Construction Hoist

Shaft Failure Analysis

Technical Safety BC

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1. Objective and Executive Summary

There was an incident where a drive shaft on a rack and pinion hoist failed. The particular rack and pinion construction hoist that failed is driven via the use of three (3) pinion driving gears (Appendix A: Figure 1). The lowest of the three pinion gears failed during operation of the hoist and as such, a new gear pinion was installed in its place. After roughly 15 days of operation the splined shaft that connects the bottom gear to the driving motor failed by fatigue failure (Appendix B: Acuren report). The purpose of this report is to consider possible causes leading to the fatigue failure in the splined shaft, and to make recommendations for the prevention of a similar occurrence in the future.

Prepared by: ______________________________

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Apex Elevator Consulting Inc. Permit to Practice Number:1001069

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2. Hypothesis

The replacement of a single gear on a construction hoist with three driving motors (without replacing the other two driving gears) can result in the new gear taking a disproportionate amount of the load, resulting in fatigue failure of the splined shaft that is connected to and driving the replacement gear (Appendix A – Figure 1).

3. Assumed Facts

The following outlines what was known about the incident based on witness statements and lab results of failure mechanisms:

1. Tall Crane employees stated that when the bottom gear failed, the entire motor assembly was replaced before being put back into service. This method of repair was chosen as it is the quickest way to repair the hoist while in service. As such, a different motor was attached with a brand new driving gear (pinion) and splined shaft (connecting the pinion to the driving motor).

2. Investigation findings indicate the top two gears were not replaced and showed significant signs of wear (Appendix A, Figure 1).

3. Witness statements say the hoist was in service for approximately 15 days after the bottom motor was replaced and before the bottom splined shaft failed.

4. During the 15 days of operation, the 6th floor was under construction, therefore a majority of the trips the hoist made were transporting personnel and materials from ground level to the 6th floor.

5. Metallurgical analysis of the failed shaft performed by Acuren, (Note, the Acuren Report is not attached to this report, Section 2.1.1) indicated that the shaft failed by **rotational fatigue**.

6. Acuren Report (Section 2.3.6 & 2.3.7) indicated that the new gear was hardened through the root of the gear teeth while the old gears were only tooth hardened. This difference was likely a result of the new gear being from a different batch of gears.

7. Acuren Report (Section 2.1.1) indicated rough machining on the splines of the splined shaft.

4. Analysis

There are four contributing factors that can lead to rotational fatigue: number of cycles, change in load, wear on gears, and stress concentrations in splined shaft and all four of these factors were exhibited.

4.1. Gear Tooth Profiles

All of the gears were initially manufactured with involute tooth profiles (Section 2.3.1 – Paragraph 4). Involute profiles are chosen because they ensure that the direction of the force imparted by the pinion gear onto the rack maintains constant (same direction) throughout tooth engagement.

The tooth profile of the new gear most closely represented an involute profile, and as such the direction of the force it imparts on the rack should remain relatively constant as it rotates.

The wear on the old pinion gears (top two) significantly degraded the involute profile (Appendix A, Figure 3) such that the direction of the force imparted by the worn gears (to the rack) varied throughout rotation (specifically at the point where the tooth first engages the rack).

4.2. Shaft Machining Quality

The splined shaft had a poor machining quality of the splines. “The rough surface finish at the fatigue critical spline roots/fillets would have substantially reduced the fatigue resistance of the shaft” (Section 2.1.1 – Paragraph 4).

4.3. Number of stress Cycles

The theoretical number of cycles that the shaft undertook is calculated by assuming that each tooth engagement is a cycle.

- During the time leading up to the incident construction was underway on the 6th floor (15m up)
- Gear was roughly 15cm in diameter therefore the circumference is 47.12cm
- The number of rotations per trip:
- $\frac{15m*2 \ \ per\ trip\ (up\ and\ down)}{0.471m\ per\ rotation\ (circumferance)} = 63.67\ rotations\ per\ trip$
- The lift was in service for 15 days before the shaft failed. Assuming 8 hour days, 10 trips per hour, 64 rotations per trip, and 15 teeth per gear. This would result in roughly $1*10^6$ stress cycles. This indicates that the gear was operating just below the infinite fatigue life of the shaft (Appendix B).

4.4. Loading of Shaft

For this calculation we will assume that the average total weight of the hoist was ½ of the Max Capacity.

Max Capacity of car = 2700kg; ½ Capacity = 1350kg
Weight of the car = 3700kg

$$\frac{1}{2} Loaded\ Car = 5050kg * \frac{9.81m^2}{s} = 49541N$$

Assuming a circular cross section at the root of the teeth the polar moment of inertia would be:

$$J = \frac{\pi D^4}{32} = \frac{\pi * 0.1016^4}{32} = 1.0461 * 10^{-5} m^4$$

The torsional moment in the splined shaft is

$$49541N * 0.075m = 3716N * m$$

The Torsional stress in the splined shaft would be:

$$\tau_s = \frac{T * r}{J} = \frac{3716Nm * 0.075m}{1.0461 * 10^{-5} m^4} = 26638kN/m^2$$

It was found that the force imparted to the shafts could have varied as much as 26,600kN/m^2. Given the poor machining quality coupled with the potential for substantial variation of load, it is believed that the use of disproportionately worn pinion gears contributed to the fatigue failure of the spline.

5. Conclusions

Our hypothesis was that the splined shaft failed in fatigue due to additional and oscillating loads on the shaft caused by gear wear in the two pinion gears that were not replaced. The factors that contributed to the fatigue were all present:

1. High number of shaft cycles below infinite fatigue life of shaft
2. Additional and variable loads
3. Rough machining contributing to concentration of stress loads

Due to these factors being present, there is evidence to suggest that rotational fatigue occurred earlier than normal since variable loads could have been introduced to the shaft.

6. RECOMMENDATIONS

We recommend to owners of construction hoists, that when a gear is replaced on a hoist:

1. All three gears be replaced at once to ensure uniform performance, and
2. The replacement gears should all be from the same manufactured batch such that they exhibit similar metallurgical and manufacturing properties.

We recommend to hoist manufactures that splined shafts be manufactured in such a way to minimize sharp edges, rough surfaces, and burrs to reduce stress concentrations that contribute to premature fatigue failure.

END OF REPORT

7. Appendices

Appendix A: Figures

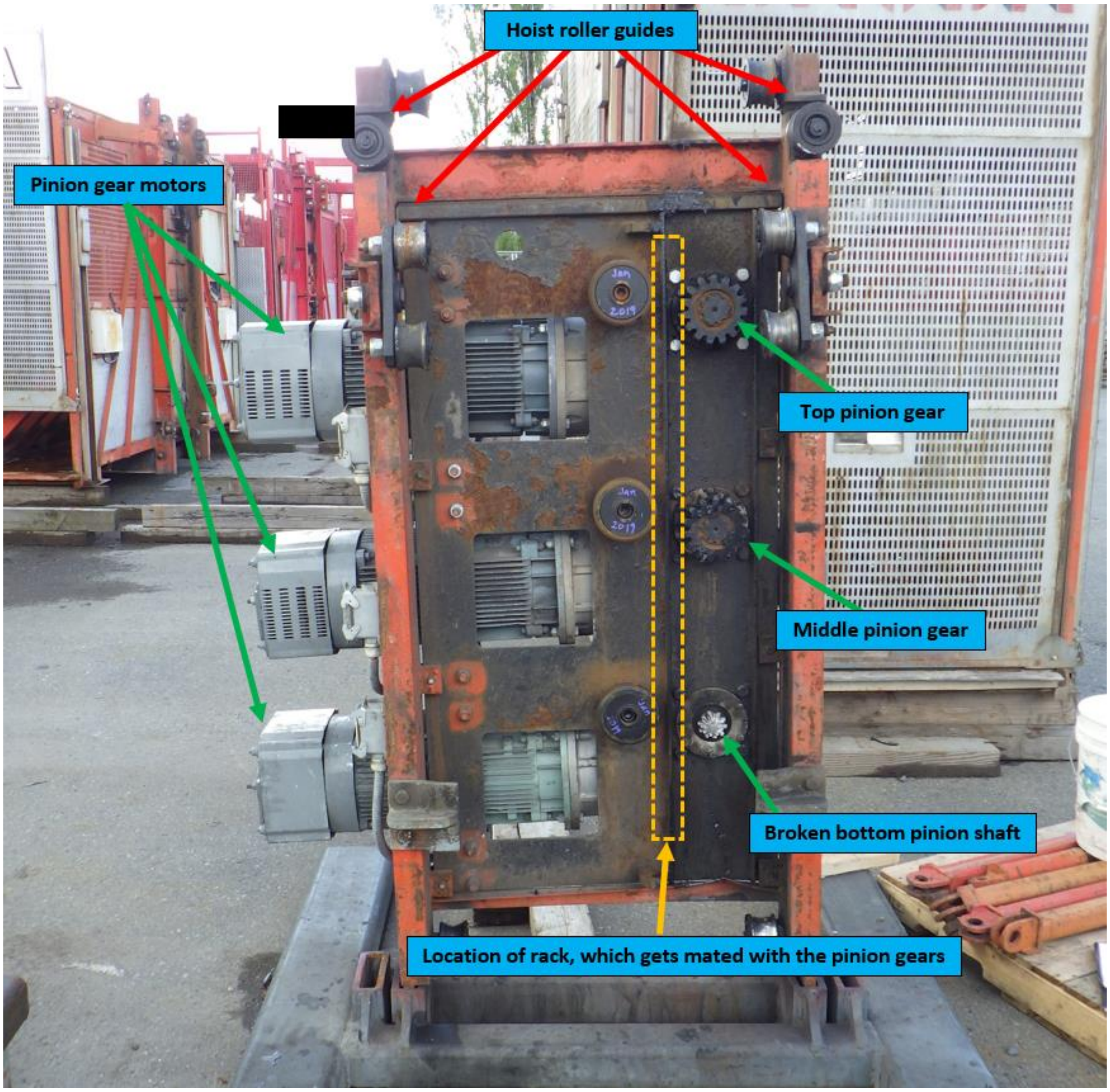

Figure 1: Construction Moist Motor Assembly

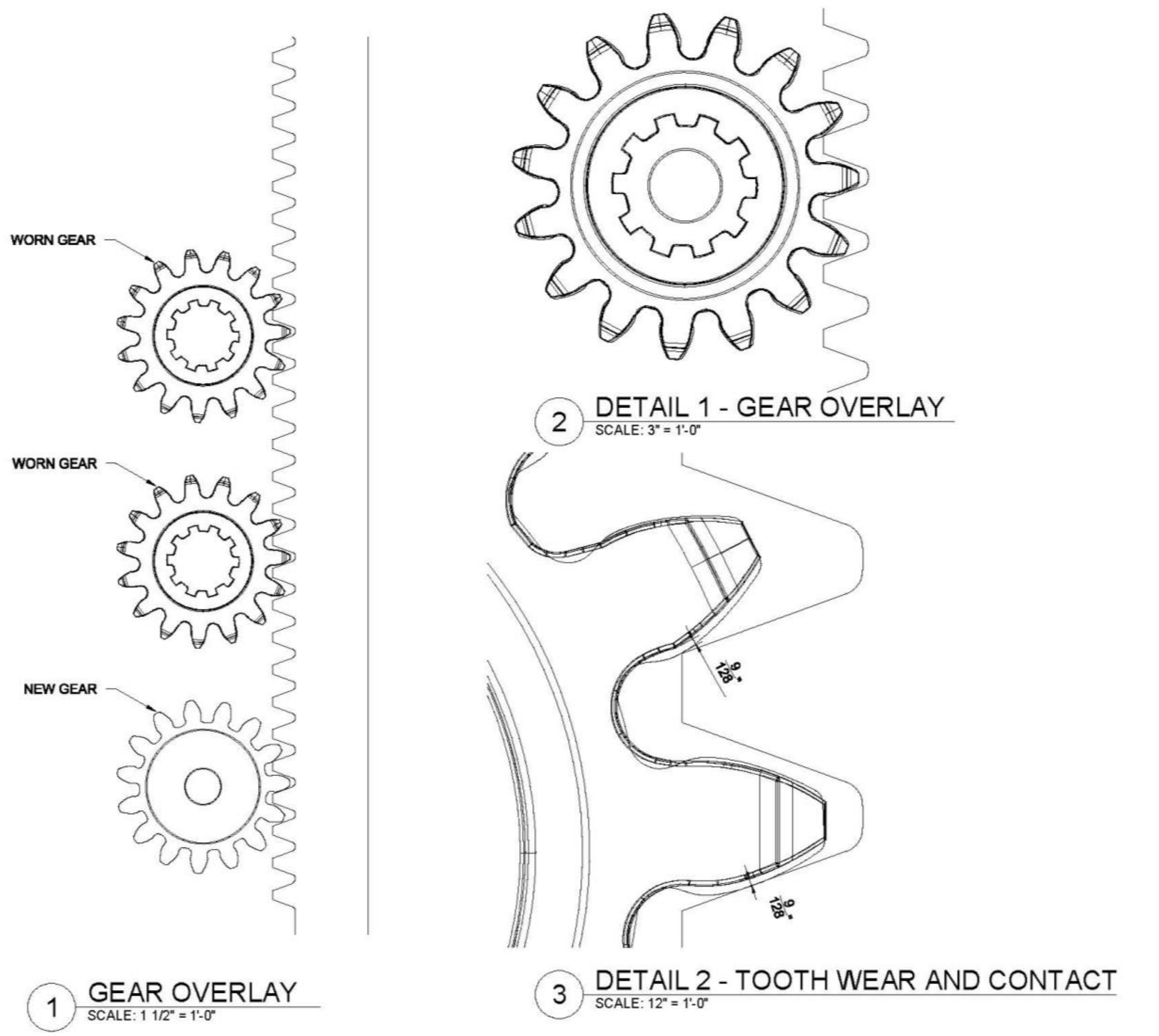

Figure 2: Orientation of Pinion Gears (1.1), Overlay of a worn pinion gear (side profile) over the new pinion gear (1.2), Detailed view of overlay showing extent of tooth wear (1.3)

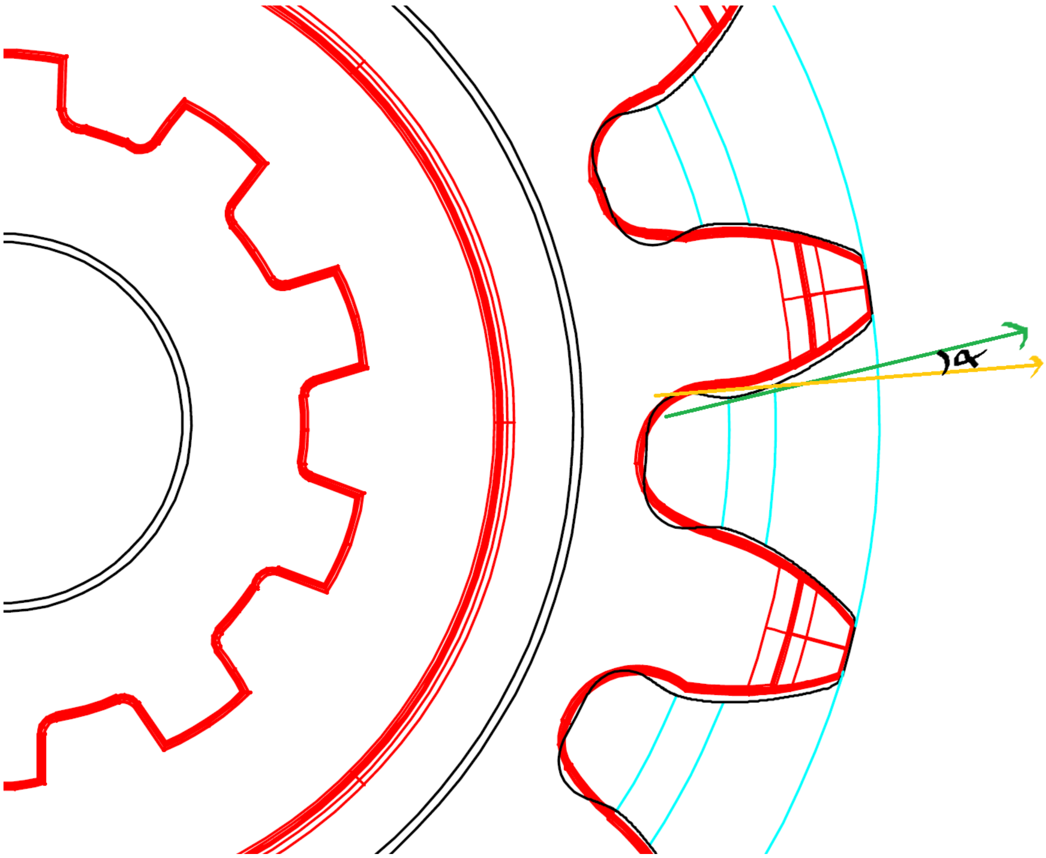

Figure 3: Black gear profile represents the new gear and green line is a line tangent to the gear tooth at the point where the gears first engage the rack. Red gear profile represents the worn gear and the yellow line is a line tangent to the gear tooth at the point where the gear first engage the rack. The difference in tooth angle at the point where the gears first engage the rack Would cause fluctuations in the angle at which the worn gear exerts force on the rack.

Appendix B: SOCIETY OF AUTOMOTIVE ENGINEERS: Design and Analysis Procedures for Shafts and Splines