Study of Counterweight Addition to Improve Structural Stability of Ship Unloader at Pulang Pisau CFPP

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Abstract. The ship unloader at Pulang Pisau CFPP is a crane type machine that is used to transport coal from barges to stockpile. This machine uses slewing bearing as component that support for slewing movement to transport coal from the barge to the belt conveyor. Meanwhile this machine also has boom that moves up and down to lift the coal towards to the hopper provided. Several times the slewing bearing was damage with the failure mode is lifted up the inner race bearing and causing the roller inside damaged. Investigation and testing are carried out to find out the strength of the structure and what are the forces that acted. From the results of the investigation and testing, it was found that the ship unloader suffered excessive moment in the front side (boom side), thus making the bearing was frequently damaged. And the limitation about lifting angle of boom is considered. This study tries to find the balance of forces, moments, and lifting angle, and then to add a counterweight that are sufficient to reduce the impact of the unbalance moment with limitation of boom lifting angle. With the addition of counterweight and limitation angle of boom make the moments are more stable to the structure, and so the lifetime of slewing bearing is longer.

1. Introduction

The coal transportation system at Pulang Pisau CFPP is divided into two lines, they are the unloading and loading lines. Unloading line is the transportation of coal from the barge to the coalyard. While the loading system is the transportation of coal from the coalyard to the bunker or direct from the barge to the bunker. Reliability of the coal transportation system is very necessary because ensuring the continuity of coal supply. As shown in Figure 1. The type of SU (ship unloader) in Pulang Pisau CFPP is a type of fixed crane, HGQ1025 type and made in China. The crane is a lifting device that remain in a fixed position to lift coal from barge to belt conveyor system toward to stockpile. This crane is supported with slewing bearing to move in slewing movement. Slewing bearings are large sized rotary elements used in applications in which large rotational functional elements are involved, such as boring machines, tower cranes, wind turbine generators, etc. There are many different types of slewing bearings depending on the number of rows and on the type of rolling elements. Thus, there are bearings with one, two or three rows, whereas the rolling elements can be balls or rollers [1].
Table 1. Main technical data

| Parameter                                      | Details                                      |
|------------------------------------------------|----------------------------------------------|
| Hoisting capacity                              | 10t (grab)                                  |
| Work range                                     | 25m/8m                                      |
| Hoisting height                                | 20m/12m                                     |
| Working speed of mechanism                     | Lifting mechanism: 60m/min                  |
|                                                | Luffing mechanism: 52m/min                  |
|                                                | Rotary mechanism: 1.6r/min                  |
| Working grade of the mechanism or electric     | Lifting mechanism: M8                       |
| machine                                        | Luffing mechanism: M7                       |
|                                                | Rotary mechanism: M7                        |
|                                                | Complete mechanism: A8                     |
| Wind speed                                     | Max. working wind speed: 20m/s              |
|                                                | Non-working max. wind speed: 55m/s          |
| Max. turning radius of tail                    | 6.5m                                        |
| The max. height of the whole machine           | 36.4m                                       |
| Slewing bearing                                | 131.45 2500                                 |
| Hoisting wire rope                             | 28NAT18x7SW-FC1670-ZS/SZ                    |
| Power supply                                   | AC380V 50Hz                                 |
| Crane weight                                   | ≥ 158t                                      |

Figure 1. (a) Ship Unloader, (b) Ship unloader drawing

Figure 2. Type failure of SU (a) broken pinion gear, (b) base plate lifted, (c) worn pinion gear, (d) inner race of slewing bearing lifted, (e) crack on frame structure

The frequently problems of SU are heavy slewing movement, crack on structure, broken rotary bolt, broken pinion gear, and finally slewing bearing is damaged. It needs long time to replace with new bearing about 20 days. It affected the coal inventory in critical level for operation and then decided to derate of operation. Therefore, it needs to do more investigation to find root cause of this failure. Especially about forces and moments balance, and strength of materials to solve the problem.

2. Data and method

In order to understand the root cause of the failure, some investigations and tests conducted to obtain data for analyze the root cause.
2.1. Visual Check.
This check conducted to understand the equipment actual conditions by directly seen the damages that occur in ship unloader. This check scopes include pinion gear, slewing bearing, baseplate bolt, bearing housing and others. Figure 3 shows the specification of slewing gear bearing, with outer diameter size 7100 mm and inside innering size 5960 mm.

![Figure 3. (a) slewing bearing (b) Outer gear](image)

2.2. Hammer test.
This test carried out to get the strength of concrete. The tool used was type Smitch hammer test. Data was obtained from 40 points. The final values of concrete quality are as follows: $f_c$ unit 2 = 30 MPa, and 30 Mpa value will be used as a reference.

2.3. Bolt and Base plate Checking.
Checks carried out by using a measuring tool, fuller gauge and others, which aims to determines how large deviations that occurred. Figure 2 (b) shows measurement point at baseplate.

2.4. Dimensional Checking.
Re-measurements are carried out to ensure actual dimension of concrete as same as in drawing design document. It found that there was difference with both dimensional.

Drawing documents = 4 x 4 x 1.5 meters
Actual measurement = 3.9 x 3.8 x 1.5 meters

2.5. Load calculation.
Calculations are carried out to determine the loads that work on the ship unloader. To calculate the moment of force that works using the formula as follows [6]:

$$M = F \times L \times \cos \Theta$$  

(1)

Where: $M$ = Moment (KNm)
$L$ = arm length of boom (m)
$F$ = Force of boom (KN)
$\Theta$ = angle of boom

Moment is the ability of a force to cause a rotation, amount of moment at a point equal to the product of multiplied force and arm length. A construction is good if the construction is stable, and the forces and moments that work in the vertical and horizontal direction eliminate each other or equal to zero. To calculate the equilibrium force and moments, equation used is [6]:

$$\Sigma M = M - F_y \frac{L}{2} + F_h \frac{d}{2} = 0$$  

(2)
Where: \( \Sigma M \) = sigma moments  
\( F_y \) = vertical force of counterweight (KN)  
\( F_h \) = horizontal force of wind (KN)  
\( d \) = height of cabin support (m)  
\( L \) = length of counterweight from center that is needed (m)

| Data                     | Support                  | Calculated vertical forces | Calculated moment | Wind moment | Bucket Moment with varying boom angle |
|--------------------------|--------------------------|----------------------------|-------------------|-------------|--------------------------------------|
| support height (m)       | 1.87 Number Section      | 1 Arm Length (m)           | 25.85             | 100         | 40 2648.57                           |
| support width (m)        | 2.2 Weight Per Section (KN) | 12.03 Arm Weight Per m² (KN/m) | 3.20             | 1.2         | 45 2493.17                           |
| foundation support length (m) | 4 Cat Head + Cabin (KN) | 39 Length of CW (m) | 4.64             | 0.3         | 50 2323.58                           |
| Foundation support depth (m) | 1.5 Jib Section | 357.73 Arm Weight of CW (KN) | 0 Section Width (m) | 2.2         | 55 2141.09                           |
| foundation support width (m) | 4 Counterweight (KN) | 95 CW (KN) | 95 Width of wind plane (m) | 3.11         | 60 1947.09                           |
| concrete strength (MPa)  | 30 Mass Section (KN)     | 156.56 Max Loading (m)     | 0 Support height (m) | 1.87         | 65 1743.06                           |
| Steel strength (Mpa)     | 400 Max Loading (KN)     | 70 Max length of load (m)  | 25.85             | 1.12        | 70 1530.55                           |
| Modulus of Elasticity for steel (MPa) | 200000 Total (KN) | 718.29 Moment in normal loading (KN) | 628.7437 Moment (KNm) | 1.95836 |                                  |
| Estimated Plugin (KN)    | 576 Moment in max loading (KN) | 628.7437 Horizontal force (KN) | 2.09             |             | 630.7                               |
|                          |                          |                            |                   |             |                                      |

From thus if \( L \) is lower than length of arm that provided, it is accepted. And if \( L \) exceed than provided, it is not accepted. Provided Length of arm counterweight is 4 m.

The provided drawing is:

![Drawing Image]
Figure 4. Design drawing

And then calculate shear strength of concrete [6]:

\[ \Phi V_c = (1 + \frac{1}{\beta_c}) \frac{1}{6} \sqrt{f'_c} b_o d \] (3)

Where:
- \( \beta_c \) = effective width of concrete surface (mm)
- \( b_o \) = area ratio reinforcement
- \( d, h_k, b_k \) = diameter concrete reinforcement (mm)

\[ \beta_c = \frac{1}{1.5} \]
\[ b_o = 2(h_k+d)+(b_k+d) \]
\[ d = 2.2 \text{ m} \]
\[ f'_c = \text{concrete tensile strength (N/mm}^2\text{)} \]
\[ \Phi V_c = \text{Concrete shear strength (N)} \]
\[ \Phi V_c = 30 \text{ N/mm}^2 \]
\[ \Phi V_c = 40531.47 \text{ KN} \]

From thus if total vertical forces is lower than \( \Phi V_c \), it is accepted. And if total vertical forces exceed than \( \Phi V_c \), it is not accepted.

In this calculation an evaluation with empty buckets, full coal on bucket, with and without counterweight, as shown in Figure16, are available. Bucket weight is 32 KN, coal on bucket is 70 KN and counterweight is 90 KN and evaluated on 7 angles as described in Table 3 below.

**Table 3. Calculation result for variation angle of boom, empty and full coal on bucket, and with and without counterweight**

| No | Angle of boom arm | Without Counterweight and empty bucket | Without counterweight and full coal on bucket | With counterweight and empty bucket | With counterweight and full coal on bucket |
|----|------------------|----------------------------------------|---------------------------------------------|-----------------------------------|------------------------------------------|
|    | moments Shear forces | Shear forces | moments Shear forces | Shear forces | moments Shear forces | Shear forces |
| 1  | 40   | Accepted | Not Accepted | Accepted | Accepted | Accepted | Not Accepted |
| 2  | 45   | Accepted | Not Accepted | Accepted | Accepted | Accepted | Accepted |
| 3  | 50   | Accepted | Not Accepted | Accepted | Accepted | Accepted | Accepted |
| 4  | 55   | Accepted | Not Accepted | Accepted | Accepted | Accepted | Accepted |
| 5  | 60   | Accepted | Accepted | Accepted | Accepted | Accepted | Accepted |
| 6  | 65   | Accepted | Accepted | Accepted | Accepted | Accepted | Accepted |
| 7  | 70   | Accepted | Accepted | Accepted | Accepted | Accepted | Accepted |

The evaluation results that it is not accepted when operational is at an angle of <60 degrees, while the structure is without counterweight and full coal on bucket. It caused crane to be unbalanced moment and will lift inner race of slewing bearing because crane will fall forward. The process will cause a pull in the pilecap section and is characterized by a reduced bolt tightness and the lifting of the base plate.

2.6 Finite Element Method

After from force and moment balance has been evaluated, then the strength of the structural material is calculated whether it is able to accept existing loads and also new loads due to the
addition of counterweight. The finite element model used refers to conditions in the field. The profile used is the same as the profile used on the element. Because the model is symmetrical, half of the tower crane construction is used as a reference. The reference welding stress values used are in the Figure 5 below. This stress-strain curve has yield stress point at 390 Mpa for welding. Meanwhile, the steel element has $f_y = 240$ MPa (low yield steel).

| No | Shear (%) | Stress (MPa) |
|----|-----------|--------------|
| 1  | 0,00      | 0,00         |
| 2  | 0,20      | 390,00       |
| 3  | 3,12      | 390,00       |
| 4  | 4,87      | 520,12       |
| 5  | 6,62      | 579,60       |
| 6  | 8,37      | 611,66       |
| 7  | 10,12     | 630,23       |
| 8  | 11,87     | 641,16       |
| 9  | 13,62     | 647,37       |
| 10 | 15,37     | 650,43       |
| 11 | 17,12     | 651,30       |

Figure 5. (a) strain and stress of welding (b) stress-strain curve for multilinear steel

2.7 Finite element model

The finite element model used is as shown in the figure 6 below.

Figure 6. (a) finite element model (b) crane structure (c) variation of structure profile
Detail profile that are used, shown at Figure 6 above. Welded profiles are made with C profiles and form hollow profiles. The weld used is E6xx with 6 mm thickness. The model is tested with load at the centered point of force that acted on the crane and the counterweight. Loads on the frame structure can be seen in Figure 6 (a) and (b) for models without counterweight and with counterweight respectively.

![Figure 6](image)

**Figure 7.** (a) model without counterweight (b) model with counterweight

As shown in Figure 7, P1 is a centered load that press towards the crane frame due to the load acting on the crane arm. T1 and T2 are centered loads that pull on it. P2 is a centered load that works as a counterweight.

![Table 4](table)

**Table 4.** Details of the model to be analyzed

| No | Code | Profile | Angle (°) | Counterweight |
|----|------|---------|-----------|---------------|
| 1  | 30TC | U welded | 30        | N             |
| 2  | 50TC | U welded | 50        | N             |
| 3  | 70TC | U welded | 70        | N             |
| 4  | 30C  | U welded | 30        | Y             |
| 5  | 50C  | U welded | 50        | Y             |
| 6  | 70C  | U welded | 70        | Y             |

Refer to table 4 the variation of load used at each angle is according to the moment equilibrium report and for the rear counterweight taken with 9 tons.

3. Result and discussion

**Figure 8** refers to location of the stress concentration that occurs in steel elements for 30TC, 50TC, 70TC models with a stress of 284.56 MPa, 240 Mpa and <240 Mpa respectively. Location of the strain concentration on the steel element is the same as the stress concentration location. The maximum strain value is 0.002819, 0.01013 and 0.0035 respectively. Meanwhile figure 8 for the welding element can be seen the location of the stress concentration which occurs in the welding element with a stress of 479.86 MPa, 457.88 Mpa, and < 400 Mpa respectively. which indicates that the welding element has exceed the yield point and the strain is 0.0158 mm, 0.0049 mm respectively. So from Figure 8, 9 and 10, the conclusion is the 70TC model has stress and strain that are still within the safe range.
Figure 8. Welded profile contour stress without counterweight and angle of boom (a) 30TC model (30°) (b) 50TC model (50°) (c) 70TC model (70°).

Figure 9. Welded profile contour strain without counterweight and angle of boom (a) 30TC model (30°) (b) 50TC model (50°)
Figure 10. Stress-strain curve at welded profile (a) 30TC model (30°) (b) 50TC model (50°) (c) 70TC model (70°).

Figure 11. Stress-strain condition at welded joint (a) 30TC model (30°) (b) 50TC model (50°) (c) 70TC model (70°).

Figure 12 refers to location of the stress concentration that occurs in steel elements for 30C, 50C, 70C models with a stress of 284.03 MPa, < 240 Mpa and <240 Mpa respectively. Location of the strain concentration on the steel element is the same as the stress concentration location. The maximum strain value is 0.02778, 0.00988, and 0.0027 respectively.
Figure 12. Welded profile contour stress without counterweight and angle of boom (a) 30C model (30°) (b) 50C model (50°) (c) 70C model (70°).

Meanwhile Figure 13 for the welding element for 30C, 50C and 70C models can be seen the location of the stress concentration which occurs in the welding element with a stress of 457.88 MPa, 457.47 MPa and 251.32 MPa respectively. which indicates that the welding element has passed the yield point and the strain is 0.00486 mm, 0.00466 mm and 0.00126 respectively. So from Figure 13, 14 and 15, the conclusion is that the 70C model has stress and strain that are still within the safe range.

Figure 13. Welded profile contour strain counterweight and angle of boom (a) 30C model (30°) (b) 50C model (50°)
4. Conclusion

Based on evaluation of force and moment equilibrium, it can be concluded that the addition of counterweights make operation more in wider range. It is safe to operate from the previous angle of the boom arm ≥ 60° to the angle of the boom arm ≥ 45°, furthermore after evaluating the material strength of the frame structure with finite element method (FEM) obtained that operation is safe with range at the boom arm angle ≥ 70° according to Table 5. While considering with forces equilibrium and strength of structure will give solution to the next action that if the machine needs operate with wide range of boom angle ≥ 45° than the crane should be strengthened with stiffner so that it can withstand the stress. This is because the crane need to operate with wider range of boom angle to reach coal at long distance especially in the corner of barge area.

Figure 14. Stress-strain curve at welded profile (a) 30 model (30°) (b) 50 model (50°) (c) 70 model (70°)

Figure 15. Stress-strain curve at welded profile (a) 30 model (30°) (b) 50 model (50°) (c) 70 model (70°)

Figure 16. with counterweight addition (a) Drawing, (b) Actual condition, (c) Angle of boom arm
Table 5. simulation result with ANSYS for models

| No | Model | Profil Stress (MPa) | Limit of Profil Stress (Mpa) | Condition | Welding Stress (Mpa) | Limit of Welding Stress (Mpa) | Condition | Note |
|----|-------|---------------------|-----------------------------|-----------|---------------------|-----------------------------|-----------|------|
| 1  | 30TC  | 284                 | 240                         | Not Good  | 479                 | 450                         | Not Good  | Broken on welding and profil |
| 2  | 30C   | 284                 | 240                         | Not Good  | 480                 | 450                         | Not Good  | Broken on welding and profil |
| 3  | 50TC  | 240                 | 240                         | Good      | 457                 | 450                         | Not Good  | Plastic displacement on welding |
| 4  | 50C   | 240                 | 240                         | Good      | 457                 | 450                         | Not Good  | Plastic displacement on welding |
| 5  | 70TC  | < 240               | 240                         | Good      | 254                 | 450                         | Good      | Good |
| 6  | 70C   | < 240               | 240                         | Good      | 254                 | 450                         | Good      | Good |

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