Journal of the National Academy of Forensic Engineers®

http://www.nafe.org
ISSN: 2379-3252
DOI: 10.51501/jotnafe.v39i2

Vol. 39 No. 2 December 2022

FE Investigation into Manufacturing- and Design-Related Issues Contributing to the Failure of a Climbing Treestand

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Abstract

The foot platform of a climbing treestand fractured while a user was standing on it in the process of securing his harness to a tree. Analysis of the frame's fracture surface revealed a manufacturing defect in the form of a ¼-inch diameter hole next to the fracture area, likely created during the welding process. To prove that this defect was the proximate cause of the treestand's failure (under reasonably expected and foreseeable use conditions), a series of tests on exemplar treestands as well as finite element analysis were performed. It was concluded that the defect reduced the fracture toughness of the treestand by 40%. In addition, it was found that the manufacturer failed to account for additional stress caused by dynamic loading experienced during normal use. The authors opined that both the reduced strength and the omission of dynamic loading in the design resulted in the treestand's frame failure. Appropriateness of the manufacturer's reliance on users always wearing their full body harness is also discussed. This paper examines the contribution of the drilled hole to the integrity and suitability of the ASTM-required Factor of Safety (FOS) of 2.

Keywords

Treestand, aluminum weld, manufacturing defect, dynamic overload, forensic engineering

Introduction

Hunters often use a variety of equipment to augment their experience. One such piece of equipment is a treestand — a platform affixed to a tree that allows the hunter to take an elevated position (typically between 15 and 30 feet above the ground). Treestands are commonly utilized to allow hunters to ambush their prey at short ranges, making the use of bows and other short range or less precise weaponry more viable. According to conducted marketing research, treestands are utilized by around 87% of hunters in North America, making it one of the most utilized pieces of hunting equipment[1,2].

A treestand typically consists of a two-by-two-foot platform seat with straps and cords that affix the device to the trunk of the tree. As expected of such a well-utilized device, treestands come in a variety of distinctive styles and configurations. Fixed or hang-on treestands utilize straps, chain, and/or serrated metal teeth to secure the stand to the trunk of a tree. To reach a fixed stand that has been previously set up, hunters use climbing sticks that they insert into the trunk of the tree. Ladder stands, on the other hand, provide the user with a ladder they can use to reach the stand platform. These stands offer greater stability because the load is carried by the ladder and the tree. Another commonly used variant is the climbing treestand. These two-piece stands (consisting of a foot-platform and a seat-platform) allow users to ascend the tree by wrapping the stand's cables around the tree trunk and moving one piece at a time until they reach their desired height.

According to available literature, falls from treestands are currently the most common cause of hunting-related injuries (50%), while accidental gun wounds account for 29% of injuries[3,4]. Of those who fell from a treestand, 80% were noted to have required surgery and 10% experienced permanent neurological disability or death[5]. Therefore, it is clear that falls from treestands present a significant hazard to the average hunter.

Treestands are known to experience failure from a variety of different mechanisms. For example, the plastic deformation or fracturing of the load-bearing sections of a treestand can result in loss of load-bearing capability,

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causing the user to plummet to the ground. Repeated usage can gradually induce fatigue in the load-bearing components, which can reduce the load-bearing capacity of the treestand to the point where normal operation can result in failure. Treestands that rely upon supporting cables or chains can have these components snap, resulting in the stand and its user falling. A treestand and its load-bearing components can also experience excessive corrosion, which renders the stand unfit for use. The mechanism engaging the stand to the trunk of a tree may also experience failure or a loss of efficiency, leading to the stand disengaging from the tree.

Background

In the present case, a 5-foot, 9-inch male user (weighing approximately 200 lb) suffered injury after the foot platform he was standing on snapped in two pieces, resulting in his fall from the tree while standing on the foot platform section of the stand. Based on the climber's testimony, the incident occurred while he was in the process of finalizing his climb and setting the stand in place. The climber had reached a fork in the tree about 18 to 20 feet above the ground, and was attempting to throw a rope around the tree to tie off his safety harness. In the process of throwing the rope, the foot section slipped, causing the treestand to fall a short distance with him on it before re-engaging. This motion of the foot section of the treestand caused the frame rail to experience dynamic loading that resulted in its fracture and the ensuing fall of the user to the ground.

Figure 1
Photograph showing a new treestand of the same model as the subject treestand.

The authors were retained to review provided documents pertinent to this case — as well as to determine the root cause of the treestand's failure — to render an expert opinion within a reasonable degree of engineering and scientific certainty, regarding the safety and suitability of the foot section as it related to the incident.

ASTM standards require the treestand to withstand static load twice the rated load. Initial review of the failed treestand revealed a manufacturing defect in the form of a weld hole at the failure site. This paper examines the contribution of the drilled hole to the integrity and the suitability of the ASTM-required FOS of 2.

Analysis of the Treestand

The treestand at issue — a climbing treestand constructed from an aluminum frame — was stated to have a rated weight capacity of 300 lb. Manufacturing documents failed to state what grade/alloy of aluminum was utilized in the construction of the treestand.

The treestand was comprised of two main sections, the seat (upper) section and the foot (lower) section, as shown in **Figure 1**. As described earlier, while the user was standing on the foot platform, the treestand lost its grip on the tree and slipped down a short distance before re-engaging. The dynamic loading created by this motion caused the foot platform to fracture into two pieces, as shown in **Figure 2**.

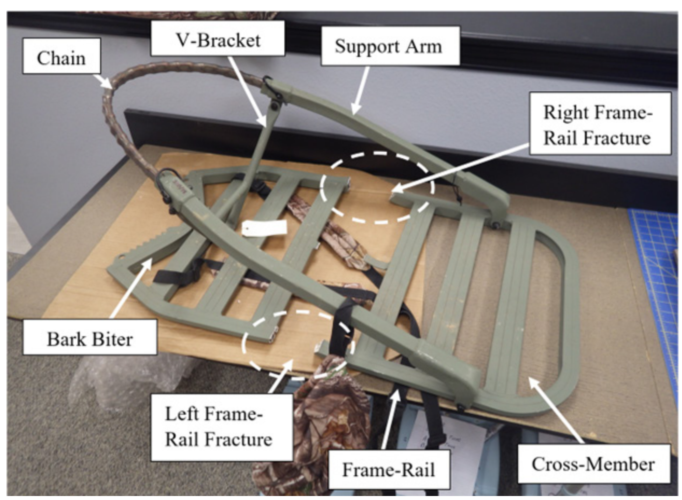

Figure 2
Photograph showing overall foot section of treestand with circles indicating failure locations.

The frame rail for the foot section of the treestand fractured at both the right and left sides of the frame rail (approximately halfway between the contact point with the tree and support arm). The bolt, which is used to connect the “V-bracket” to the support arms, was also fractured with its tab plastically deformed.

Closer examination of these three failure locations on the foot section revealed the presence of a ~¼-inch hole near a fillet welded cross-member connection to the frame rail (**Figure 3**). This hole, which appears to have been caused by improper welding during manufacturing, was located approximately 0.18 inches from the bottom of the frame rail adjacent to a weldment connecting the cross-member to the frame-rail.

When a climber is standing on the foot platform, the lower portion of the frame-rail’s cross section (where the hole is) would be subjected to tensile bending stresses during normal usage of the device when the user is standing at the center of the platform. The presence of a ~¼-inch hole in the portion of the frame railing subjected to tensile bending stesses resulted in increased stresses (due to stress concentration effect of a hole) that exceeded the material’s strength, causing the failure observed in **Figure 4** and **Figure 5**.

The presence of the protective coating on the inner surface of the hole (**Figure 6**) indicates that the hole existed at the time of the treestand’s manufacture. Testimony from the manufacturer representative confirmed that this hole was accidentally created during the process of welding the treestand — and that the presence of such holes was common.

This hole was observed by the climber and his family

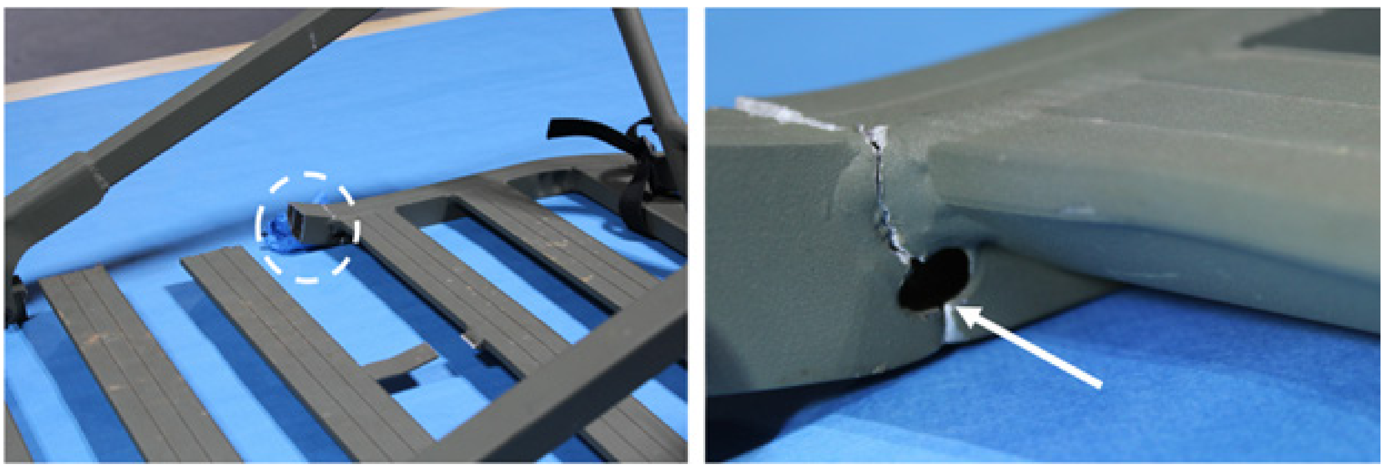

Figure 3
Photograph of the left frame-rail fracture in the treestand’s foot section (left) and close-up of the hole (right), showing failure origin and direction of failure.

Figure 4
Photograph of the right frame-rail fracture in the treestand’s foot section (left) and close-up of the fracture (right).

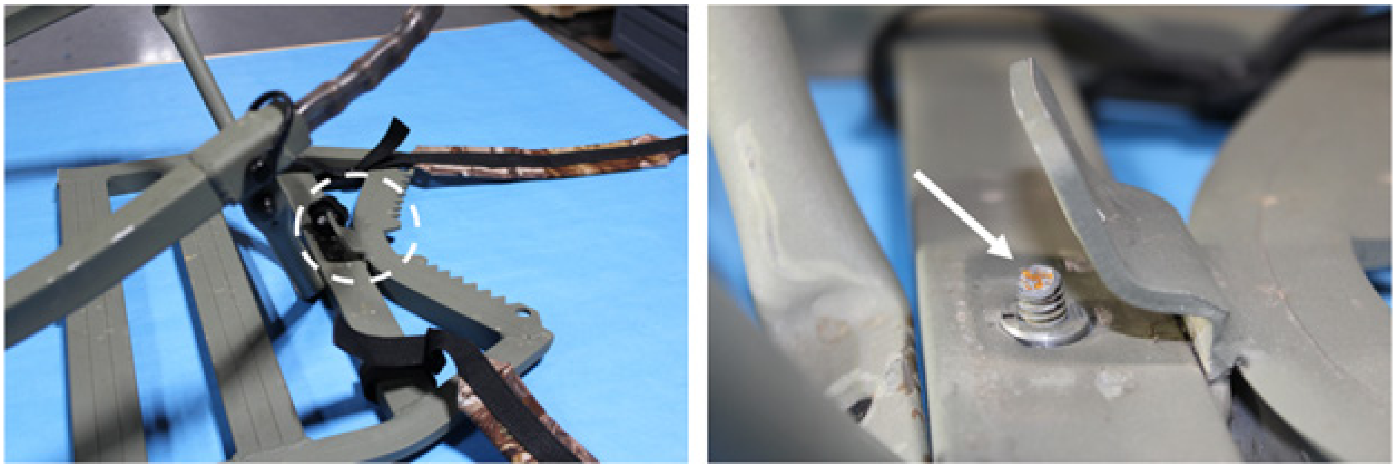

Figure 5
Photograph of the bolt fracture in the treestand's foot section (left) and close-up of the bolt fracture and bent tab (right).

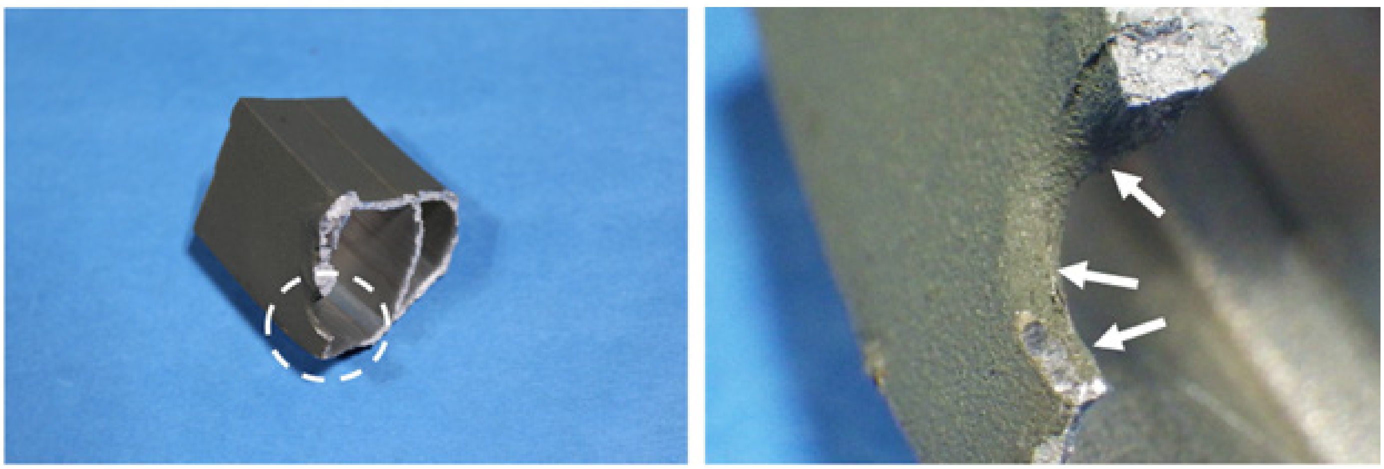

Figure 6
Overall (left) and close-up (right) of the failure area, showing the presence of protective coating around the periphery of the hole, indicative of hole being present prior to the application of coating.

during their inspection of the failed treestand after his fall. This observation led them to pursue legal compensation on the basis of a manufacturing defect.

Finite Element Analysis

To assess the stress-concentration effect of the discovered ¼-inch diameter hole (**Figure 6**) on magnifying the tensile stresses present in the side rail under the weight of the user (~200 lb), a finite element analysis (FEA) model of the treestand was created. A mesh sensitivity analysis was performed to arrive at the optimum mesh size for this analysis. The boundary conditions for the FEA model consisted of geometrical constraints where the foot platform is attached to the tree and supported by the support arms, as indicated by the white squares (**Figure 7**). The total weight of the user (200 lb) was equally distributed on the cross-members where the user would have been standing, as shown in **Figure 7**. The FEA model was run in a comparative study (with and without the discovered ¼-inch diameter hole) to assess the additional stresses created in the railing due to the presence of the hole. As this was comparative in purpose, the V-brace was not considered in the constructed model. The results of the FEA analysis revealed that the presence of the hole (a manufacturing defect) resulted in a 52.2% increase in Von Mises stress at this location — from 7.1 ksi to 10.7 ksi.

Experimental Analysis

Since the failure in this instance occurred as a result of the energy delivered by the user to the foot platform cross-members, it was sought to determine (through a series of experiments) the reduction in the energy absorption capability of the foot-platform's frame with and without the presence of the hole. To this end, two exemplar treestands were acquired. One was tested in as-received condition; the other was modified by drilling a ¼-inch hole at the

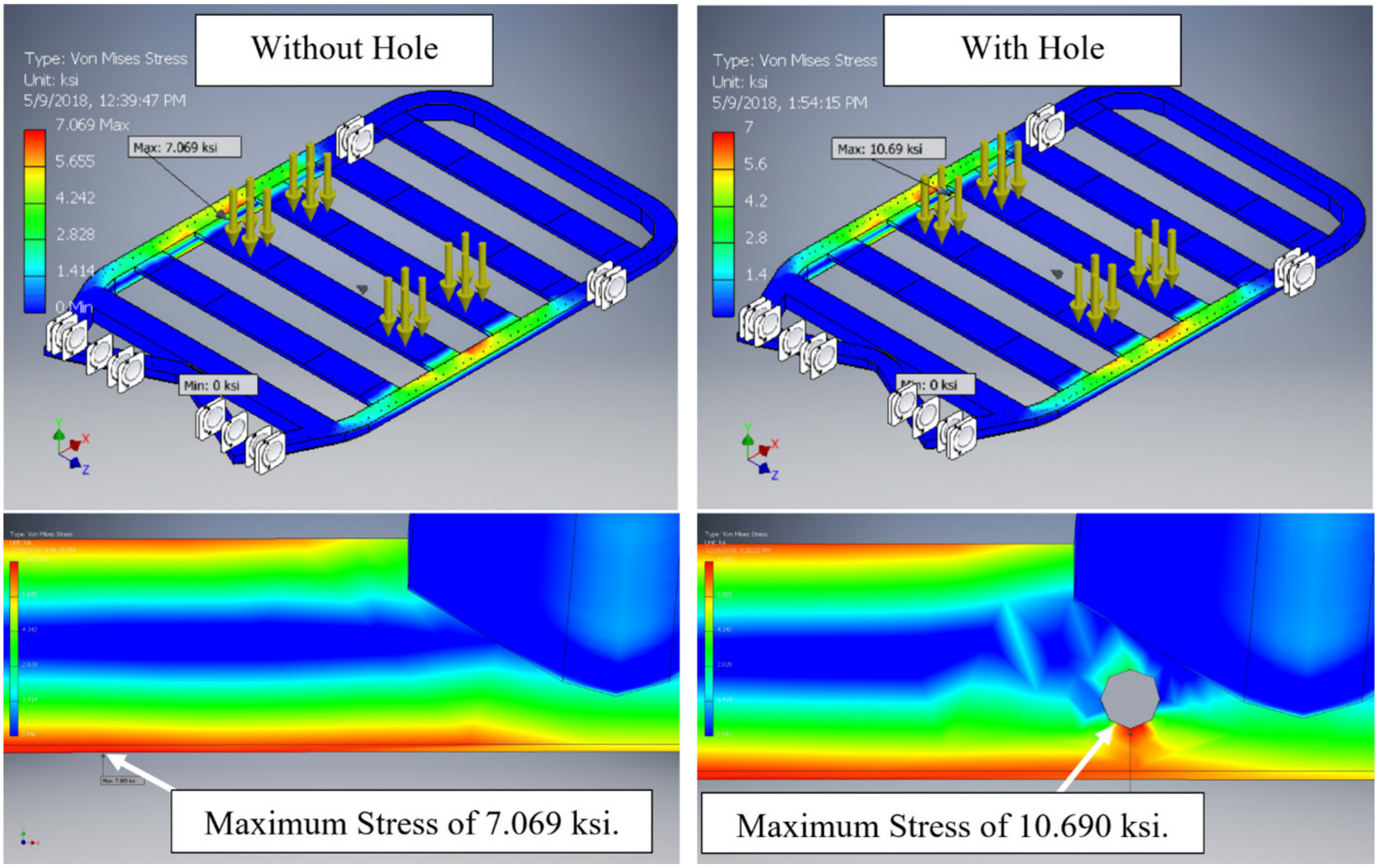

Figure 7
FEA analysis results comparing the Von Mises stresses of the frame railing with (right) and without (left) the discovered hole.

same location as the ~¼-inch hole identified on the frame rail of the treestand (**Figure 8**).

The experimental test setup (**Figure 9**) consisted of a ~10-inch diameter wooden pole on which the treestand was mounted. A 10-inch by 10-inch square steel plate was used to apply an increasing load to the cross-members of the frame in accordance with the TMS 11 standard for load testing of treestands. As the applied load to the cross-members was increased, the corresponding deflection of the frame was measured to arrive at the load-displacement response of the treestand's foot platform. The load was continually increased until the foot platform experienced failure of the frame railing. The area under the load-displacement response curve for each test was then utilized to arrive at the energy necessary to cause failure of the treestand's foot platform. The results indicated that the treestand without a manufacturing defect was capable of withstanding of 2,380 lb-in. of energy (max load of 1,120 lb) while the treestand with the hole was only able to withstand 1,425 lb-in. of energy (max load of 950 lb), representing ~40% reduction in energy absorption capability of the treestand.

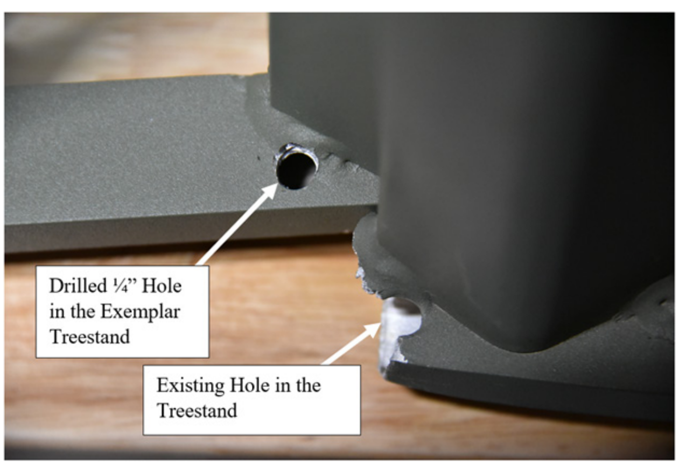

Figure 8
Photograph of hole drilled in exemplar next to manufacturing-induced hole.

Following completion of the tests, comparison of failure characteristics (crack origin and propagation direction) of the exemplar test treestand to that of the subject treestand revealed identical features, which is evidence of the validity of this test setup and

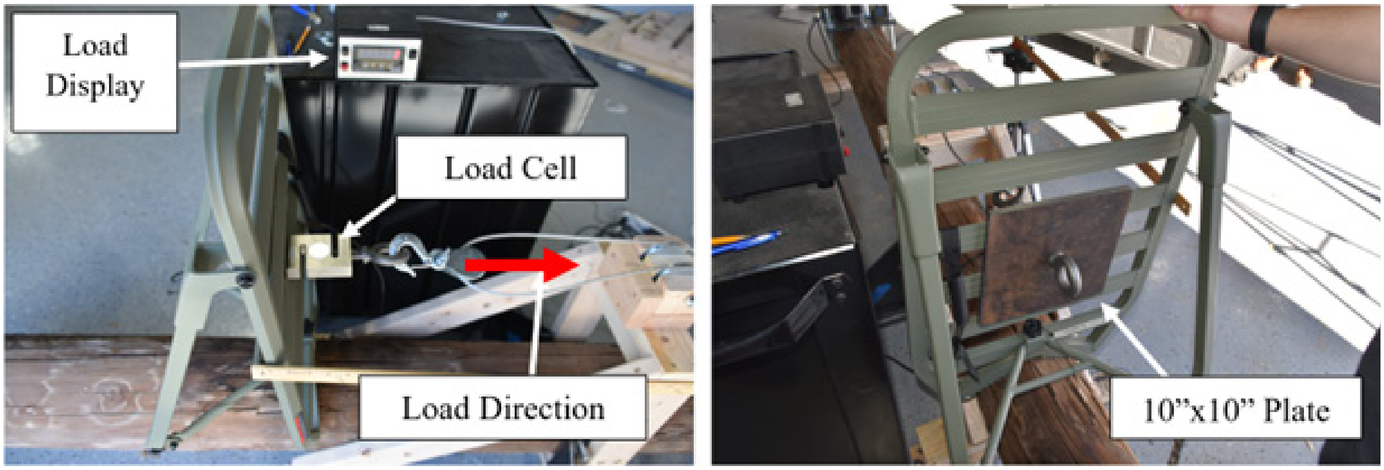

Figure 9
Photographs of test setup with red arrow indicating the direction of the applied load.

procedures used for the experimental phase of this study (**Figure 10**).

Based on the results of the experimental tests previously described, the 200-lb climber must have fallen a distance of at least 7.125 inches for his body to create the necessary energy of 1,425 lb-in. to cause failure of the foot platform's rail. Had the manufacturing-induced hole not existed at the time of the incident, the same 200-lb climber would have had to have fall 11.9 inches to reach the failure threshold energy of 2,380 lb-in. energy for a non-defective treestand. Given the climber's testimony that the foot platform slipped by a few inches before it reengaged with the tree, it is reasonable to conclude that the presence of the hole was the proximate cause of the treestand's failure.

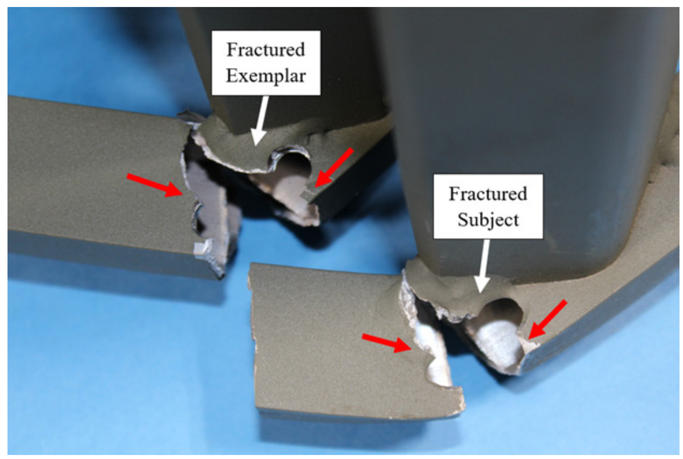

Figure 10
Near identical failure features between exemplar and subject treestands as evidence of the validity of experimental setup and procedures.

Manufacturer's Inadequate Quality Control Procedures

The Treestand Manufacturer's Association (TMA) Standard TMS 09[6] section 5.1 states that:

"A procedure shall be in effect so that appropriate inspections are made on manufactured parts and subassemblies to ensure conformance with engineering specifications."

In addition, section 5.3 of the same standard states that:

"A procedure shall be in effect so completed units are inspected prior to delivery."

As such, a manufacturer that is responsible for the design and/or distribution of the treestand should implement quality control procedures to ensure each part and each completed unit is properly inspected. If the treestand's frame rail or the assembled treestand had been properly inspected by the manufacturer, the presence of the hole near a sensitive area (heat-affected zone near the weld) would have been identified, and the treestand should have been rejected.

The manufacturer stated that the presence of welding-induced holes in treestand frames is a common occurrence that does not constitute a defect. While it is true that aluminum is notorious for being difficult to weld and "burn through" (causing a hole in one of the welded members) can occur, the results of the authors' experimental and numerical studies clearly indicate that such holes constitute a manufacturing defect as the stress concentration effect associated with such holes results in significant reduction of the load-bearing and energy-absorption capabilities of the treestands under normal and anticipated use conditions.

Inadequacy of Treestand Design

The manufacturer testified that it is unreasonable to foresee a treestand being subjected to dynamic loads. However, the manufacturer also testified that treestand users are warned about the treestand disengaging from the tree and then reengaging, a mechanism that can result in the climber imparting a dynamic load upon the treestand (as was the case in this incident). Therefore, the manufacturers knew of the situations that might result in a dynamic loading environment. As such, the design of the treestand should have been commensurate with such a dynamic loading environment foreseen and warned against by the manufacturer.

Moreover, the load rating for the treestand was 300 lb. As indicated earlier, the authors' experimental results showed that this treestand (without any manufacturing defect) was only capable of withstanding 2,380 lb-in. of energy before failure. As such, a 300-lb individual would have to fall only 7.8 inches to reach the failure energy threshold of 2,380 lb-in. This indicates the presence of a design defect because the treestand can fail due to slippage of the foot platform (loaded at its rated capacity) by approximately 8 inches. Such an occurrence is not an unforeseeable event. In fact, it's one the manufacturer knows and warns about.

The manufacturer testified that the treestand was tested to TMS 11-98[7] and ASTM F2126-06[8] standards regarding the load capacity of climbing treestands. Both of these standards require climbing treestands to be tested to twice the rated capacity — or an FOS of 2 with respect to yield for static loading conditions. These standards only require an FOS of 2; however, TMS 11-98 section 4.1 and ASTM F2126-06 section 5.1 state the following regarding the significance and use of the standards:

"This test method is intended for quality assurance and production control purposes."

This indicates that the purpose of the standard is not to provide a guide for the sufficiency or safety of the design under foreseeable loading conditions, but rather to provide a method for providing quality assurance. In fact, in section 1.3 of both standards, it is clearly stated that:

"This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use."

Therefore, the manufacturer of the treestand should not have solely relied on these standards for its design or establishing the safety of its design. Instead, it should have identified foreseeable loading conditions that are beyond the scope of the above standards, including dynamic loading associated with a climbing treestand, for which an FOS of 2 is insufficient.

In 29 CFR 1917.118[9], "Fixed Ladders," subsection (d)(1)(ii), OSHA requires fixed ladders, a product designed to support users at an elevated height, to have an FOS of 4. Further, in 29 CFR 1926[10], "Safety and Health Regulations for Construction," subsection 451(a)(1), OSHA requires scaffolds, a product designed to support users at an elevated height, to also have an FOS of 4. Furthermore, in the manufacturer's own quality assurance document, section III(b)(i) states:

"Our quality assurance coordinator determines the pass/fail requirements. This is based on the weight rating, and they type of use. Every component and assembly must pass a 4-time weight rating test. (i.e., 300 lb. weight rated product: all components and assemblies pass up to 1,200 lb.)"

Although the treestand at issue was created for recreational purposes, this alternative use does not change the nature of consequences of the hazards that are present. Since these hazards have been identified and recognized by OSHA, a prudent designer would have incorporated their recommendations. By failing to do this, the manufacturer ignored a hazard present in their device and the well-known methods to alleviate it.

The designers deviated from their holding company's internal quality assurance standards by not testing to an FOS of 4 (which the subject treestand would have failed according to the authors' load-to-failure testing) and also deviated from applicable inspection standards and guidelines that would have rejected the subject frame rail based on the manufacturing defect present at the time the treestand was constructed. As a result of these deviations from design and manufacturing guidelines, the treestand suffered catastrophic failure resulting in the climber's subsequent injuries.

Inadequacy of Treestand Warnings

Figure 11 is a set of photographs showing a warning label attached on the treestand. This warning label states:

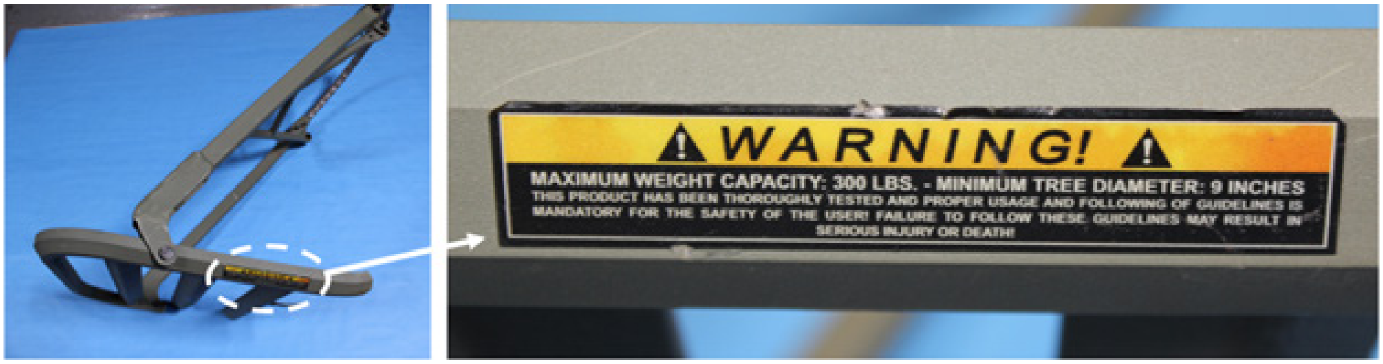

Figure 11
Warning label location on the treestand (left) and close-up of the warning (right).

"MAXIMUM WEIGHT CAPACITY: 300 LBS. — MINIMUM TREE DIAMETER: 9 INCHES"

This is a warning informing the user of the treestand's capacity and tree conditions. The warning label continues with the following statement:

"This product has been thoroughly tested and proper usage, and following of guidelines is mandatory for the safety of the user! Failure to follow these guidelines may result in serious injury or death!"

There are several issues with this section of the warning label.

The label shown in **Figure 11** states "this product has been thoroughly tested…" however, the treestand had never been tested. The overall design was tested under static conditions, but not tested to foreseeable dynamic loading conditions that the manufacturer both knew and had warned about. The manufacturer testified that the treestands are shipped directly from the manufacturer to the supplier without each individual treestand being tested. This indicates that the subject treestand was never tested. Additionally, the manufacturer stated that it had no knowledge as to whether or not the treestand's foot section was ever inspected.

Inappropriateness of Reliance on Safety Harness

The climber was criticized for not attaching the safety harness to the tree when beginning to climb prior to the incident. The climber stated that, when having done so in the past, the top portion of the treestand would disengage from the tree, presenting another safety hazard. In addition, the climber stated that he was aware of risks associated with utilizing a safety harness.

Treestand manufacturers recommend the use of safety harnesses, yet the use of such a device is not without risk. An HSC Contract Research report[11], entitled "Harness Suspension: Review and Evaluation of Existing Information," presents a study conducted on the Wright-Patterson Air Force Base in Ohio. In this study, young and healthy individuals were suspended in four different designs of full-body harnesses.

During the study, the tests were terminated when either the test subject voluntarily chose to end the study (due to symptoms including nausea, tingling and numbness of the extremities) or on-site medical professionals chose to end the test. The average suspension time was 14.38 minutes before the test was terminated. Further, an OSHA Safety and Health Information Bulletin (SHIB) 03-24-2004[12] describes the hazards associated with suspension trauma. It states that if a worker using a fall arrest harness can experience venous pooling, which can result in death in as little as 30 minutes.

The climber was hunting with a friend who was able to assist him in getting medical attention after the incident. The friend's testimony states that it took approximately 30 minutes to reach the climber after the incident — and that, if the climber would have still been suspended in the tree by his safety harness, it would have taken additional time to rescue him.

The hierarchy of controls (also known as the engineering hierarchy) represents the necessary steps to reduce exposure to a known hazard[13]. **Figure 12** is a graphic representation of the hierarchy of controls. These controls begin with the most effective steps and go down in order of effectiveness. The steps in order of effectiveness are: elimination, substitution, engineering controls, administrative controls, and PPE.

Providing the user with personal protective equipment

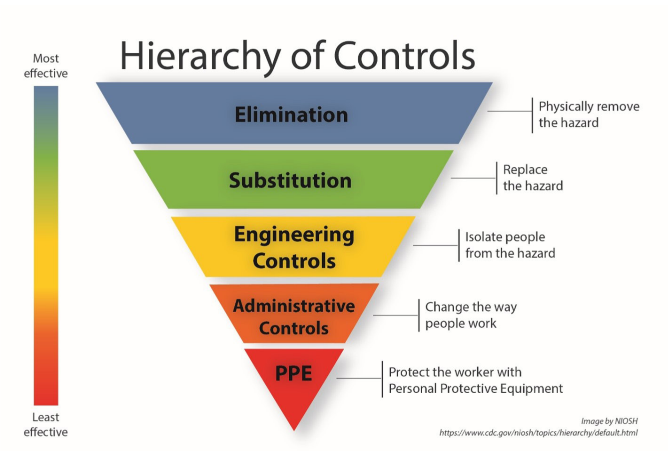

Figure 12
Hierarchy of controls[13].

(PPE) is the final, and therefore least effective, way to protect users from a hazard.

The engineering hierarchy for reducing/eliminating hazards requires that a known hazard should be eliminated by designing the hazard out of the system when possible. If a hazard cannot be eliminated through design, the next step is to guard against the hazard. Providing a safety harness/fall arrest system, which is accompanied by its own set of risks and hazards, does not give the designer/manufacturer free reign to produce and introduce into the stream of commerce defective and unreasonably dangerous treestands.

Summary

It was determined that the foot section contained a preexisting hole near a welded cross-member connection to the frame rails. More likely than not, the hole was generated during manufacturing of the treestand during the welding process.

Two exemplar treestands were experimentally tested to determine the threshold of energy as well as the maximum load to failure. One was tested in its as-received condition; the other was modified before testing to include a similar sized hole located at the same position as the hole found in the treestand. It was determined that a total energy of 1,425 lb-in. (max load of 950 lb) was required to induce an identical fracture in the exemplar treestand with a simulated hole. In contrast, it was determined that the exemplar treestand without a hole required a total energy of 2,380 lb-in. (max load of 1,120 lb) before fracturing. Therefore, it was concluded that the presence of the manufacturing-induced hole in the treestand's foot section resulted in ~40% reduction in load-bearing capacity of the treestand, thereby effectively eliminating the FOS of 2 that is reportedly used in the design of the treestand.

The Treestand Manufacturer's Association (TMA) standard (TMS-09 Rev. C) requires that each individual part and each assembled unit be inspected. The manufacturing-induced hole in the treestand was large enough and at a location on the treestand that would have been easily discoverable upon routine visual inspection. If the frame rail or assembled foot section had been inspected according to the above standard, this manufacturing-induced defect would have been discovered.

The design of the treestand relies on standards (TMS 11-98 and ASTM F2126-06) that require a minimum FOS of 2 with respect to the rated load capacity of the treestand under static loading conditions. However, due to the inherent nature of a climbing treestand (where the user is sliding the treestand up and down the tree during installation and disassembly), it is highly likely that at some point during this process, the user could slip, thereby imparting a dynamic load (impact energy) onto the treestand. As such, the design of the treestand was defective because it was only designed to withstand static loads without any consideration to additional stresses sustained by the treestand in the event of dynamic loading.

OSHA standards (29 CFR 1926.451 and 29 CFR 1917.118) require that scaffolds and fixed ladders, respectively, be designed to withstand four times the rated load capacity, or an FOS of 4. Both these devices are used to suspend individuals at a height, similar in function to the treestand that was only tested to an FOS of 2. This is in contradiction with the manufacturer's own quality assurance document, stating that components and assemblies should be tested to an FOS of 4.

Results of the authors' load-to-failure tests showed that the design of the treestand was defective, because as-designed, the tested exemplar treestands (with or without a hole) required 950 lb and 1,120 lb before fracturing, respectively, which is clearly less than four times the rated capacity (300 lb) of the treestand.

It has been reported that using safety harness/fall arrest systems can cause the user to be suspended for extended periods of time. This can lead to suspension trauma that can lead to death in as little as 30 minutes. A friend of the climber, who was hunting with the climber at the time of the incident, testified that it took him approximately 30 minutes just to find the climber's location after the incident occurred. It is possible that the climber could have sustained suspension related injuries following the collapse of his treestand had he attached his harness to the tree prior to his fall. By not utilizing the safety harness, the climber in no way contributed to the failure of the subject treestand's foot platform.

Conclusions

The results of the investigation indicated the weld hole reduced the load bearing capacity of the treestand by approximately 40%. In addition, examination of the overall design showed the current ASTM requirement of an FOS of 2 was inadequate because it failed to account for reasonably expectable dynamic loads that might occur during the use of the treestand.

Since the failure of the frame rail sections occurred under bending stresses, alternative designs incorporating a larger cross-sectional moment of inertia (bending resistance) should have been utilized.

Manufacturers must be cognizant that simply meeting a design standard does not ensure their product meet with acceptable engineering and design. The manufacturer should utilize the available codes and standards for design work, but they cannot blindly assume that meeting them is sufficient for a safe and effective design, as the standards are the floor, not the ceiling, for safety considerations. Manufacturers must consider what could be reasonably expected to occur during the life of the product and how these conditions can alter the integrity and efficiency of the device. Finally, the manufacturer's reliance on safety harnesses to make up for the deficient design of its product was inappropriate and does not shield the manufacturer from liability should an incident occur.

Acknowledgements

The authors would like to thank the legal experts they worked with on this case as well as their dedicated team of forensic engineers and interns.

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