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Failure Analysis of the Tower Crane Counterjib

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Abstract

Failures of the cranes' structural parts unavoidably lead to serious damages or total collapses; these accidents are often followed by very high financial losses and possibly serious injuries or crane-related fatalities. The objective of this research was to identify the causes that led to the failure of the hammerhead tower crane (x1425C) counterjib. The crane is used for assembly works at the hydropower dam. The counterjib collapse resulted from a gusset plate failure and caused such significant damage of the whole crane structure that the crane was dismantled and removed from operation. The study of the accident includes: (1) Identification of the stress-state, where a FEM model is developed to provide a useful tool for studying stress analysis; (2) Laboratory investigations are conducted in order to define the chemical composition and mechanical properties of the material, the tensile properties, hardness, impact toughness, as well as the metallographic analyses. The analysis of the obtained results showed that the principal reasons behind the gusset plate failure originated from design and fabrication faults. The working stress was higher than the allowable one. Also, impact toughness was too low and the fabrication of welds was incorrect.

Keywords: tower crane counterjib collapse; failure analysis; FEA; experimental investigation

1. Introduction

Exploitation of heavy duty and high-capacity lifting/conveying and earthmoving machines such as cranes (tower cranes, container cranes, ship unloaders, gantry cranes, etc.), bucket wheel excavators and stacker/reclaimers under the action of highly pronounced dynamic loads, may lead to failures of their structural parts, substructures and subassemblies - plastic deformations, cracks and fractures. Their failures may cause collapse of the whole structure with catastrophic consequences and are followed, among other things, by a substantial financial loss (millions of €) and serious risks to the worker's safety and life [1-8]. Additionally, exploitation in harsh working conditions provides fertile ground for the occurrence of fatigue cracks, while extreme environmental conditions may also cause disastrous consequences, even when machines are out of operation. Brittle fracture occurrence of vital parts of the structure is also possible in the installation stage of the machine [9]. The above examples confirm that a failure with disastrous consequences is possible at any stage of the product life cycle [1,10]. In addition, they confirm the factual

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existence of four main reasons for the collapse of high-capacity lifting/conveying and earthmoving machines [10]: (1) design faults, the so-called 'designing-in' defects, [10,11], Fig. 1(a); (2) manufacture faults causing the so-called 'manufacturing-in' defects, [10,11], Fig. 1(b); (3) exploitation faults – according to [11], these causes can be named 'operating-in' defects, Fig. 2(a); and (4) extreme environmental impacts – unusual occurrences (extreme storm, earthquake, fire) – according to [11], these causes can be named 'environment-in' defects, Fig. 2(b). Of course, machine failures are often the result of a combination of several different causes [10].

Several different examples of crane failures and accidents, reported in the last decade, can be found in the following references: Failure analysis of mobile harbor crane wheel hub [12]; Failure analysis of a large ball bearing of a dockside crane [13]; Fatigue damage analysis and repair procedure at the large portal crane placed in the shipyard [14]; The catastrophic collapse of the crane on the Milwaukee Brewers baseball stadium retractable roof project (Miller Park) that could be the most awesome lift accident of all time [15]; Failure analysis of container crane boom failure occurred while the boom were being lowered [16]; Investigation of the cause and origin of the collapse of an overhead tower crane at an office building construction site in Bellevue, USA [17].

Tower cranes are used to lift and move load, they often give the best combination of height and lifting capacity and are widely used in construction works, for instance construction of tall buildings, dams, etc. Currently, no one seems to be tracking tower crane accidents worldwide and nobody seems to know the exact number of tower crane accidents, this being primarily because industry sources are not comprehensive and web sites are inconsistent. According to the source [18], there is 30 plus major accidents annually worldwide with around 50 deaths. Also, according to [19] since the year 2000 there have been over 1112 tower crane accidents which have resulted in over 778 deaths and countless injuries. Of course, many accidents are never reported on, so the data can perhaps be doubled. Following the same source, worldwide tower crane accident statistics in the year 2009 gives 176 accidents resulting in 75 deaths, while in the year 2010 we have 112 accidents with 62 deaths [19]! The incident analyses statistics show that a non-negligible number of reasons leading to the accidents remain unknown. Consequently, these accidents caused substantial financial losses. These facts underline the necessity for a thorough analysis of crane failures. Also, making the diverse failure analysis accessible to the public may lead to better understanding of its reasons as well as preventive measures.

This paper will discuss failure analysis of the tower crane that was used during the construction of a hydroelectric power plant. Due to the breakaway of the gusset plate of the counterjib truss structure, Figs. 3 and 4, plastification occurred and the counterjib ballast fell from the crane. This caused the crane's loss of static stability whereupon the jib leaned (at a distance of approximately 29 m from the axis of rotation) onto the structure of the adjacent portal crane. Because of this there was no total overturning of the crane. On the day of the accident the weather was cloudy with moderate wind speed (from 4.3 m/s to 6.2 m/s), while the temperature varied in the range from -4°C to -2°C.

In order to diagnose the cause of the gusset plate fracture, the following had to be done:

- Calculate the working stress state of the gusset plate;
- Chemical composition and mechanical properties testing;
- Microstructure testing.

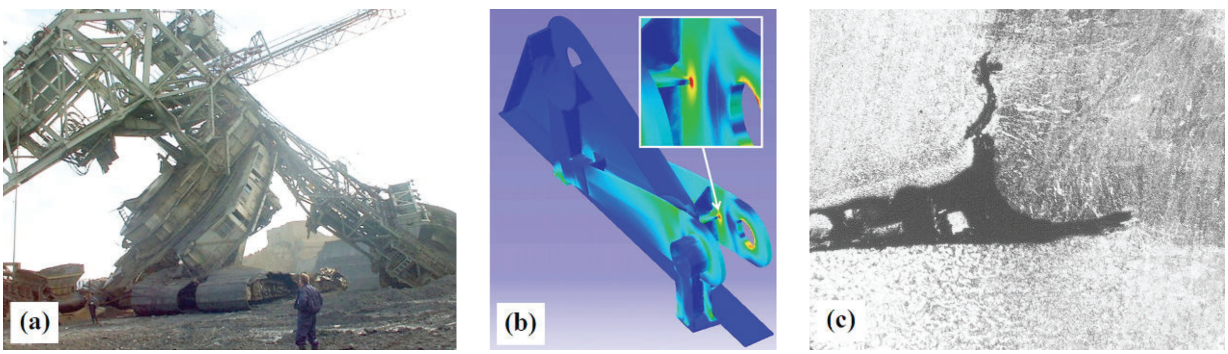

Fig. 1. Collapse of the BWE Sch Rs 1760 caused by the fracture of the end eye connection of the support of the portal tie-rod: (a) BWE after collapse; (b) very pronounced stress concentration in the structure of the portal tie-rod as a result of poor design – the 'designing-in' defect; (c) cracks in the root of the weld joint of end eye and lengthwise plate – the 'manufacturing-in' defect

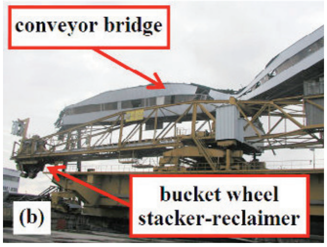

Fig. 2. (a) Overturning of the mobile crane caused by operator mistake i.e. the ‘operating-in’ defect; (b) conveyor bridge fall caused by hurricane i.e. the ‘environment-in’ defect

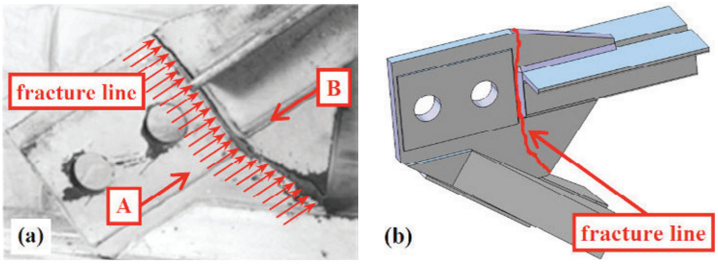

Fig. 3. Fractured gusset plate: (a) after the damage (the parts were assembled in the laboratory of FME); (b) 3D model of the joint fracture

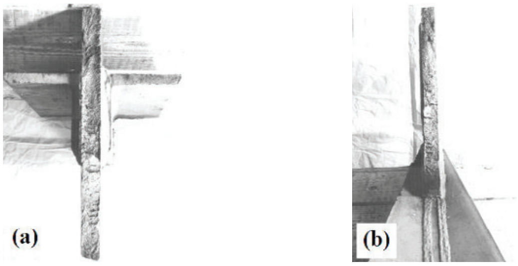

Fig. 4. Gusset plate crack surface (see also Fig. 3(a)): (a) view A; (b) view B

Nomenclature

HB	Brinell hardness
A	Elongation
ρ_3	Impact toughness
σ_{UTS}	Ultimate tensile strength
σ_{YS}	Yield strength

2. Calculation of the working stress state

Identification of the stress state of the portal tie-rod support is done by applying the linear finite element method (FEM). The 3D model of gusset plate is discretized by tetrahedron elements, Fig 5. The analysis of external loads is carried out according to the code DIN 15018. Maximum values of von Misses stresses occur in the zone of hole, Fig. 6. Bearing in mind that in them is dominant the effect of contact forces, it is concluded that they do not compromise the structural integrity. Maximum value of von Misses stress $\sigma_{eq,max}$ = 276 MPa in the HAZ, Fig. 6, are substantially greater than the allowed values 160 MPa) against the code DIN 18800 (03/81).

3. Experimental investigation

3.1. Chemical composition and mechanical properties of the parent metal

The sampling scheme and position of the measuring points is shown in Fig. 7. Based on the results of the chemical composition and mechanical properties investigation, Tables 1 and 2, it is conclusive that the parent metal matches the quality class of the steel S235 according to the code EN 10025. However, it is noticeable that the impact toughness values are lower than the prescribed ones. The values of impact toughness in the fracture zone, in HAZ and beyond, are also very low, Table 3.

Table 1. Chemical composition of the parent metal out of the fracture zone

Element	C	Si	Mn	P	S
Percent	0.16	0.18	0.43	0.018	0.020
Steel quality class S235, EN 10025	max. 0.17	-	max. 1.40	0.045	0.045

Table 2. Mechanical properties of the parent metal out of the fracture zone

Property	σ_{UTS} (Mpa)	σ_{YS} (Mpa)	*A* (%)	*HB* (daN/mm^2)	ρ_3 (J/cm^2)	
					20°C	-4°C
Value	374	280	31.0	106 – 115	14.3; 21.4	1.28
Steel quality class S235, EN 10025	340-470	min. 235	min. 26		min. 27	

Table 3. impact toughness of the parent metal in the fracture zone

Specimen	9 (20°C)	11 (20°C)	6 (20°C)	7 (20°C)	10 (-4°)	12 (-4°)	5 (-4°)	8 (-4°)	15 (20°C)	16 (-4°)
ρ_3 (J/cm^2)	4.0	9.1	11.4	3.7	2.2	1.1	1.3	1.4	14.8	1.2

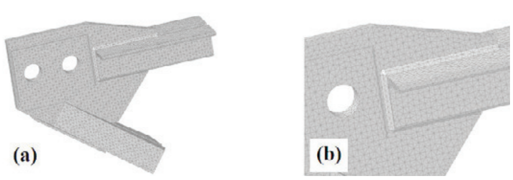

Fig. 5. (a) FE mesh of the model (total number of nodes ???, total number of elements ???; (b) detail of the mesh in the failure zone

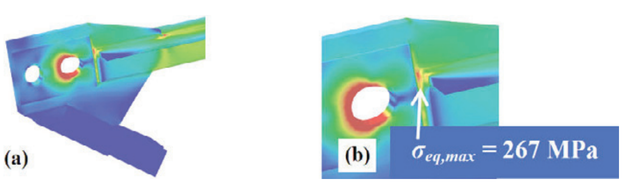

Fig. 6. (a) Distribution of von Misses stresses; (b) detail in the fracture zone

3.2. Microstructure of the material

Out of the fracture zone the parent metal has a ferrite/pearlite microstructure, Fig. 8(a). In the fracture zone, Fig. 8(b), parent metal has a bainite microstructure.

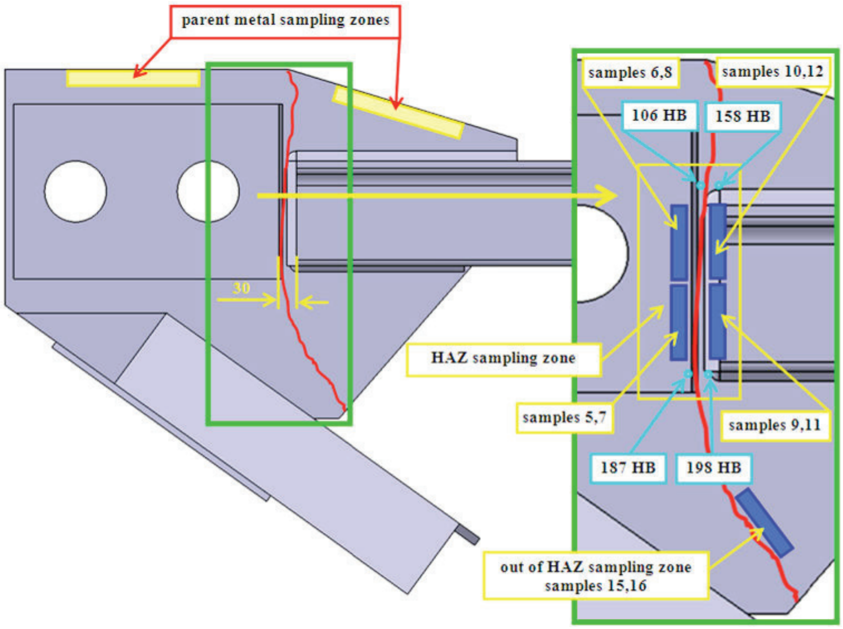

Fig. 7. Sampling locations and position of hardness measuring point

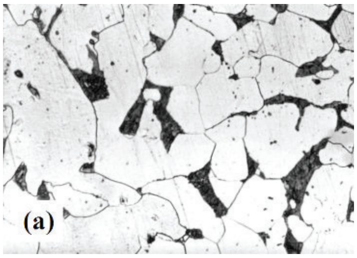

Fig. 8. Microstructure of the parent material: (a) ferrite/pearlite - out of the fracture zone; (b) bainite – at a distance of ≈ 8 mm from the fracture line

4. Conclusion

Based on the presented results it is evident that the fracture of the gusset plate originated from the cumulative influence of the following factors:

- Influence of the parent metal hardening in the fracture zone (transition from a ferrite/pearlite to a bainite microstructure), followed by a jump in hardness (198 HB) and a significant decline in toughness especially in low temperature conditions, as confirmed by the appearance of fracture surfaces (coarse-grain structure, the absence of plastic deformation – brittle fracture), Fig. 4,
- Influence of the weld seam perpendicular to the direction of the force action;
- Influence of the excessive proximity (inadequate clear distance) of the gusset plate welded joint – between profiles of the truss chord and plates to reinforce the opening (designed distance between profiles endings and

plates for reinforcement is 30 mm, Fig. 7) – which is significantly less than a clear distance of five times the plate thickness between welds (in our case the truss chord profile thickness is 15 mm) considered as adequate by Soderberg [16]. Also, the clear distance is even considerably less than three times the plate thickness, recommended in [16] as the minimum value in certain cases.

- Influence of the opening of the gusset plate.

The high stress state of the designed gusset plate, together with the detrimental effects of faults in the execution of the welded joints and the dynamic character of loads, is the principal reason of gusset plate failure and tower crane collapse. Finally, it is conclusive that the presented failure is caused by superimposing designing-in and manufacturing-in defects.

Acknowledgements

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