.8m depth), crawler chain release, positioning of the excavator above the hole, leaning the damaged TWB on specially designed lifting tool, dismantling, descending and extracting the old and positioning and attaching the new construction, followed by chain tensioning, as presented in [3]. Estimated duration of this operation is about eight hours, during which, the excavator cannot be functional.

Defect inspection showed that the majority of TWB structures suffered the same problems, plastic deformation and crack occurrence in the vertical plate clamping zone and shearing of the axle nut. Frequent failures, followed by the same problems detected during maintenance procedures were the main reason for comprehensive structural integrity analysis of the TWB construction. Diagnosis of the cause of the TWB structure failure will be presented in this paper as Case 1.

Figure 2: Typical failure of the TWB structure

On 3rd of December 2005, after merely sixteen years of exploitation, a heavy accident caused the total collapse of the machine, Fig. 3. Revitalization process, which included dismantling of the complete BWE structure, transport to the erection site, repair and manufacturing of almost every part of the superstructure, erection, testing and putting back to service, lasted for almost five years. On 22nd of October 2010, BWE SchRs 1760 was, once again, included into the production process. Direct expenses in terms of material and labour were estimated to be around fifteen million Euros.

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However, indirect losses, caused by the BWE’s downtime considerably exceed revitalization costs, having in mind that one hour of machine exploitation is valued at 11000 € to 15000 €.

Figure 3: BWE Sch Rs 1760 after the collapse

Damage diagnostics, conducted immediately after the breakdown, concluded that the straightforward cause of the BWE collapse is the failure of the end eye connection of the support of the right portal tie-rod, Fig. 4, which will be analyzed as Case 2 of this paper.

Figure 4: Broken-down support of the right portal tie-rod: (a) element on the counterweight arm and (b) broken-away part.

2. CASE 1 – TWO WHEEL BOGIE FAILURE

Two wheel bogie (TWB) presents the vital part of BWE crawler carrying structure. It distributes the load statically determinate to the individual wheels and also provides the necessary freedom of movement of the travel wheels to adapt to undulating ground conditions in travel direction [4].

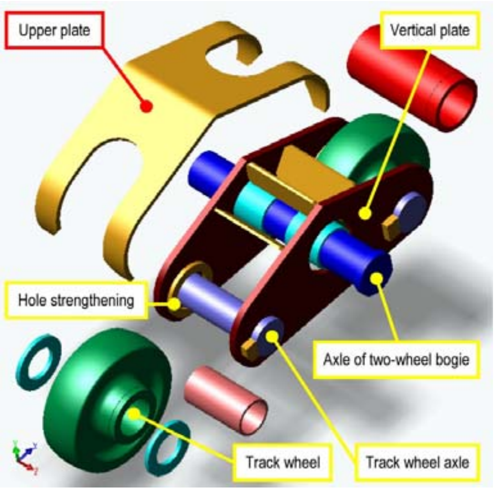


Figure 5: 3D model of the bucket wheel excavator Krupp 1760 TWB

Fig. 5 shows the main TWB subassemblies. It can be observed that there is no connection between the vertical plates in the TWB structure under the hole for bedding the track wheel axles. On the other hand, based on the looks of the TWB damaged structure, shown in Fig. 2, it is conclusive that the main cause of its failure is insufficient strength during the action of lateral forces which are dominantly applied during the BWE curve travel [5]. The verification of this conclusion is done by applying the linear FEA.

Load analysis of the TWB structure is carried out according to the recommendations given in [6,7]. The track wheel is affected by the average vertical load for maximum load on the crawler track $R_{z,m,max}$ = 384.3 kN and the corresponding horizontal load $H_{ym,max}$ = 230.6 kN, as presented in [8].

In order to simulate the behaviour of the TWB structure predefined by the project documentation, a model which includes the track wheel axles was analyzed. Lateral forces act on one vertical plate - annular surfaces of the holes' strengthening, blue coloured surfaces, whereas track wheel axles are loaded by vertical forces and bending moments (M_L) gained by a reduction of lateral forces, Fig. 6.

One of the main problems detected in the process of defect inspection was, as previously stated, shearing of the axle nut, which leads to the appearance of a relatively great axial gap between the TWB vertical plates and the track wheel axle subassemblies. In this case, an FE model was created by supposing that the lateral forces act only on one vertical plate, while the second is the support in the corresponding direction, Fig. 7.

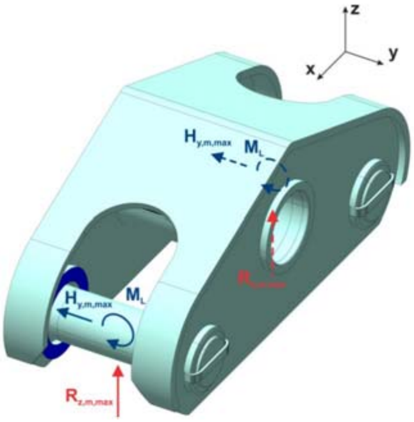


Figure 6: Loading of the TWB structure model which includes the track wheel axles subassemblies

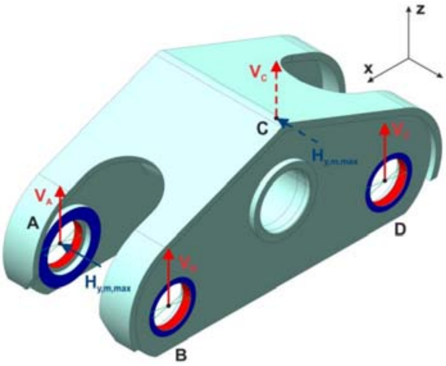
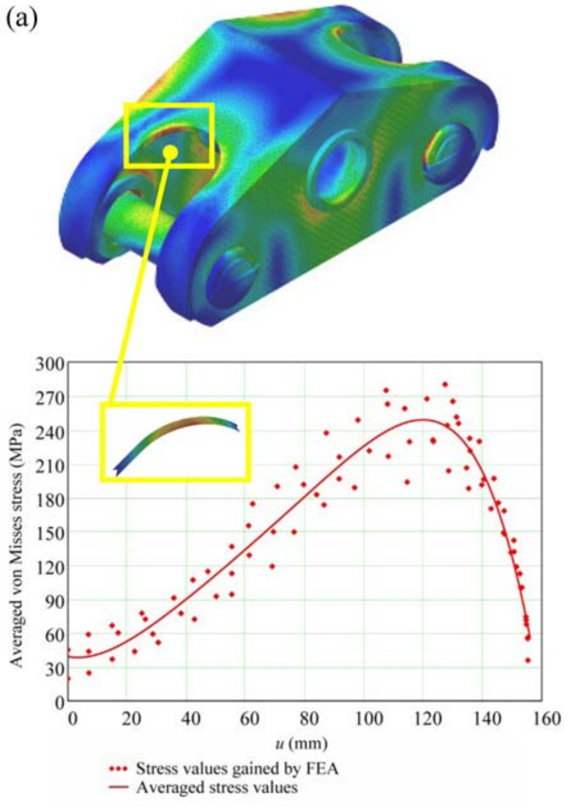
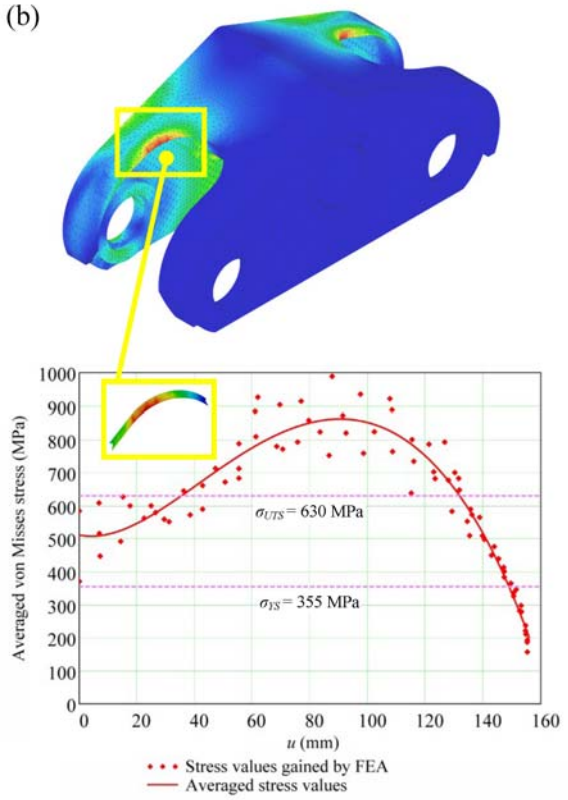


Figure 7: The TWB structure loading in case of an axial gap between the vertical plate and the track wheel axles subassemblies

The maximum calculated stress values appear in the vertical plate clamping zone. Distribution of von Misses stresses in the critical zone is shown in Fig. 8, while averaging of the calculation stress values along the upper plate thickness is done according to [8].



(a) track wheel axle included



(b): without track wheel axle

Figure 8: Distribution of averaged von Misses stresses in critical zones

If the track wheel axles are included in the model of the TWB structures, the maximum averaged von Misses stress (MAvMS) for the original (249 MPa) TWB structure is lower than the minimum yield stress value (σ_{YS}=355 MPa for steel quality grade S355J2G3). But, if track wheel axles do not distribute the lateral loads, MAvMS (862 MPa) for the original TWB structure is considerably greater than the ultimate tensile strength (σ_{UTS}=630 MPa). This fact fully explains the occurrence of cracks in the case of an axial gap between the TWB structure and the track wheel axle subassemblies.

The authors of this paper strongly suggest the conservative approach to calculating the TWB structure, using models which do not include the track wheel axles, since it provides sufficient TWB carrying capacity even in the case of unforeseen loads, the appearance of which is quite possible having in mind the extremely hard working conditions.

3. CASE 2 –FAILURE OF THE PORTAL TIE ROD END EYE CONNECTION

The portal tie-rods supports, Fig. 9, are the vital parts of BWE structure. By means of tie-rods (rope diameter 110 mm), they accept a part of the BWB and portal loads and transmit it onto the counterweight boom. At the same time they are supports of the rope system drum for BWB hanging. The straightforward cause of BWE collapse, as it was previously stated, is the failure of the end eye connection of the support of the right portal tie-rod (Fig. 4).

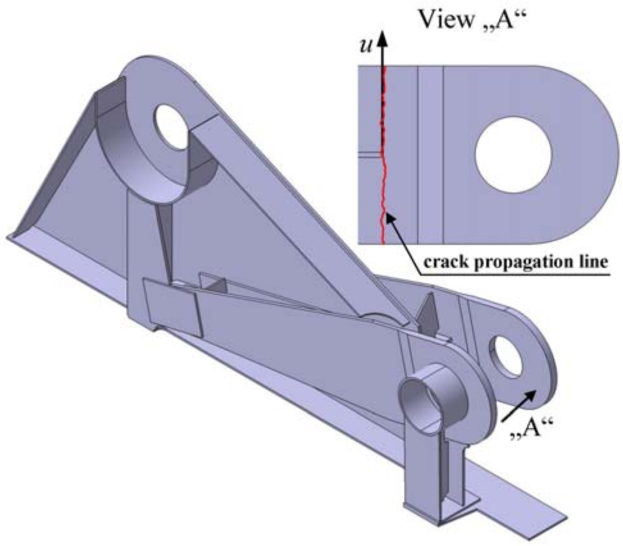


Figure 9: 3D model of the support of the right portal tie-rod

In order to detect the reason of the end eye connection failure it was necessary to calculate the stress state of the eye assembly, conduct visual, metallographic and SEM inspection of the crack surface and determine chemical composition and mechanical properties of the end eye connection plate.

The identification of the portal tie-rod support stress state is done by applying linear finite element method (FEM).

The load analysis of the support of the portal tie-rod is carried out according to the rules given in the German code [6], based on which the considered BWE was designed. The intensities of forces in the portal tie-rods (F_{TR}) are defined for four characteristic load cases (LC) that are: H1 (F_{TR} = 2980 kN), H2 (F_{TR} = 3755 kN), HZ1 (F_{TR} = 4040 kN) and HZS1 (F_{TR} = 4260 kN).

Maximum value of uniaxial stress, calculated according to the Huber–Hacky–von Misses hypothesis, is obtained in the left eye, in the zone of its connection with the lengthwise supporting plate, Fig. 10.

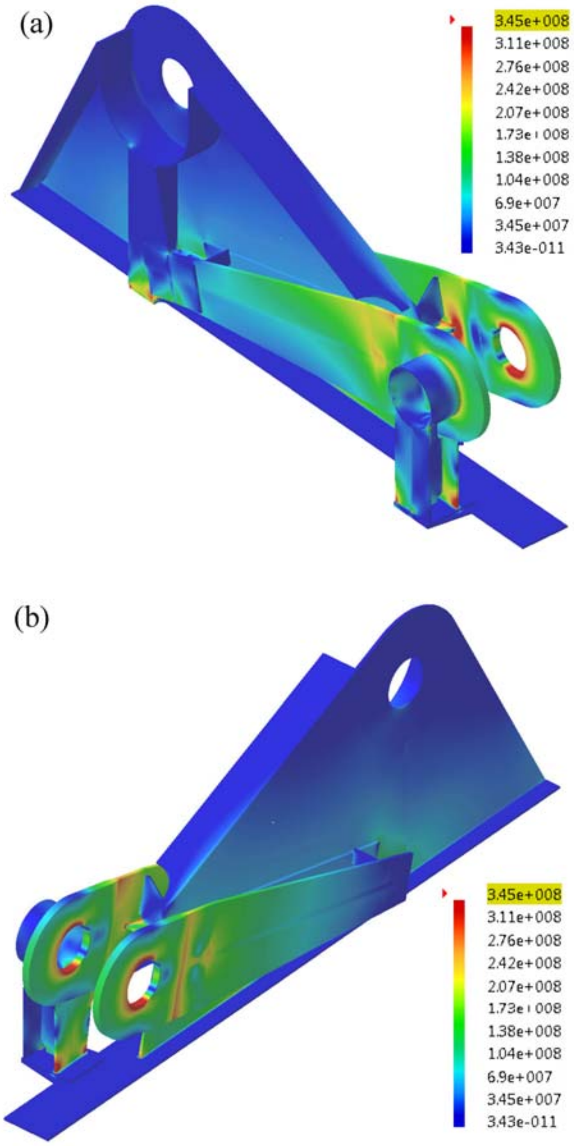


Figure 10: Uniaxial stress field of the portal tie-rod support structure for LC HZS1: (a) right side view and (b) left side view (values higher than yield stress are red coloured)

Distribution of von Misses stresses in the critical zone, as well as calculation stress values along the crack initiation and propagation line are shown in Fig. 11. The maximum von Misses stress (MvMS) values and the permissible stress intensities (PSI) for all analyzed load cases are presented in Tab. 1.

Table 1: MvMS and PSI for all analyzed load cases

Load case	MvMS [MPa]	PSI [MPa]
H1	508	230
H2	640	230
HZ1	689	260
HZS1	726	288

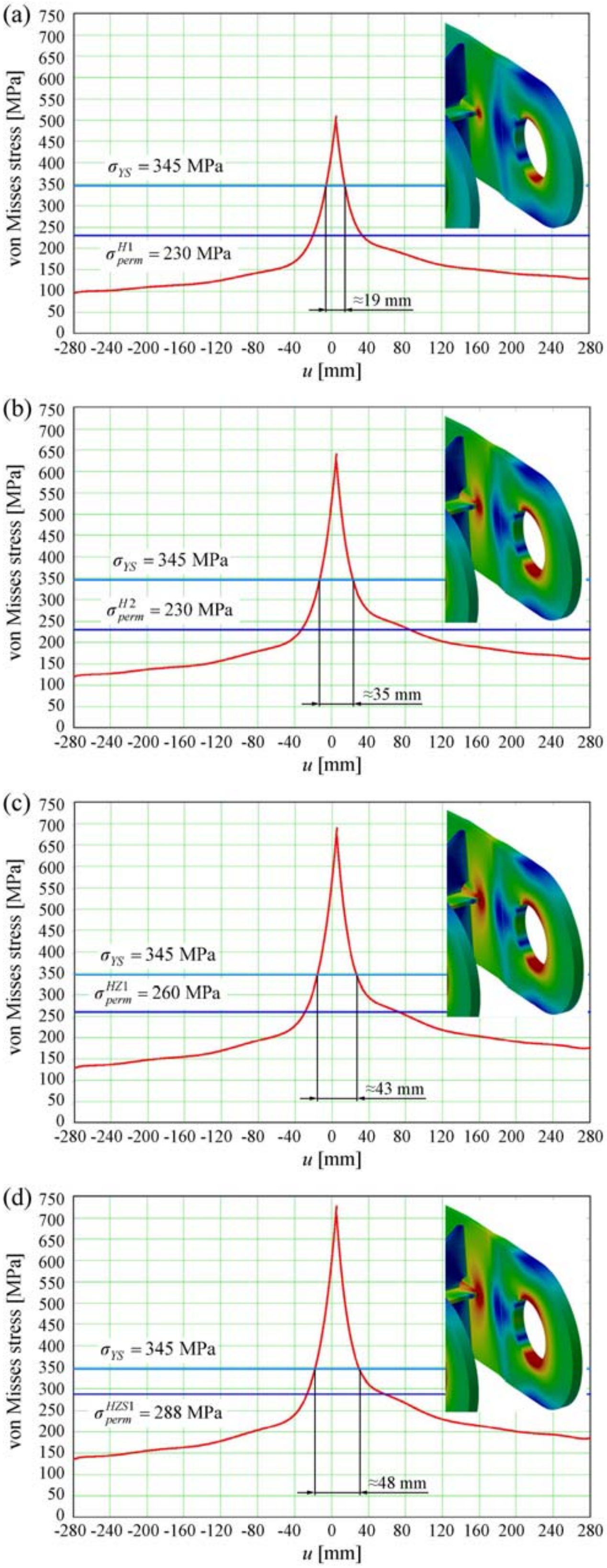


Figure 11: Distribution of von Misses stresses alonge the crack propagation line: (a) LC H1, (b) LC H2, (c) LC HZ1, (d) LC HZS1 (values higher than yield stress in stress field figures are red coloured)

Presented results point out the following:

- 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;

- In all load cases maximum von Misses stresses are considerably greater than permissible stress values (2.2 times for LC H1; 2.8 times for LC H2; 2.7 times for LC HZ1 and 2.5 times for LC HZS1);
- The reserve of elasticity is also depleted, since MvMS are 1.5, 1.9, 2.0 and 2.1 times greater than yield stress value (σ_{YS} = 345 MPa for steel quality grade S355J0 and plate thickness of 20 mm, [9]) for load cases H1, H2, HZ1 and HZS1 respectively;
- 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.

The high stress state of the designed support structure of portal tie-rods, conjugated with the detrimental effects of the welding seam (not welded through root, porosity, inclusions) perpendicular to the force direction, as presented in [10] and dynamic character of loads, is the principal reason of the end eye connection failure and the BWE collapse.

4. CONCLUSION

The natural tendency towards permanently improving the performance of the BWE, especially their capacities and mobility, as well as harsh deadlines which are always present, have not always been adequately followed by design procedures and manufacturing technologies. This statement is substantiated by various accidents and failures of carrying structures as described and analysed in [11–14]. Digging drives and their vital parts [15–17] and especially travelling mechanisms [18–22] and belonging substructures, are also exposed to failure occurrence in extreme exploitation conditions.

There are four main reasons for the collapse of a high-capacity earthmoving and lifting/conveying machines: 'design-in', 'manufacturing-in', 'operating-in' and 'environment-in' defects [23]. Common denominators to all failures of high performance machines are very high financial losses caused by production delays, which often significantly exceed financial losses caused by direct material damage.

Failures of the two vital undercarriage and superstructure subassemblies of the BWE 1760 caused periodical stoppage and eventually total collapse of the machine. The amount of damage, caused by downtime of the machine, which lasted for more than five years, is very hard to estimate, since besides negative repercussions it had on coal excavation, it also influenced the power production in Serbia.

The 'design-in' faults should not always be detected through forensic engineering, after the occurrence of failure. The amount of these faults should be significantly reduced by reanalysing the largest structures in earth based technology, such as bucket wheel excavators, using newly developed calculation methods such as the finite element analysis.

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