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Thrown Object Hazards in Forest Operations

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SUMMARY:

Mechanized equipment for forest operations provide better operator protection in this hazardous work environment. However operators of forestry cutting machines are now exposed to new hazards from the high-energy cutting devices used to cut trees and process logs. Anecdotal reports of thrown objects document a risk of injury and fatality. Two new ISO standards have been developed after a program of basic research by both US and Swedish research organizations. The chainshot hazard may be reduced by implementation of guarding systems that block or divert broken chains. Failed sawteeth are difficult to block at the cutting device and a new standard for protective cab glazing may be the most effective approach. This report describes the research tests and development of the new standards.

Thrown Object Hazards in Forest Operations

Introduction

Forest operations (NAICS 11331) are historically one of the more dangerous industrial occupations in the US as measured by fatality rates. The BLS estimates the 2009 fatality rate in this industry sector was 61.8 compared to an average of 3.3 for the total civilian workforce (BLS 2011). Most of these accidents are the result of worker contact with objects such as trees, falling limbs, or equipment. Partly driven by safety concerns and partly by the need to improve productivity and reduce overall costs, forest operations are becoming increasingly mechanized. Instead of workers on the ground with a chainsaw, it is more common to find a machine operator in a protective cab directing mechanized logging work. OSHA currently requires cabs on forest machines to protect against falling objects, rollover, and poking or cab intrusions (CFR 1910.266(f)(3)). While equipment operators in cabs are protected from the traditional hazards of forest operations, new hazards have been introduced by mechanization.

Modern, high-production forest machines cut and process wood using a variety of cutting mechanisms. Feller-bunchers and harvesters are mobile machines that cut down trees, severing the stem and directing the placement of the tree on the ground. Processors and slashers are cutting machines that pick up stems and cut the tree into measured lengths. Mulching machines are used to grind through understory vegetation and small trees clearing the forest and reducing all the material to smaller pieces. All of these machines have an operator in a protective cab and use some type of high-speed cutting mechanism.

Chainsaw-type cutters, for example, are found in harvesters, processors, slashers and feller-bunchers. The cutting chain runs at speeds up to 40 m s^{-1} (8000 ft min^{-1}). Large disk saws are commonly used on feller-bunchers. These disks rotate at speeds over 1300 rpm with a tip speed exceeding 100 m s^{-1} (19000 ft min^{-1}). Various grinding or shredding cutters are employed in mulching machines with cutting tip speeds of about 50 m s^{-1}. Under certain conditions, machine parts may become detached and thrown from these machines. Pieces of cut material, stones, or other debris can also be discharged at high velocity from some types of forest equipment. When small pieces of broken sawchain are thrown from a cutting machine, for example, it is called chainshot. These thrown objects pose a safety hazard to machine operators and bystanders.

Anecdotal reports illustrate the hazard (Garland and Rummer 2009). For example, in 1992, a 45-year-old fully trained operator was operating a knuckle-boom log loader and sawing trees into log lengths. The chain on the bucking saw broke and sent a small chain fragment flying through the air. The chain fragment penetrated the safety glazing and lodged deep in the operator's stomach (Howe 1992). In 2001, a tooth was ejected from a rotary-disc sawhead and traveled over 76 m [250 ft] through the air. The sawtooth passed through a mobile home, damaging several walls inside the home (Wetzel 2001a). In 2005 a forest worker in Tasmania was using a processing machine to cross-cut timber. The chain broke and a link penetrated the cab striking the operator in the neck (CMEIG 2008). In another type of incident, a sawtooth ejected by a feller-buncher in 2001 struck a nearby worker resulting in broken ribs and a bruised heart (Wetzel 2001b).

Thrown objects may be caused by reasons other than mechanical failure of the cutting device. The energy transferred into a material from contact with a high-speed rotating disk may cause the material to quickly break apart and small pieces of the material to be thrown at high velocities. In July 1996, a saw hand working near a feller-buncher was struck in the chest by a broken piece of a pine tree. The piece of pine penetrated the saw hand's chest leading to a critical, but non-fatal, injury (Alt 1996). In the summer of 1995, the disc on a feller-buncher scraped the side of a pine tree lying on the ground. The disc shaved off a 15-cm-wide [6 in.] x 2.5-cm-deep [1 in.] x 274-cm-long [108 in.] piece of wood. The piece of wood was launched through the air and struck an observer. The thrown piece of pine tree passed completely through the observer's body and he died in route to the hospital (Alt 1995).

These thrown object incidents can be broadly characterized as one of three types of hazards for equipment operators: 1) chainshot or broken links from a chainsaw-type cutting device, 2) sawteeth or cutters from disk saws and mulching machines, and 3) foreign objects displaced by a cutting tool. In order to stop a thrown object from entering a cab some type of solid material is required—either a steel panel or a polycarbonate (PC) glazing. Typical forest machine cabs have used some type of polycarbonate glazing to stop entry of foreign objects. However, little is known about the required thickness of material for a range of object masses, velocities and impact geometries. To develop proper standards that help machine manufacturers offer the most efficient protection available to machine operators it is necessary to investigate the phenomena of thrown object impact. The objective of this report is to summarize basic research work on these hazards and to describe the development of new equipment protection standards.

Background Analyses

There is a wide variety of cutting tools with teeth that range in mass from a few grams to several kg (Fig 1). There is also a wide range of operating speeds depending on the type of cutter and the intended application. Each of the illustrated objects have become detached although there is no information on frequency of occurrence or incident rate. While failure modes are unclear, the general assumption is that thrown objects have an initial velocity equal to the tip speed of the cutting tool.

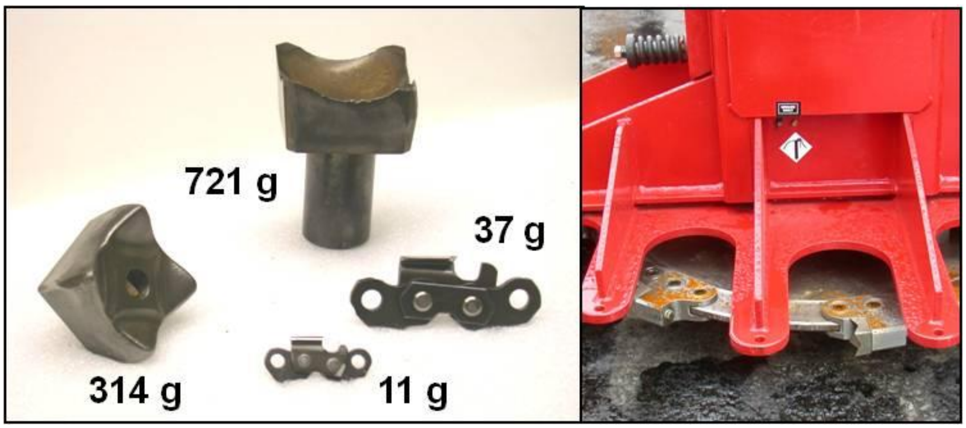

Figure 1. Representative forestry cutting devices.

In 2000, parallel efforts began to investigate different types of thrown objects. The Swedish forest research group SkogForsk began investigations of "chainshot" (the failure of chainsaw-type cutting chains) which had been reported in Scandinavian harvesting conditions. Their initial study looked at tensile strength of sawchain and failure modes (Hallonborg 2002). Normal sawchain has a tensile safety factor of about 5 and the probability of failure under normal operating conditions was deemed "low". However unusual chain wear and poor sharpening practices were identified as contributing factors to premature failure. Further testing using high-speed imagery and induced chain failure clearly defined the chainshot event (Johansson et al 2004). When a chainsaw chain fails in service the loose ends of chain continue to travel around the cutting bar. As the loose chain rounds the end of the bar it creates a whipping effect that generates high tensile loads on the terminal links of the chain sending broken pieces off at high speed (Oregon 2009). The Swedish video tests documented chainshot speeds of 250 to 350 m s^{-1} even though the chain cutting speed was only 40 m s^{-1}. Chainshot testing of different types of glazing material found that at least 19mm laminated polycarbonate is needed to avoid penetration (CMEIG 2008).

In the US, the Forest Operations Research Unit of the US Forest Service, working with the US Technical Advisory Group to the ISO Forest Machinery Subcommittee (ISO TC23/SC15) began investigation of thrown object hazards, primarily the large sawteeth typical of North American harvesting operations. A broad review of cutting devices defined potential mass, velocity and energy relationships. Table 1 summarizes typical values with comparative ballistic benchmarks. Chainshot has properties similar to a 9 mm bullet. Sawteeth and mulcher teeth, while similar in energy to a shotgun slug, are heavier and slower.

Table 1. Ballistic definition of thrown objects.

Type of object	Mass (g)	Velocity (m/s)	Energy (J)
.404 chainsaw tooth	11	300	495
50 mm sawtooth	300	85	1084
60 mm sawtooth	800	110	4840
Fixed tooth mulcher	1800	46	1904
9mm bullet[1]	8	358	513
12-gauge rifled slug[2]	28	483	3266

[1] Level 1 ballistic criteria from UL 752 (UL 2000)
[2] Supplementary Shotgun ballistic criteria from UL 752 (UL 2000)

There are existing standards that address impact properties of glazing. ANSI Z26.1 defines a suite of performance criteria for Item 10: “Safety glazing material for use anywhere in a vehicle when bullet resistance is required." These tests (Table 2) range from abrasion resistance to dimensional tolerances. The ANSI document also specifies marking requirements. Actual ballistic requirements are referenced to Underwriters Laboratory UL 752—"Bullet resisting equipment" (UL 2000). The UL standard defines testing procedures and failure criteria with 8 levels of impact depending on ammunition type. The highest energy criteria (3416-4133 J) is associated with a 9.7g round fired at 838 m/s (Level 5). UL uses a 305 x 305 mm test sample placed at a range of 4.6 m. Materials that would be exposed to outdoor conditions are to be tested at -32°C and at 49°C as well as ambient tests. Any damage to a corrugated cardboard target placed 45 cm behind the glazing indicates failure. H.P. White Laboratory (2003) specifies another ballistic testing procedure using standard ammunition (Levels A-E) at a range of 7.6 m. Failure is determined by penetration of a foil sheet placed 15 cm behind the sample. European standard prEN1063 is similar to the UL standard, specifying seven types of ammunition plus two supplementary shotgun tests.

Table 2. ANSI Z26.1-1996 tests for bullet-resistant safety glazing material (ANSI 1997).

Test	Methods	Criteria
18. Abrasion resistance	Taber abraser, 1000 cycles	<2% light scatter
27. Ballistics	UL 752	
28. Resistance to temp change	Thermal cycle -40° to 72°C	no deterioration
29. Impact	5-lb ball, 20-ft drop	no delamination >0.25"
30. Light stability	UV irradiation and spray	>70% transmittance
31. Luminous transmittance	Same as Test 30	>60% of total light
32. Optical deviation	Light target and image	Qualitative

Although the existing standards are well-defined, the characteristics of the ballistic impacts are significantly different from forestry thrown objects. Therefore tests designed to replicate forestry hazards were conducted in a special test facility (Veal et al. 2003).

Typical 12 mm (0.5 in) thick, monolithic PC panels were tested in multiple configurations to evaluate the effect of velocity, object mass, size of opening, curvature of glazing, and reduced temperatures. A high-speed camera recorded the impacts at about 7500 frames per second. Post-processing software resolved object velocity, rebound velocity and geometry of the impact events.

The sawtooth selected for the initial tests was a concave, long-shank heat-treated steel tooth with a 5-cm square face. This tooth had an initial mass of 500 g, with some minor loss during testing due to blunting. The tooth was placed in a sabot cut from polyethylene closed-cell foam with a mass of 8 g (1.6% of tooth mass). A larger, 57-mm long-shank tooth was also tested that had a mass of 800 g.

Six samples were tested at reduced temperatures ranging from -25° C to 0° C. PC has a brittle-ductile transition temperature that may be found in this temperature range depending on polymer chemistry and manufacturing processes. Samples were cold-soaked overnight to insure uniform material temperature prior to testing. Instrumented test plaques (small blocks of PC) were included in the cold-soaking process to determine internal temperatures. These showed that temperatures throughout the test samples stabilized within 90 min.

Two samples of 12 mm PC were thermoformed to a 45-cm radius uniform curve. The samples were heated on a metal form in an oven at 150°C for 1 hour. After being removed from the oven, the panels were manually forced against the form, clamped, and allowed to cool to room temperature. A matching window frame and outer frame were constructed using manufacturer’s recommended engagement and bolting details.The curved samples were mounted so that the impact would occur on the crown of the curve, at the center of the panel.

Six samples of 12 mm PC were impacted by the standard test tooth at velocities increasing from 65 to 112 m s^{-1}. Nine samples of 18 mm laminated PC were tested at velocities increasing from 74 to 127 m s^{-1}. Finally, two samples of 12 mm PC were tested as larger panels to evaluate effect of opening size.

The results of this series of tests showed that 12 mm PC was able to absorb impacts of about 3 kJ without total failure when the material is at room temperature. At panel temperatures below 0° C the material exhibited brittle failure even at lower velocities. Larger panel samples (84 x 84 cm vs. 54 x 54 cm) absorbed a higher percentage of the impact energy (98% vs. 90%) although the panels still failed at about 3 kJ. Curved panels performed similar to flat panels if not slightly better. The initial hypothesis was that curved panels would be stiffer and thus more susceptible to failure. However, the reverse was true. The curved panels actually absorbed more of the impact energy (ave. 95%) than the flat panels. This may have been an effect of the heat treatment cycle to induce curvature. None of the impacts actually broke through the curved panels, even the long-shank 0.8-kg tooth with one of the highest impact energy levels. The 18 mm laminated PC was substantially stronger, withstanding all impacts even at reduced temperatures.

The key conclusions from the testing were:

1) Reduced temperature performance of PC is the critical limiting factor,
2) Flat panel samples (54 cm x 54 cm) provided a conservative performance test,
3) Simulated forestry thrown object tests could replicate hazard conditions.

Standards Development

The 2003 edition of ISO 11850 "Machinery for forestry—Safety requirements" (ISO 2003) included a placeholder in clause 4.2.2.3 noting that criteria would be developed for protection of operators from "hazards caused by failed chains, teeth and similar failures using polycarbonate or equivalent glazing." From the Swedish and US testing it was apparent that chainshot and sawtooth impacts are very different hazards with different protective glazing requirements. Two separate ISO work items were initiated to address these hazards. For chainshot the approach is to guard the saw, for failed sawteeth the approach is to provide adequate protective glazing that can withstand impact.

As chainshot became better understood several designs of chainshot guards were developed. Generally these consist of a shield around the rear of the drive sprocket that catches the chain and reduces the whipping effect. ISO 11837 (ISO 2010a) "Chainshot guarding system—Test method and performance criteria" was developed along this approach. It does not specify a particular design but rather defines a test procedure to insure that a guarding system will block chainshot directed to the rear and/or top of a cutting head. Multiple tests must be run across a range of operating conditions up to 1.2 times the maximum operating speed. The final standard was published in 2010 and manufacturers are now using chainshot guards.

The hazard of failed sawteeth was addressed by developing a test procedure for glazing material intended to provide operator protection on equipment cabs. Like other ballistic standards, ISO 11839 (ISO 2010b) defines a test method that simulates the actual hazard condition. Two test levels are defined—a lower energy object that may be appropriate for smaller machines and a high energy object that represents the upper limit of currently produced cutting designs. PC material must be tested at both cold and warm temperatures. Manufacturers are now evaluating cab glazing material using this test.

Discussion

The development and publication of these two new standards represent the application of research on forestry thrown objects to provide improved operator protection. While definitely an important step, only time will tell whether these tests will adequately address the hazard. There are clearly some limitations.

First, ISO standards are international consensus standards and are not regulatory. Even though standards are published there is no legal requirement for application unless a regulatory body adopts the document as a performance requirement. In the US, for example, the OSHA logging safety standard does not cite all current forest equipment protection standards. Larger, global equipment manufacturers will be the first adopters but smaller regional equipment manufacturers or specialty attachment manufacturers may not immediately adopt these new tests.

Second, forest equipment has a relatively long service life. Even if all equipment manufactured from this point on were in compliance with the new ISO standards there will be many machines in service without this level of protection. Chainshot guards may be relatively easy to install as retrofits, proper PC cab glazing may be harder to retrofit to older cab designs. Some regulatory bodies may adopt these tests with requirements for implementation by in-service dates. This usually involves compromises around technical and economic feasibility vs. perceived hazard.

Finally, there are elements of the thrown object hazard that are not fully addressed by the two published documents. Bystanders are still at risk from both chainshot and thrown teeth. Modified equipment, for example construction machines adapted to forestry work, may not have OEM guarding systems. Operator behaviors such as poor maintenance, intentional misapplication (ie, overspeeding saws), or unsafe cutting positions may still create hazardous conditions.

Improving workplace safety is a continuous process of hazard recognition, engineering analysis and adoption of improved countermeasures and practices. Thrown objects in forest work are a hazard associated with new mechanized operations. The new ISO standards represent an initial step to address these hazards.

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