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# STRUCTURAL INTEGRITY ASSESSMENT OF WELDED BUCKET-WHEEL BOOM
# PROCENA INTEGRITETA KONSTRUKCIJE STRELE ODLAGAČA ROTORNOG BAGERA

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- bucket-wheel boom
- damage
- structural integrity assessment
- repair

**Ključne reči**
- strela odlagača rotornog bagera
- oštećenje
- procena integriteta konstrukcije
- reparacija

*Abstract*

*Research is conducted on the causes of damage and the structural integrity assessment of the bucket-wheel boom welded lattice structures, before and after the repair of vital structures. Additionally, the paper describes the investigation conducted based on the results of non-destructive tests (visual-, magnetic particle-, dye penetrant-, and ultrasonic tests), results of tensometric measurements that refer to the stress-strain state, and results based on numerical calculation of stresses by finite element method, performed through the use of a 3D model in the software Radimpex Tower 6.0®. The results of tests and research performed after the repair of damaged structural welded sections show that the integrity of the lattice structure of the bucket-wheel boom is not in danger when being properly handled and when the operational procedures are being obeyed.*

*Izvod*

*Obavljena istraživanja obuhvataju uzroke oštećenja i procenu integriteta zavarene rešetkaste konstrukcije strele odlagača rotornog bagera, pre i posle reparacije vitalnih delova konstrukcije. Osim toga, u radu je predstavljeno istraživanje obavljeno na osnovu rezultata ispitivanja bez razaranja (vizuelno, magnetnim česticama, penetrantima i ultrazvučno ispitivanje), zatim na osnovu rezultata tenzometrijskih merenja stanja napon-deformacija, kao i na bazi rezultata numeričkog proračuna napona metodom konačnih elemenata, izvedenog primenom 3D modela u softveru Radimpex Tower 6.0®. Rezultati ispitivanja, kao i istraživanja izvedena posle reparacije oštećenih delova zavarene rešetkaste konstrukcije pokazuju da nema opasnosti za integritet rešetkaste konstrukcije strele rotornog bagera, ako se pravilno rukuje i ako se poštuju postupci u radnim uslovima.*

## INTRODUCTION

There are 2 bucket-wheel excavators at the coal landfill of thermal power plant 'Nikola Tesla A' in Obrenovac (Serbia), DU1 and DU2, produced in France /1/. These bucket-wheel excavators move along the circular track (widely known as polar track). Non-destructive tests (visual-, magnetic particle-, dye penetrant-, and ultrasonic tests) and tensometric measurements of strains are performed in order to analyse causes of the occurrence of damage on welded sections of the bucket-wheel boom of excavator DU1 and evaluate its integrity after the execution of repairs.

Taking into account the long period of operation under severe working conditions (dynamic loading with changeable amplitudes), and the fact that during their design there were practically no possibilities to carry out detailed stress-strain analysis, the highly loaded elements and their joints had to be checked discretely or continuously /2-11/. This especially refers to welded joints and welded structures, /2, 3, 6, 7/.

The quality of welded joints and the integrity of welded structures depend on a large number of technological and metallurgical factors (form of welded joint, stress concentration, heterogeneity of structural and mechanical properties of parent material, heat-affected zone and weld metal, residual stresses and strains that occur due to welding and the existence of defects within welded joints), while the integrity of welded structures, apart from technological and metallurgical factors, also depends on structural and exploitational factors.

The paper contains the methodological approach to the analysis of causes of damage at vital components of welded lattice structures that are sections of the bucket-wheel boom, and the evaluation of its integrity after repair. Taking into account that the user of the excavator does not possess the project and technical documentation, all tests and research presented here are conducted under the assumption that welded lattice structures are made of structural steels of the type S355 and S235.

## DAMAGE AT VITAL SECTIONS OF THE WELDED BUCKET-WHEEL BOOM

The presented damage is detected mainly through visual testing (VT) of parent material and welded joints. No other defects are detected through the use of other non-destructive testing methods, and no deviations from expected results had occurred during hardness tests. Locations of repaired welded joints are shown in Fig. 1. Sections of the vital structure in the upper zone of the bucket-wheel boom where defects were detected after repair are presented in Fig. 2.

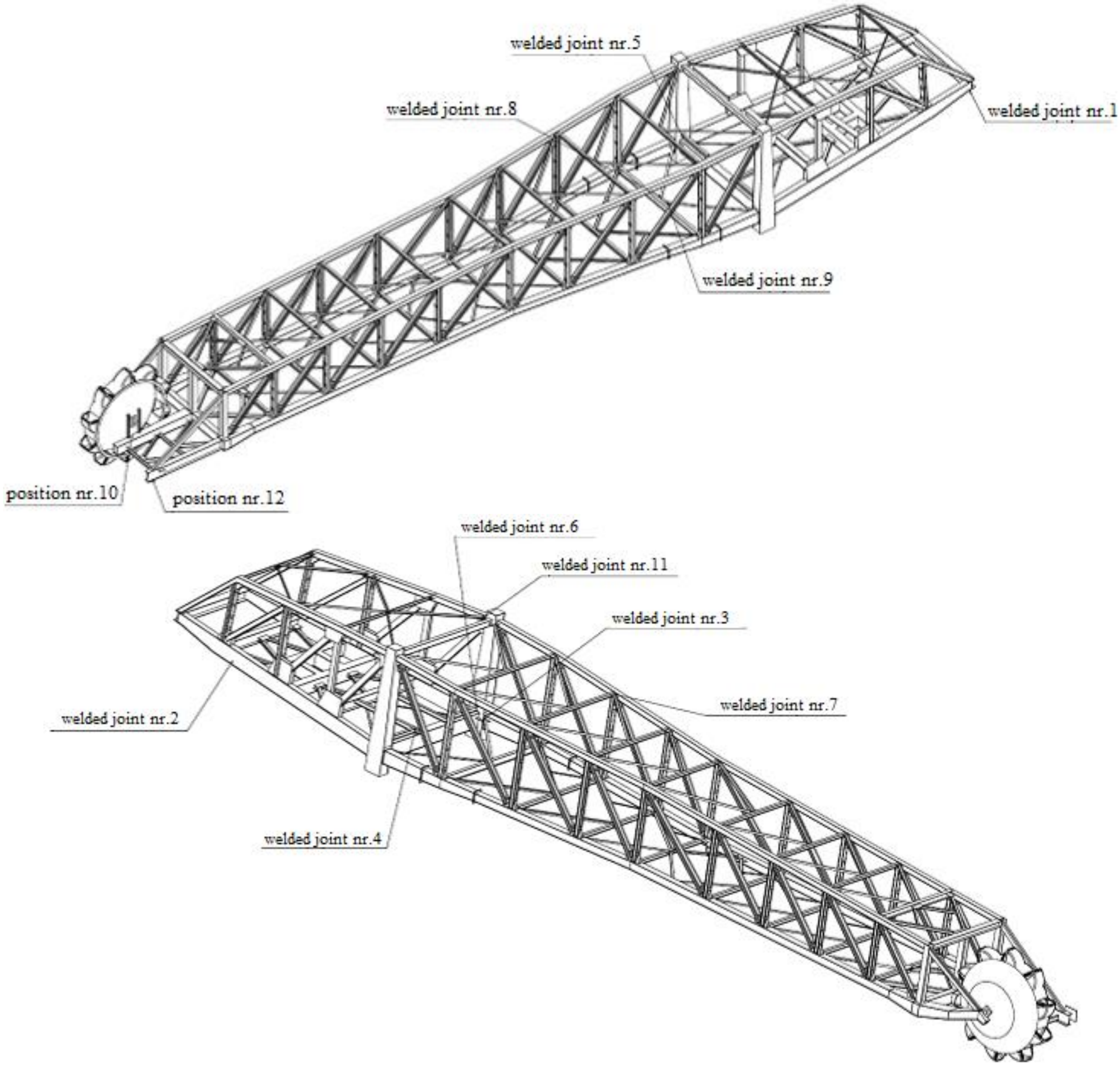



Figure 1. Locations of repaired welded joints.

Figure 2. Sections on vital structure of bucket-wheel boom.

## REPAIR OF VITAL WELDED STRUCTURES OF THE BUCKET-WHEEL BOOM

The repair of vital welded structures of the bucket-wheel excavator, designated DU1, is performed by fillet and butt welding of sheets and profiles of structural steel, executed by repairing damaged sections and/or embedding reinforcements, while applying previously defined welding technology, /12/.

Taking into account the fact that user of the equipment does not possess design and technical documentation, the welding technology is defined for structural steels S355 and S235, mostly being used for manufacturing steel structures on bucket-wheel excavators.

Chemical composition and tensile properties of structural steels S235 and S355 are presented in Tables 1 and 2, respectively.

Table 1. Chemical composition of steels S 235 and S 355, /13/.

| Steel | C | Si | Mn | P | S | N |
|---|---|---|---|---|---|---|
| S 235 | ≤ 0.19 | - | ≤ 1.50 | ≤ 0.045 | ≤ 0.045 | ≤ 0.009 |
| S 355 | ≤ 0.23 | ≤ 0.60 | ≤ 1.70 | ≤ 0.045 | ≤ 0.045 | ≤ 0.009 |

Table 2. Mechanical properties of steels S 235 and S 355, /13/.

| Steel | Yield stress, YS [N/mm$^2$] | Tensile strength, TS [N/mm$^2$] | Elongation, $A_5$ [%] |
|---|---|---|---|
| S 235 | 240 | 370-450 | 25 |
| S 355 | 355 | 520-620 | 22 |

*Weldability of parent material*

According to the IIW equation for chemical composition of sheets and profiles presented in Table 1, $C_{eq}$ is lower than 0.40, which indicates that their weldability is good:

- for chemical composition of profile materials presented in Table 5 and taking into account the most unfavourable content of hydrogen in weld metal of H = 6 ml/100 g, it can be concluded that no preheating is necessary;
- maximum hardness in the heat-affected zone for presented chemical compositions should not be over 350 HV, the upper limit for material not to be prone to cold cracking;
- critical cooling rate at which purely martensitic structure, which may cause the occurrence of cold cracks, is created in the heat-affected zone, should be lower than 32 °C/s. So, it is not necessary to predict lower cooling rates;
- if tensile strength of profile and sheet steels is lower than 700 MPa, there is no possibility of the occurrence of hot cracks.

*Selection of the welding process and filler material*

As the most suitable, the welding process 111 is used. Due to limited possibilities of the execution of preheating and post weld heat treatment, the optimum solution is to use electrodes with basic coating.

Surface cracks in parent material are eliminated by fine grinding, while in vital welded joint areas, surface welding is carried out after the elimination of cracks by using EVB 50 electrodes (Electrodes Jesenice, Slovenia), /14/. The chemical composition of pure weld metal is defined in Table 3, while the mechanical properties are presented in Table 4.

Table 3. Chemical composition, values in [%].

| Electrode | C | Si | Mn |
|---|---|---|---|
| EVB 50 | 0.08 | 0.60 | 1.0 |

Table 4. Mechanical properties of pure weld metal.

| Electrode | Yield stress [N/mm$^2$] | Tensile strength TS [N/mm$^2$] | Elongation $A_5$ [%] | Impact energy $KV_{300/2}$ [J/cm$^2$] |
|---|---|---|---|---|
| EVB 50 | > 440 | 510 – 610 | > 24 | 47 (-20 °C) |

## STRESS STATE OF BUCKET-WHEEL BOOM VITAL STRUCTURES

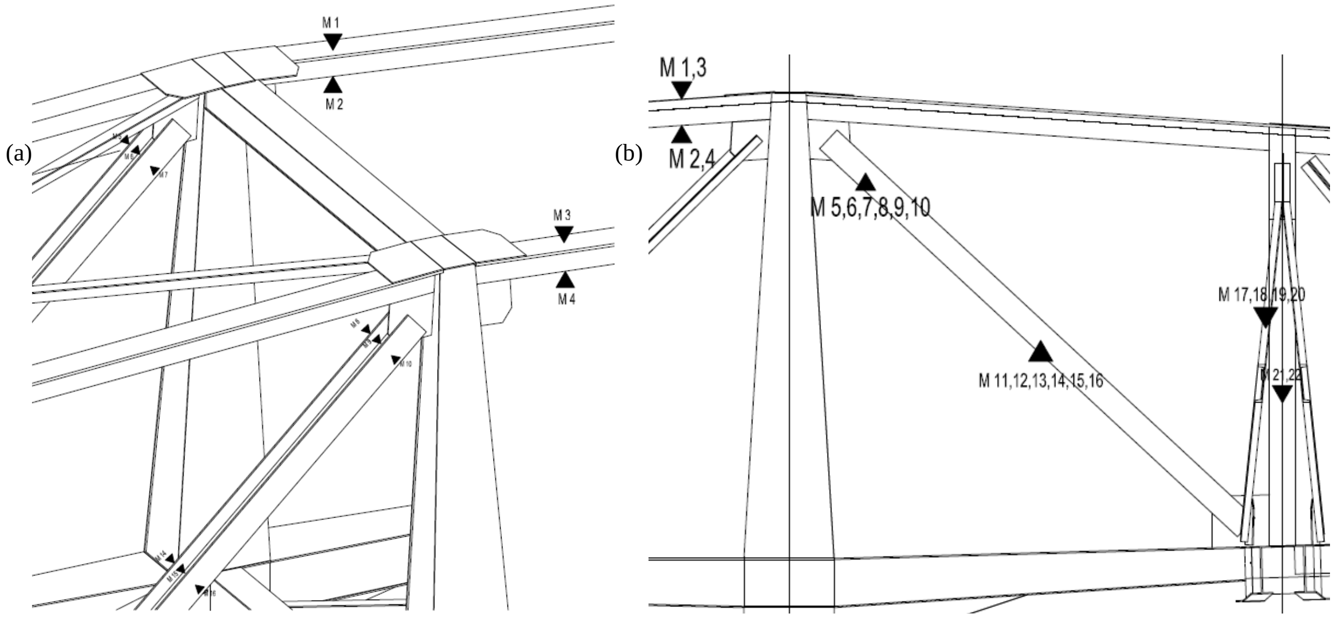
The stress state of bucket-wheel boom vital structures is determined by finite element numerical calculation of stresses, performed through the use of a 3D model in software Radimpex Tower 6.0®, and based on tensometric measurements of local deformations through the application of strain gauges.

*Numerical calculation of stresses of bucket-wheel boom vital structures*

Numerical calculation of stresses in vital structures of the bucket-wheel boom is carried out by the finite element method performed through the use of a 3D model in Radimpex Tower 6.0, which is a professional software for static and dynamic calculations, as well as for dimensioning all types of steel, concrete, and wooden structures. Maximal stress values calculated through Radimpex Tower 6.0 are presented in Tables 5 and 6.

*Tensometric measurements and calculation of stresses in bucket-wheel boom vital structure*

Measurement areas and locations on the vital lattice structure of bucket-wheel boom, as an integral part of excavator DU1 are presented in Figs. 3-4. Stress results as calculated based on measured strains are presented in Tables 5-7.



(c)

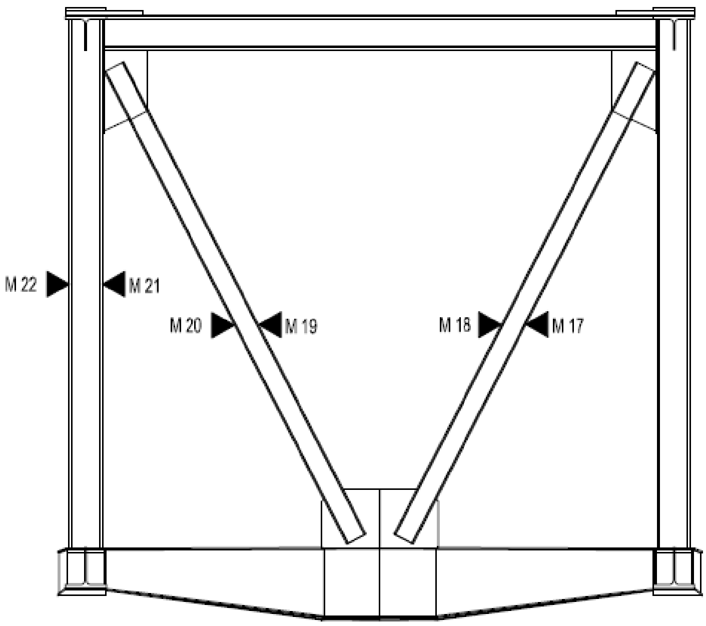



Figure 3. Measurement locations on the bucket-wheel boom shown in three different cross sections.

Table 5. Measured and calculated stresses in the vital structure of the bucket-wheel boom (Fig. 3a).

| Loads on the bucket-wheel excavator DU1 | Measurement locations at cross-section 0 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $M_1$ | $M_2$ | $M_3$ | $M_4$ | $M_5$ | $M_6$ | $M_7$ | $M_8$ |
| Measured stress for boom position at 0°, MPa | - | - | 15.2 | 16.0 | 32.8 | 32.4 | 31.2 | 31.2 |
| Numerical stress for boom position at 0°, MPa | - | - | 20.6 | 20.6 | 29 | 29 | 29 | 27.5 |
| Measured stress for boom position at 12°30', MPa | - | - | 28 | 19.0 | 21.2 | 22 | 19.2 | 17.2 |
| Numerical stress for boom position at 12°30', MPa | | | 20.4 | 20.4 | 28.7 | 28.7 | 28.7 | 27.3 |
| Maximum stress for boom position at 0°, MPa | 32.8 | | | | | | | |
| Maximum stress for boom position at 12°30', MPa | 28.7 | | | | | | | |

Table 6. Measured and calculated stresses in the vital structure of the bucket-wheel boom (Fig. 3b).

| Loads on the bucket-wheel excavator DU1 | Measurement locations at cross-section 0 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $M_9$ | $M_{10}$ | $M_{11}$ | $M_{12}$ | $M_{13}$ | $M_{14}$ | $M_{15}$ | $M_{16}$ |
| Measured stress for boom position at 0°, MPa | 32.8 | 27.6 | 31.2 | 30.8 | 28.4 | 27.2 | 30.0 | 29.6 |
| Numerical stress for boom position at 0°, MPa | 27.5 | 27.8 | 29.0 | 29.0 | 29.0 | 27.5 | 27.5 | 27.5 |
| Measured stress for boom position at 12°30', MPa | 20.4 | 18.0 | 20.0 | 19.2 | 18.0 | 19.2 | 16.8 | 16.4 |
| Numerical stress for boom position at 12°30', MPa | 27.3 | 27.3 | 28.7 | 28.7 | 28.7 | 27.3 | 27.3 | 27.3 |
| Maximum stress for boom position at 0°, MPa | 32.8 | | | | | | | |
| Maximum stress for boom position at 12°30', MPa | 20.4 | | | | | | | |

Table 7. Measured and calculated stresses in the vital structure of the bucket-wheel boom (Fig. 3c).

| Loads at the bucket-wheel excavator DU1 | Measurement locations at cross-section 11 | | | | | |
|---|---|---|---|---|---|---|
| | $M_{17}$ | $M_{18}$ | $M_{19}$ | $M_{20}$ | $M_{21}$ | $M_{22}$ |
| Measured stress for boom position at 0°, MPa | 41.2 | 44.4 | 44.4 | 41.2 | 20.4 | 20.4 |
| Numerical stress for boom position at 0°, MPa | 36.4 | 36.4 | 38.6 | 38.6 | 44.0 | 44.0 |
| Measured stress for boom position at 12°30', MPa | 31.2 | 31.2 | 30.0 | 30.4 | 12.0 | 12.4 |
| Numerical stress for boom position at 12°30', MPa | 36.0 | 36.0 | 38.3 | 38.3 | 44.0 | 44.0 |
| Maximum stress for boom position at 0°, MPa | 44.4 | | | | | |
| Maximum stress for boom position at 12°30', MPa | 30.4 | | | | | |

## INTEGRITY ASSESSMENT OF BUCKET-WHEEL BOOM VITAL SECTIONS

Regarding the analysis of damages that occurred at vital sections of welded lattice structures in the bucket-wheel boom, the technical diagnostics should be based on predetermined procedures which refer to non-destructive testing, history of their application taking into account expert knowledge that relates to similar structures and conditions of exploitation of bucket-wheel excavators.

Structural integrity a relatively recent scientific and engineering discipline which in a broader sense comprises the state analysis and technical diagnostics that refers to structural behaviour, revitalization of structures and service life evaluation. Apart from the usual procedure for structural integrity assessment, when defects are detected through application of non-destructive tests, this discipline also comprises the stress state analysis in the defectless structure. This procedure enables plotting of stress-strain states, which helps identification of weak spots in analysed components of supporting structures, even before defects occur.

Bases on the results of executed non-destructive tests; numerical calculation and stress state determination through tensometric measurements before and after repair of vital sections of welded structures of the bucket-wheel boom where damages had occurred, it was determined that the integrity of the bucket-wheel boom is not compromised if there are no cracks and other defects within welded joints, as well as when bucket-wheel excavators are properly handled and work procedures are respected. However, the bucket-wheel boom is compromised when excessive loading occurs due to improper manipulation by the operator of the bucket-wheel excavator, or from the influence of extremely strong winds.

Significant presence of defects is caused by a complex geometry, due to the fact that those areas are nodal spots that are principally critical in lattice structures, Fig. 4.

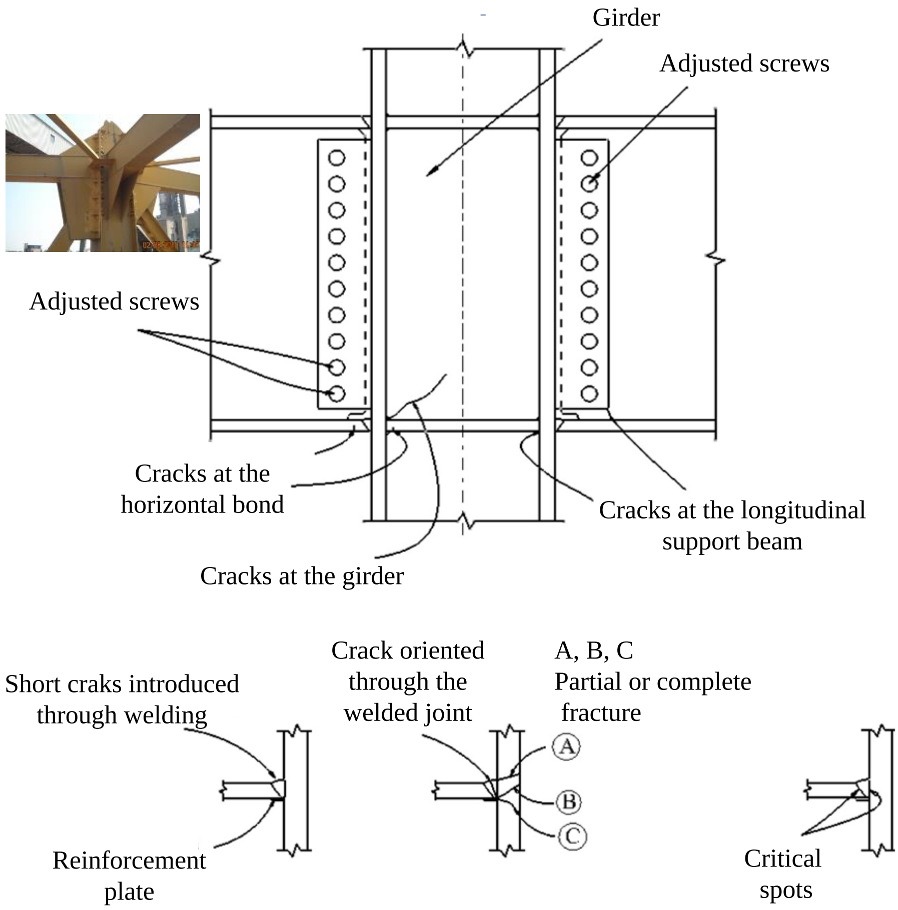



Figure 4. Locations of welded joints in which fatigue cracks mainly occur, /15/.

## CONCLUSIONS

Since the maximum measured working stress (44.4 MPa) is much smaller than the stress that would cause any damage in the bucket wheel boom, including welded joints, one can conclude that the detected damage occurred as a result of manufacturing defects.

Presented results emphasize the importance of execution of non-destructive tests on welded joints of vital structural sections not only during the manufacture, but also during exploitation.

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