Incident Summary #II-860382-2019 (#13027) (FINAL)

SUPPORTING INFORMATION	Incident Date		May 31, 2019
	Location		Richmond
	Regulated industry sector		Elevating devices – Construction hoist (personnel & equipment)
	Impact – Injury	Qty injuries	0
	Impact – Injury	Injury description	None
	Impact – Injury	Injury rating	None
	Impact – Damage	Damage description	During operation of a construction hoist damage occurred to several components that included cracking of the hoist rack, a pinion gear tooth, and the splined shaft connecting the pinion gear to the gearbox [Figure 3].
	Impact – Damage	Damage rating	Moderate
	Incident rating		Moderate
	Incident overview		While using a construction hoist, the operator heard a loud noise followed by the hoist suddenly shutting down.
INVESTIGATION CONCLUSIONS	Site, system and components		A temporary construction hoist is used to transport personnel and equipment to various floors of a building while it is under construction. The hoist consists of a mast, car, electrical motors, rack and pinion propulsion system. The mast [Figure 1] is a vertical metal structure that is anchored to the ground and outside of the building at fixed intervals. The mast contains rails for the car to ride along as well as a rack gear that runs the entire length of the mast. The car is a metal cage that travels up and down the mast via the rack & pinion drive system. The car is equipped with three independent driving units (each with a motor, gearbox, and splined drive shaft) that each drive a pinion gear along the rack attached to the mast. The three driving units are oriented vertically above and below each other [Figure 2] and act together to drive the car up and down the rack. During normal operation, an input is provided by the operator and the motors will react by driving the car up or down the mast to the requested floor(s) of the building.
	Failure scenario(s)		During operation of the construction hoist, a tooth broke off the bottom pinion gear [Figure 4] and the hoist remained in operation without immediately replacing the gear. Every time the pinion gear made a full rotation, the rack experienced an impact due to the missing tooth on the pinion. Due to this impact loading at the location of the missing tooth, the rack eventually fractured at a location where it was bolted to the mast [Figure 5]. The bottom gear was eventually replaced during routine maintenance and the hoist was put back into service (note: the broken rack was not repaired when the pinion gear was replaced). The new bottom gear was subject to greater operational loads due to the severe wear on the flanks of the top and middle pinions. Lastly, the splined shaft connecting the bottom pinion to the gearbox sheared off and the pinion gear wedged between the car and the mast, causing the hoist to come to an abrupt stop.

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Facts and evidence	An independent engineering laboratory conducted metallurgical testing and analysis to determine the cause of failure for each component. The laboratory engineers also identified design and materials factors that contributed to the failure. The results and conclusions of this engineering failure analysis are summarized below, (full report available in Appendix A): Original Bottom Gear (with broken tooth): The original bottom gear failed by fatigue cracking that had started long ago. The fatigue failure of the original bottom gear was caused by the use of a gear having inadequate wear and fatigue resistances for the application. • Gear was found to have hardened teeth and flank, but minimal hardening at root [Figure 7], resulting in insufficient fatigue strength for its intended application. • The hardness of the teeth and flank was not sufficient to resist flank wear. • Substantial corrosion was observed on the exposed face of the broken tooth, indicating it had fractured well before the hoist failed to operate. Top and Middle Gear The middle gear was through-hardened, as opposed to tooth hardened. It sustained severe wear and suffered fatigue cracking due to inadequate wear and fatigue resistances for the application. The top gear sustained severe wear and suffered fatigue cracking, also indicative of inadequate wear and fatigue resistances. • Severe wear/material flow on the flanks of the teeth indicate insufficient hardness for the intended application. • Fatigue cracking was noted at the roots of both gears. • Rough surface finish was due to the manufacturing processes. Rough surface finishes can act as stress risers and promote formation of cracks. • Middle gear was determined to have insufficient hardness for the intended application. Replacement Gear The replacement gear exhibited a better tooth hardening pattern and higher hardness on the fillet/root area than the other gears. However, fatigue cracking of this gear occurred after only a month in service. This premature fatigue cracking was likely due to excessively high load due to unbalanced load sharing among the gears. Rough surface finish was also a contributing factor to the fatigue cracking. • The ends of the teeth on this gear were rounded to a smaller radius by the manufacturer [Figure 6] compared to the other three gears, indicating it was manufactured from a different batch of gears. • This gear was hardened through the root [Figure 6], which resulted in increased fatigue resistance. • Fatigue cracking was identified at the roots of the teeth.

Broken Rack

The brittle failure of the rack section was caused by an impact load by the bottom gear after its tooth broke off.

- The rack exhibited brittle fracture at its bottom bolt hole [Figure 5].
- Excessive plastic flow was found on both the drive and non-drive flanks near the fracture, and the fracture surface was worn, indicating that the lift was operated after the rack fractured.
- The fracture pattern of the broken rack indicated the fracture was caused by impact loading.

Splined Shaft

Torsional fatigue cracking of the bottom gear shaft may have started after the tooth broke off the original bottom gear. The cracking may have been accelerated after installation of the replacement gear, which took a higher share of load. The shaft ultimately broke by torsional fatigue cracking a month later.

- The shaft failed by rotational fatigue cracking in its splined section.
- The fracture appeared to be relatively recent in comparison to the other failed parts (minimal corrosion).

Engineering analysis was conducted on the rack and pinion system by mechanical engineers, including specialists in elevating equipment. The results of this analysis are summarized below.

The pinion gears used on the construction hoist drive motors were spur gears with involute tooth profiles. An involute tooth profile on a gear ensures that for a constant input speed (angular velocity of pinion), a constant output speed is achieved (speed of car). When the flanks of the teeth begin to wear, the profile of the tooth will change and the above will no longer hold true. This means that a gear with a worn flank will result in a varying speed of the car (potential for increased vibration).

Due to the characteristics of an involute gear, if only one of the three pinion gears on a construction hoist is replaced, and the other two pinion gears have significant flank wear, then the gears may experience abnormal loading (new gear provides constant force input while worn gears provide a variable force input). This could increase the chance that the new gear will fail prematurely.

The elevating engineers report concluded the following, (full report available in Appendix B):

The engineers 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.

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Summary

Insufficient hardening of the bottom pinion gear (particularly at the root) lead to a tooth breaking off during operation. The operation of the hoist with this broken pinion gear caused impact loading to the rack and increased torsional stresses to the splined gear shaft.

The rack was determined to have failed due to sustained impact loading as a result of the hoist being operated with a broken pinion gear. The repeated impact load was imparted to the location where the rack was bolted to the mast (the thinnest/weakest part of the rack), causing the rack to fracture.

The splined gear shaft experienced repetitive torsional loading with each full rotation of the pinion. This torsional loading was found to have contributed to the development of fatigue cracks on the shaft. As such, when the broken pinion was replaced, the shaft likely contained micro cracks. Due to excessive wear on the top and middle gear, engineering analysis found that the new bottom gear sustained a majority of the operational load. Subsequently, the shaft would have experienced a higher than normal torsional load, which further promoted the growth of the fatigue cracks in the spline and ultimately led to failure.

This investigation and analysis identified that the following actions may have been helpful to prevent the incident from occurring:

1. All three gears be replaced at once to ensure uniform performance.
2. The replacement gears should all be from the same manufactured batch such that they exhibit similar metallurgical and manufacturing properties.
3. 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.
4. Regular inspections of the pinion gears, splines and rack for any signs of damage and cracks. If any pinion gear is found to have a broken tooth, the hoist should not be used until the condition is addressed.

Causes and contributing factors	The cause of the incident is highly likely due to the replacement of one of the pinion gears while leaving the other two worn gears in operation, which led to the failure of the splined gear shaft damaging the lift and rendering it inoperable. A contributing factor to the incident was insufficient hardening of the original pinion gears. Continued operation of the lift with a broken pinion gear contributed to the failure of the rack.

Figure 1: Construction hoist components.

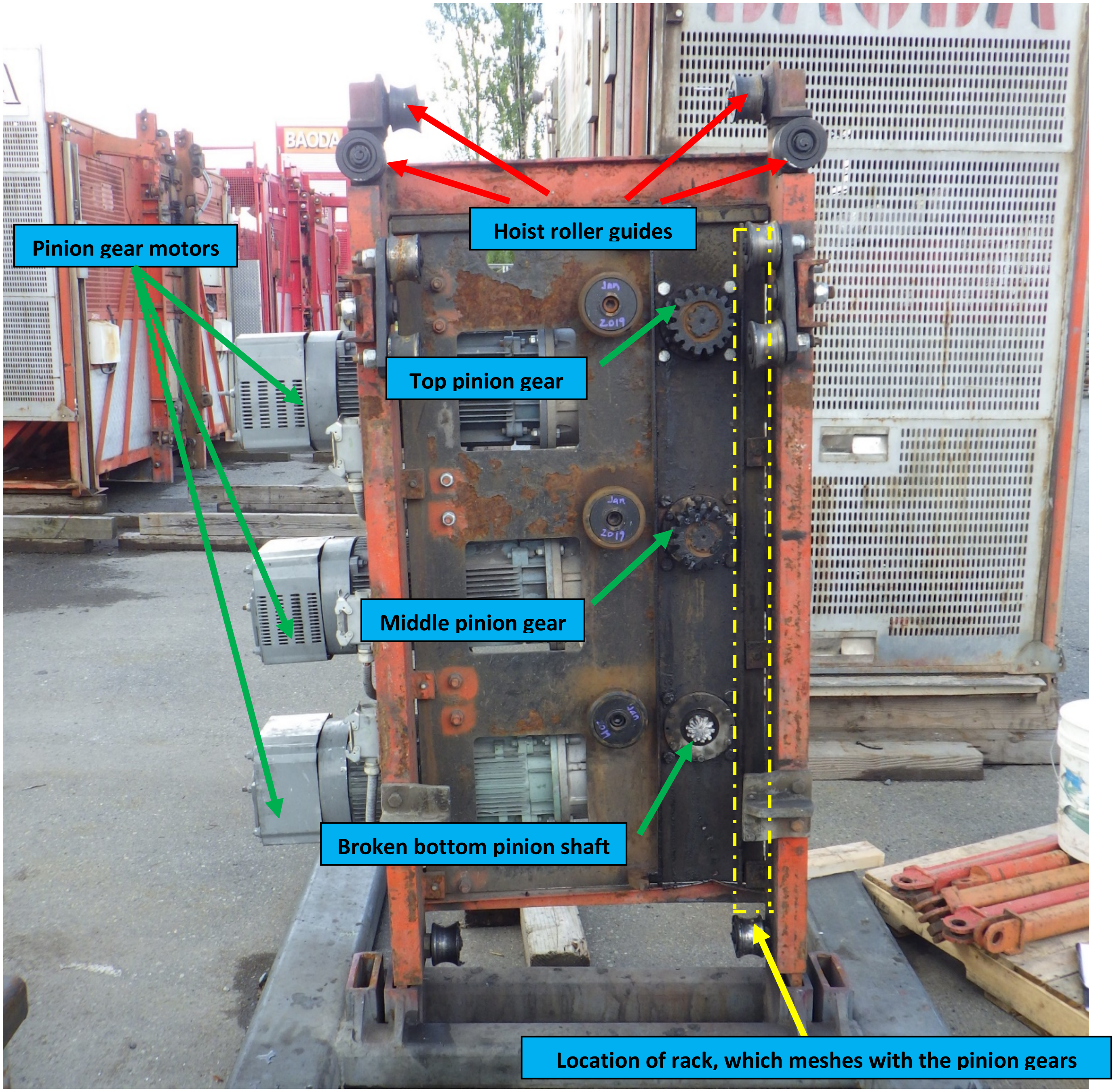

Figure 2: Hoist motor assembly

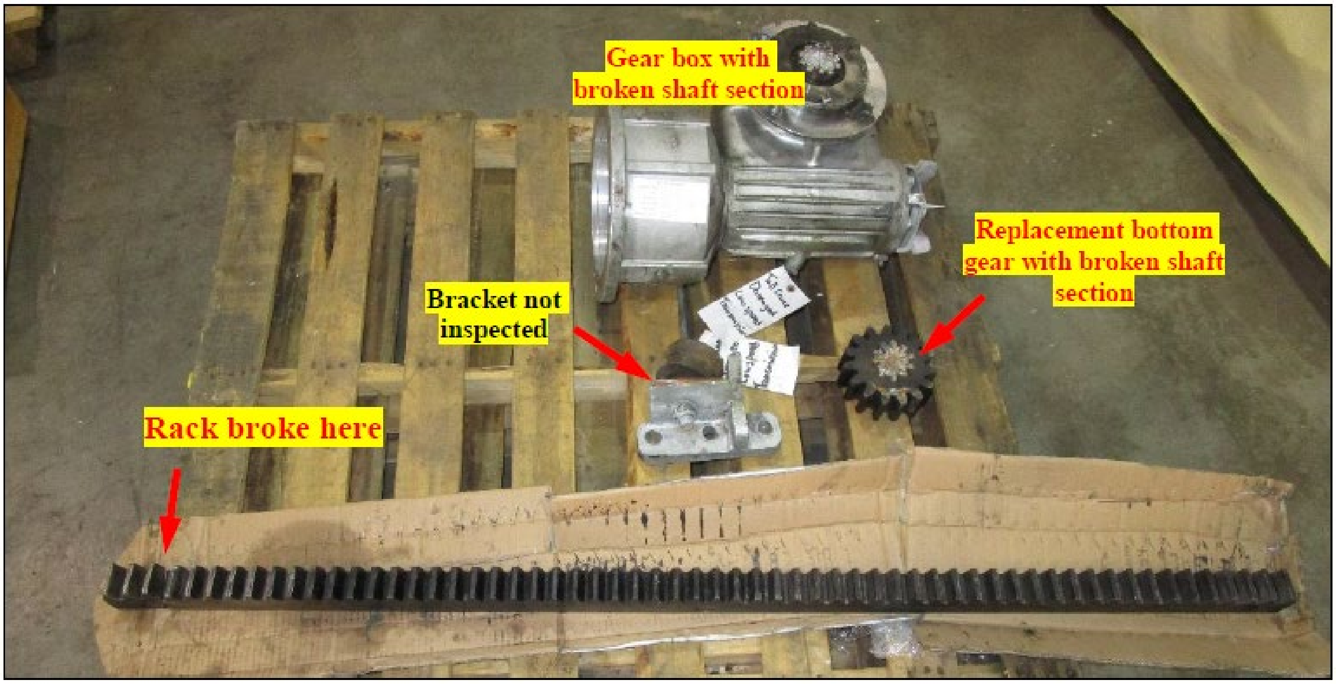

Figure 3: Various components from the failed hoist.

Figure 4: Top and middle pinion gears, and the original bottom pinion gear.

Figure 5: The failed bottom pinion gear shaft and broken rack section.

Figure 6: Comparison between replacement bottom pinion gear and the original bottom pinion gear.

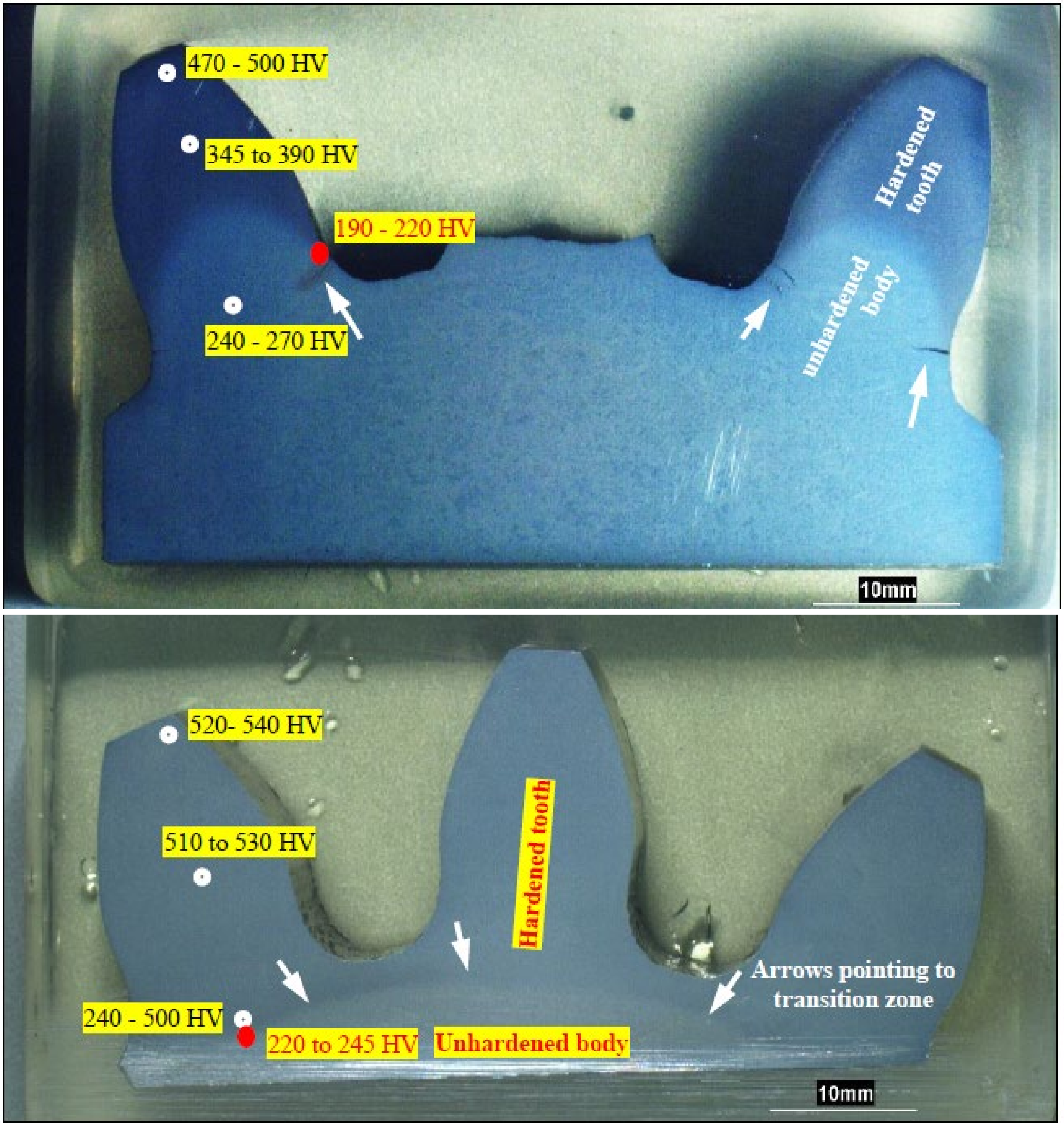

Figure 7: Metal hardness gradient of original bottom pinion gear (Top) and the replacement gear (Bottom).

Appendix A: Examination of Failed Components of a Construction Hoist Acuren Group Inc.

Appendix B: Construction Hoist Shaft Failure Analysis, by APEX Elevator