Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org
ISSN: 2379-3252

Vol. 36 No. 1 June 2019

Forensic Engineering Analysis of Common Failures and Inspection Procedures for Residential and Commercial Chairs

By Anthony Sasso, PE (NAFE 986S)

Abstract

Chairs have been designed, manufactured, and used by humans for thousands of years. Eventually, all chairs wear out and fail. When someone is injured due to this failure, costly litigation can ensue. Forensic engineers are consulted to investigate the root cause of failure, and whether the mechanism of failure could have been detected prior to the accident to avoid injury. Materials used in chair manufacturing and several examples of failures are discussed in this paper. Industry safety standards and manufacturers' guidelines are used as a basis for a proposed inspection and maintenance program for chair owners.

Keywords

Chair, failures, forensic engineering, safety standards, inspection, maintenance

Introduction

Chairs, which have been designed and created for thousands of years, eventually wear out or break. Since humans rely on chairs to physically support them in everyday activities, serious injuries can occur when an unexpected failure occurs. In 2017 alone, the Consumer Product Safety Commission estimated that 669,992 injuries from chair, sofa, and sofa bed-related accidents were reported by hospitals to its National Electronic Injury Surveillance System (NEISS)[1]. A failure that leads to an injury can develop into litigation and lead to an investigation by a forensic engineer. Most chair failures are caused by one of three reasons: abuse by the occupant, a design/manufacturing defect, or improper maintenance/repair.

Modern chairs, which are typically not designed and manufactured using a single material, may have a variety of hardware used to assemble the parts and allow for adjustments. Manufacturers tend to market and sell chairs in a residential or commercial grade based on the intended usage of the chair. For example, residential chairs are usually designed with a weight capacity of 250 pounds or less, and intended for private residences where they will be used only a few hours a day. Commercial chairs are designed for heavier occupants (254 pounds to 400 pounds) who use the chair for many hours each day. This increased usage can be a single occupant in an office chair working a full day or at a retail business like a restaurant with many users throughout the day.

Determining which grade or category the chair was designed for may be difficult by simply looking at the chair. In some instances, the manufacturer will make the same style chair and use a weaker fastener (furniture staple) for the construction of the residential model and a stronger fastener (lag bolts or screws) for the commercial model. The sales price may not be an indicator of the category the chair was designed for (i.e., more expensive is better). Many commercial chairs are designed stronger but use lower-grade upholstery or fabric that can lower the sales price compared to a residential chair.

Most chairs feature structural components made from wood, metal, or plastic. These basic components (as shown in **Figure 1** on page 2), which represent traditional basic "stick-built" wood construction, include the seat pan (seat and front/back/side frame rails underneath), legs (with or without horizontal supports called stretchers), back rest, and arms. Most failures occur in the high stress points of the chair when occupied or loaded. The juncture of the seat pan with the rear leg and back rest is a common high stress point where failures often originate due to racking forces in the chair structure, especially if the occupant leans back and raises the front legs off the ground.

Anthony Sasso, PE, P.O. Box 12516, Tallahassee, FL (850) 524-4335; engineer@sassoengineering.com

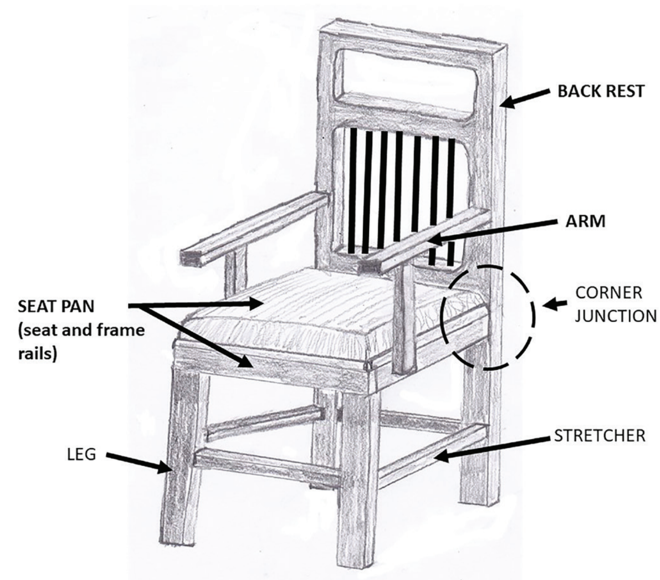

Figure 1
Basic chair components consist of the seat pan (seat and frame rails), legs, horizontal supports (stretchers), back rest, and arms. The rear joint where the seat pan connects to the back rest is called a corner junction.

Wood Construction

Chairs manufactured out of wood often use the same or similar construction techniques as in ancient times, such as mortise (square hole) and tenon (square peg) joints. Chairs are often assembled using adhesives and/or structural hardware, such as screws, nails, and lag bolts. These additional components can facilitate manufacture, improve strength, and reduce costs.

An example of a wood chair failure is shown in **Figure 2**. This chair was being used in a busy restaurant. Based on testimony, the seat was removed to be re-upholstered with new material. The seat was then reassembled improperly using different hardware.

Originally, the seat was attached using six lag bolts and washers, but it was reassembled using only four wood screws. The wood screws kept the seat loosely attached to the chair, but effectively eliminated the seat as a structural component in maintaining the original square shape of the seat frame rails. This greatly increased the stress on the mortise and tenon joints until eventually all the glue bonds broke. Wood shards torn away from the tenon were found on the surface of the glue within the mortise due to the stronger glue tearing the weaker wood material as the mated parts separated. A lag bolt that was screwed into the leg was the only component still holding the joint together after the glue bonds broke.

Internal wear and grooves on the mating surfaces of the joint served as evidence of prolonged movement between the parts that were once held tightly together. When the customer sat down, the wooden leg fractured around the lag screw, and the front leg completely separated from the chair, causing the customer to fall to the floor. An examination of exemplar chairs did not find any defects or the improper use of different screws that would lead to a similar joint failure. This example demonstrates the importance of proper assembly whether initially or while maintaining the chair.

Metal Construction

Another material often used in chair manufacturing is metal, such as steel, stainless steel, and aluminum. Many metal chairs also use hardware for construction, but most use welding in an effort to eliminate parts. When manufactured properly, the welded joint is stronger than its surrounding base metal, providing increased strength in the high stress areas of chair joints.

Many failures in metal chairs originate from a crack

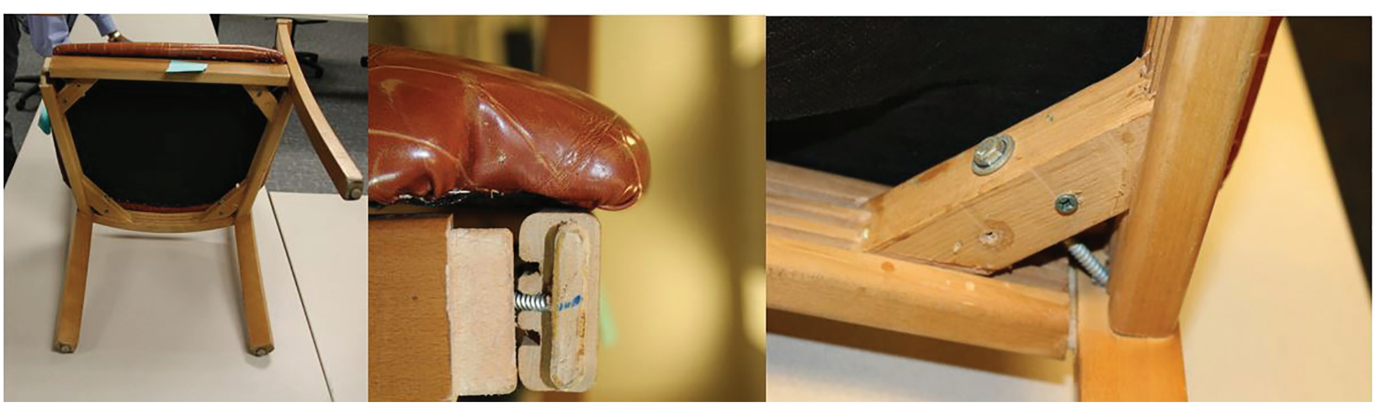

Figure 2
The wood chair's seat was reupholstered and then re-assembled improperly using different screws. This led to a failure in the front corner joint and caused the front leg to detach while a customer was sitting down.

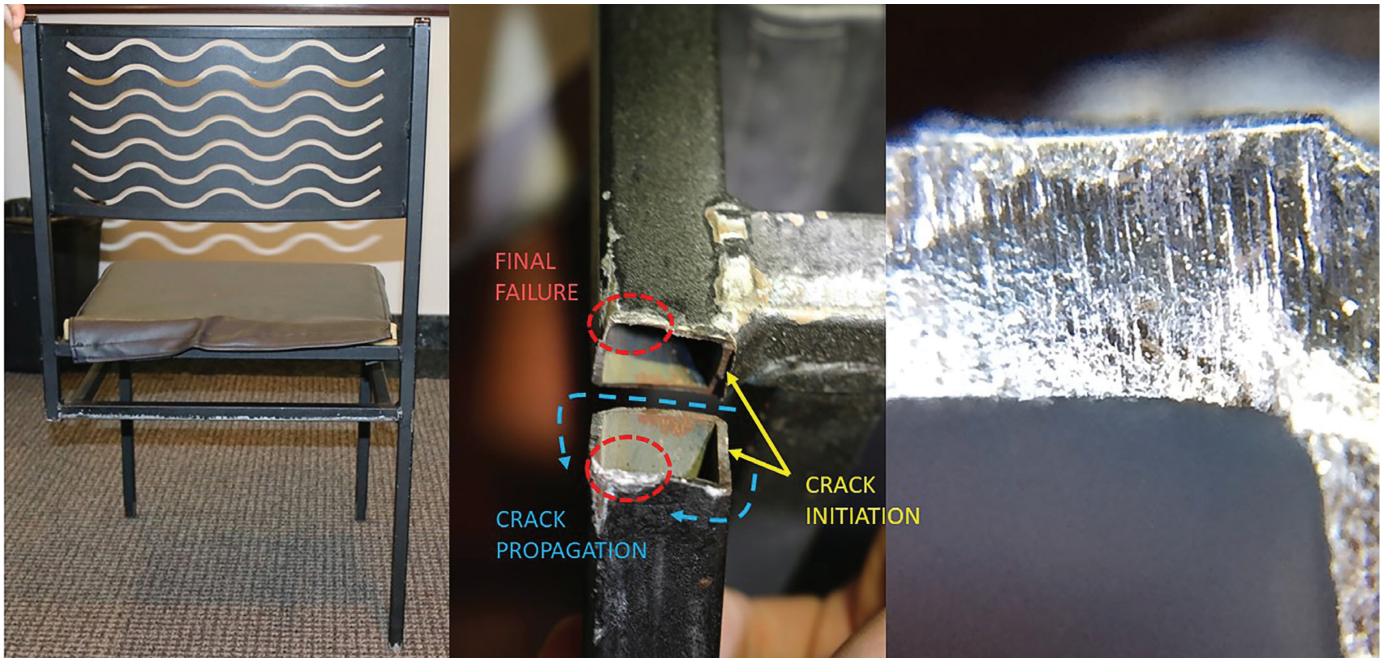

Figure 3
This welded steel chair was used in a high-traffic food court. A slowly propagating crack was created due to an internal manufacturing defect that eventually led to a leg collapse and injury to the occupant.

propagating through a joint or leg until the load is too great for the remaining material. As shown in **Figure 3**, this welded steel chair was used in a high-traffic food court. The customer was sitting in the chair for a few moments when the leg broke off, and the customer fell backward. No information tags or markings were on the chair to identify the manufacturer or any warnings, such as the weight limit. As the mall had been sold since the time of the accident, no information was available on the chairs as to where they were purchased. In addition, no exemplars from the mall were available to be inspected because the accident-style chairs had been discarded by the new owners. Through discovery testimony, the chairs had been used for approximately six years prior to the accident, and cleaned and stacked each day by the mall's employees.

The chair failure originated in the left rear leg, which is a square tube welded onto the horizontal frame rails. A crack developed at the toe of the weld, and slowly propagated over 2 inches around the tube (striations along the path of crack propagation) until approximately one-eighth of the tube was left attached, and the failure occurred. Visual observation of the fracture surface revealed an improper weld where the crack initiated. The fillet weld lacked penetration in several areas as the filler material took the flat smooth shape of the outside of the base metal tube, and did not form a proper welded bond. Evidence of porosity — or holes and bubbles in the weld — was also present along the length of the weld. The other three chair legs did not have any visible cracks at the weldments, even when a side force was applied at the bottom of the leg. Scratches and impact marks on the outside surfaces of the chair — and vertical bending or distortion in the rear legs beginning at the welded joint — were indicative of heavy usage, overloading of the rear legs, rough handling, and stacking of the chairs.

Since this case involved both product and premises liability, the forensic engineer was asked to determine the root cause of the chair failure as well as if the mall owner could have found the hazardous condition prior to the accident and injury. From the inspection, an improper weld during the manufacturing process (i.e., manufacturing defect) was found at the crack initiation point. An analysis of the strength of the chair's design revealed that an occupant weighing over 250 pounds and leaning back on just the two rear legs could distort and bend those legs. There was no information on the designed weight limit of the chair to determine if a design defect by the manufacturer existed; however, an overload and distortion of the back legs could have started the crack in the improper weld. Fatigue may have also contributed to the creation of the crack in the improper weld because the chair had been used heavily for a prolonged period of time prior to failure.

Once the crack began, it continued to propagate, leaving distinct striations until the leg finally collapsed. Crack formation and propagation rates have been extensively studied[2], and testing has shown the time it takes for cracks to propagate through a base material. Striations form during a period of accelerated crack growth after initial formation, and will continue as long as the loading reaches above a nominal threshold limit. As the crack grows larger, the propagation rate increases until the remaining material or part cannot handle the load and fractures completely.

An analysis was performed using the crack length, crack propagation rate for steel, and reasonable assumptions of the chair's usage based on testimony. The forensic engineer estimated the crack would have been present in the failed leg for a minimum of several months. During this time prior to the accident, the mall owner and employees had hands-on opportunities during daily cleaning, stacking, and unstacking to inspect the chair and find the hazardous condition. Unfortunately, the mall owner did not have any procedures or provide training in inspecting the chairs or other furniture of the food court for potential hazards.

Plastic Construction

Plastics are also widely used in chair construction, and come in many different varieties. Two of the most common styles of plastic chairs are the one-piece molded lawn chairs and plastic chairs molded into parts and assembled with metal hardware. Typically, plastic chairs are designed, bought, and used in outdoor environments where humidity and pests can rapidly degrade other types of materials.

ASTM International, formerly known as the American Society of Testing and Materials, has developed several safety performance standards[3] for manufacturers of new outdoor plastic chairs and chaise lounges. Primarily, these standards specify environmental weathering tests of the plastic material to be used and static/impact load testing for chairs intended for residential use (300 pounds weight-static) and non-residential use (400 pounds weight-static). These performance standards also include raising the front legs 3 to 4.5 inches off the ground to test the full weight on the rear legs alone.

An example of a plastic chair failure can be seen in **Figure 4**. From the date stamp, the chair was manufactured in July of 1997, and used at a busy restaurant in Florida for more than 14 years at the time of the accident in 2012. As shown in **Figure 5** on page 5, the plastic recycle symbol with the number "5" and the letters "PP" stamped below designate this chair's material as polypropylene.

The chair was molded as a single piece similar in size, shape, and material thickness to many other outside plastic chairs on the market. The chair was stacked nightly and stored uncovered outside over the 14-year time period prior to the accident. The customer was seated properly and eating dinner for 20 minutes when the chair's rear legs collapsed. The customer fell backward and was injured. The plaintiff's wife took several pictures of the subject chair and surroundings shortly after the accident. The restaurant

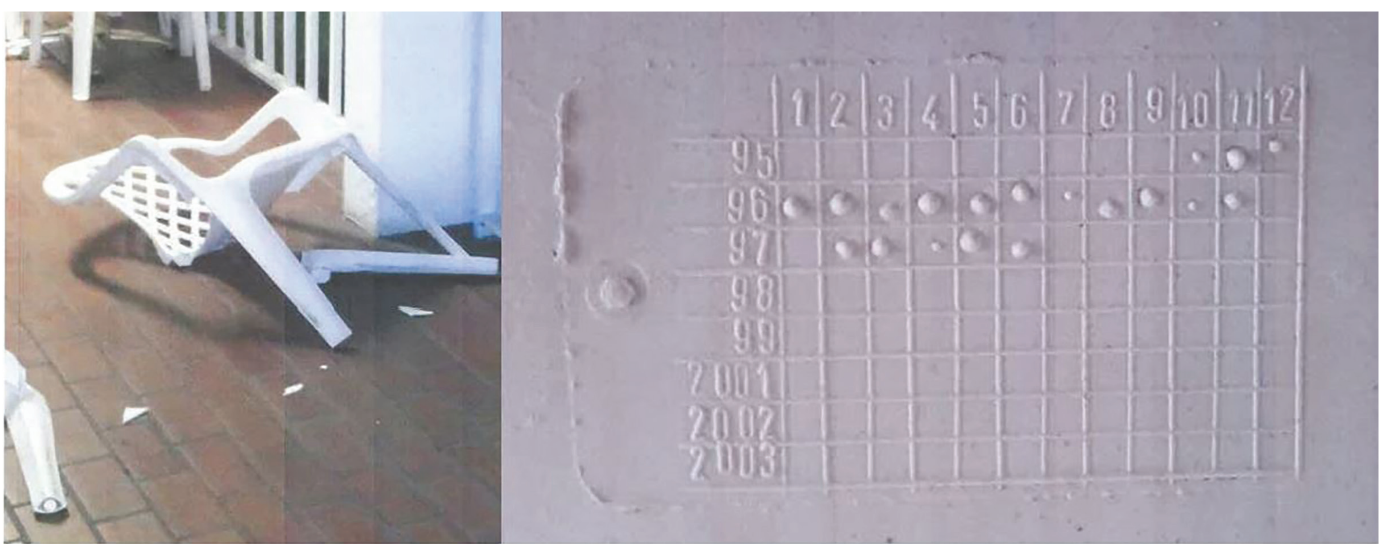

Figure 4
This molded plastic chair was used outside at a Florida restaurant for more than 14 years prior to the rear legs collapsing. The date stamp in grid form uses a dot of plastic to fill in and mark the month (column) and year (row) of manufacture. The above stamp displays this chair was manufactured in June of 1997.

employees discarded the damaged chair even though the plaintiff requested the chair be preserved prior to leaving for the hospital.

It is common for a broken chair to be discarded even though the customer has incurred injuries and requested the chair be preserved. In the absence of a physical chair, the possible causes of failure can be reduced through the use of testimony, photographic evidence, and exemplar testing. In this case, all of the exemplar chairs were also discarded shortly after the incident, which eliminated the opportunity to inspect and test these chairs. A determination could not be made from the photographs about who manufactured the chair and whether it was designed for residential or non-residential use. A published case study[4] of an accident involving a similar molded chair was tested to the ASTM F1561 (1996) performance standard[3].

Exemplar chairs preserved from the published outdoor accident location were tested six years after manufacture. The chairs were also one-piece molded plastic lawn chairs made of polypropylene, and exhibited rear leg deformation under static seat loading of 300 pounds and 400 pounds. Both back legs splayed rearward slowly over the test time period of 30 minutes.

The present case closely resembles the published study in the chair's size, shape, material, and outdoor usage in a similar climate (southeast United States) over an extended period of time. The loading of the chair (and its subsequent deformation) is also similar in that the plaintiff weighed 266 pounds or 87% of the ASTM test weight (300 pounds), and he described the collapse of the chair occurring after 20 minutes of usage. Both rear legs are fractured at the seat pan, which is indicative of the legs splaying rearward prior to failure.

Figure 5
The plastic recycle symbol with the type "5" and letters "PP" stamped below designate the material as polypropylene.

Research[5] has also shown that once significant degradation of plastic takes place due to ultraviolet (UV) light, humidity, and temperature, the surface will turn chalky and lose some of its glossiness. In addition, white or light-colored plastic will begin to turn greyish due to this environmental degradation or weathering. From analysis of the photographs, the accident chair's surface exhibited a distinguishable loss of glossiness and greyish streaks due to prolonged outdoor use and weathering. These streaks were also visible in areas that would not routinely be contacted by use or during stacking. Based on the above, the accident was determined to be caused by the chair's structural strength weakening over time due to heavy daily use and environmental degradation.

Abuse, Defects, Warnings, Intended Use, Maintenance

A common reason given for a chair failure is that the occupant was abusing the chair or simply not using it as the designer intended. Inadvertent abuse may also cause a failure when the occupant significantly weighs more than the load capacity of the chair. The customer may inadvertently sit in a chair that appears to be sturdy only to have a leg buckle when sat upon.

Some chair manufacturers include weight capacity and use restrictions on labels underneath the seat or in product information such as the owner's manual. "Residential Use Only" is a commonly used phrase that can be found on chairs not designed for heavy-duty commercial use, and is generally accompanied by a weight capacity warning of 250 pounds or less. This information is very helpful when buying chairs, but the general public relies on business owners to purchase chairs that can meet or exceed the weight capacity of their intended customers. It may be a failure to warn[6] of this hazard by both the business owner and the manufacturer if the chair's weight capacity is inadvertently exceeded. There are engineering design safety standards[7,8] that many manufacturers follow, but most of these standards are voluntary.

The second reason for chair failures is a design or manufacturing defect. Design and manufacturing defects continue to occur in chair construction due to the "human element" as they do with other products. Defects are commonly found in either the construction elements or the overall stability of the chair. Construction elements include the part and assembly design, manufacturing, and assembly instructions if the chair is intended to be assembled after purchase. For example, a construction defect might involve using a fastener that is too small for the intended load and causes a premature failure.

Stability defects can occur due to designing a chair with a base that is too small for the overhanging load produced when the seat is occupied. Stability defects are commonly found in adjustable chairs and chaises during the initial dynamic sitting motion of the occupant into a reclined position.

An example is shown in **Figure 6** of a 240-pound exemplar male sitting down into the adjustable chair. The newly purchased chair had a weight capacity of 350 pounds, and flipped over rearward the first time the plaintiff sat down. The chair's base was composed of five equally spaced caster wheels at a radial distance from a central column. Upon inspection and testing, the wheels were found to be designed too close to the center column to counteract the dynamic rearward force caused by the occupant sitting down into the chair.

The stability testing performed consisted of two parts. The first test was a static measurement of the center of gravity or overhanging weight of the occupant, back rest, and seat. For this test, the exemplar occupant sat in the fully reclined chair with the caster wheels rotated to the position that provided the least resistance to overturning[8]. The least resistance occurred when one caster wheel was positioned directly to the front of the chair (0 degrees), leaving only two wheels behind the center column and equally angled away from the rear centerline of the chair (180 degrees).

In this position, the effective moment arm of the counterbalancing force from the base is significantly reduced compared to when a single caster wheel is positioned directly to the rear. The measurements revealed the center of gravity of the occupant and chair was approximately in line with the two rear caster wheels such that the front caster wheel would briefly elevate off the ground by approximately ¼ inch when the occupant would move his arms back and forth from the armrests to the headrest. The second part of the testing consisted of having the exemplar occupant sit down normally several times into the chair that was adjusted and wheels positioned as before. The

Figure 6
The exemplar male sat down normally into the adjustable office chair, and toppled over rearward due to a stability defect in the design of the chair.

occupant and chair toppled over backward with the spotters stopping the motion before the occupant impacted the floor each time this dynamic test was performed. Further analysis of the design revealed that the base provided adequate stability for the stated weight capacity when a caster wheel was positioned directly to the rear of the chair.

By utilizing safety standards, design and manufacturing defects can be reduced or eliminated. The Business and Institutional Furniture Manufacturer's Association (BIFMA) is a trade association that promotes safety standards for commercial furniture[7]. Several standards cover general-purpose office chairs and lounge furniture, and contain tests for their structural strength, durability, and stability[8].

Over the past two decades, BIFMA has revised its standards for the increasing average weight of the American public. In 2002, the office chair standard (X5.1) utilized the 95th percentile male weight of 253 pounds in its test procedures. In 2011, based on government survey data, it began using the new 95th percentile male weight of 275 pounds. In 2015, BIFMA released X5.11 Large Occupant Office Seating, which is intended for weight capacities from 254 pounds to 400 pounds. These standards are developed for a useful life of 10 years in single-shift environments of 8 hours per day. A shorter useful life is to be expected under high-traffic or heavy usage. In addition, industrial machine safety standards[9] are beginning to incorporate the "reasonable foreseeable misuse" design criteria, which is likely to be included into the different chair standards in the near future.

Chair manufacturers also have a duty to inform customers of intended usage, proper care/maintenance, and inspection of their products. Some manufacturers will provide a care and maintenance guide for the particular variety of chair construction in the owner's manual, informational label on the seat bottom, or an online website. The guidelines are often included in the warranty requirements. Within these guidelines[10,11] is a requirement to perform a routine inspection of the chairs.

Inspections should be performed every one to three months at minimum, and range from weekly to daily for heavy usage. Beginning with a visual inspection and retightening all hardware, the guidelines recommend checking the structural joints, seat, legs, foot sliders, adjustment or moving parts, and high stress areas. The chair must be manually turned over in a hands-on approach to inspect the high stress areas underneath the seat. The assembly instructions and maintenance guidelines need to be simple to understand and follow because the chair owner has the responsibility to care for and maintain the chair after it is purchased.

The third reason for failures is the owner incorrectly assembled, repaired, or failed to implement an inspection and maintenance program. This chair owner is still responsible for creating an inspection and maintenance plan, even though the manufacturer fails to provide any guidelines or a weight capacity for the chair. Most state laws require the business owner to provide a safe environment for customers from known hazards and hazards that should have been known[6]. An owner of a chair used in a private residence should also follow all of the manufacturer's guidelines for assembly and maintenance; however, the period between inspections may be lengthened if the chair is rarely used.

A typical response from an owner after a chair collapse is that there was never an issue or complaint from customers or staff; therefore, they were unaware of any potential hazards. Under oath, many owners will admit to not having an inspection and maintenance program in place. In addition, they rely on their own or their employees' general common knowledge of chairs to discover hazardous conditions. This may be sufficient for obvious hazards, such as an exposed screw or nail. However, a structural hazard (even though it is visible) can be complex and not detectable by the general population without additional training.

As previously described in the welded metal chair failure scenario, a common example is a slow-developing crack in the frame of a chair. Cracks may not cause an immediate failure, but when left unrepaired will eventually progress into a fracture that can cause a collapse. A visual inspection alone can reveal surface defects, but it is not an adequate test of the structural integrity of the chair. In addition, inspecting the chair by simply sitting in it is also inadequate and highly subjective, since chairs may not exhibit excessive movement or instability prior to failure. The owner needs to physically handle and test the chair to expose any joint damage.

Residential and commercial chair owners should follow some basic steps in order to implement a proper maintenance program. First, follow all manufacturers' guidelines and be knowledgeable of the weight capacity and useful life of the chair. In the absence of any information and to be as safe as possible, assume the chair is meant for light use with a weight capacity of less than 250 pounds, and a maximum useful life of 10 years (single shift use) or less.

Business owners should purchase chairs that have passed performance and safety standard testing, are rated for commercial use, and have a weight capacity over 300 pounds. Second, perform a visual and hands-on inspection every month — or more frequently for heavy usage — and every three months for light usage. A visual inspection should look for damage, cracks, gaps between parts, and foot slider wear. The hands-on inspection should begin by tightening all hardware, checking for instability, turning the chair over to inspect the joints underneath the seat, and pushing and pulling on the legs to check for any cracking or excessive movement.

A "flex test"[12] should be performed to check the structural integrity of the chair. This test mimics the BIFMA chair strength tests in stressing the rear corner junctions, back rest, and legs. For example, the backrest strength test uses a 150-lb functional load applied to the backrest while the legs are restrained from movement.

Research[13] has shown that the greatest force generated on the backrest is when the occupant first sits down into the chair. This force can be a substantial fraction of the occupant's weight.

Based on this published research by Hu, et.al., the BIFMA backrest strength test's functional load of 150 pounds would be equivalent to an occupant with a weight of 435 pounds sitting down into the chair. For an occupant weighing 250 pounds in a residential use chair, this correlates to a backrest force of 86 pounds or 43 pounds on each backrest corner

Figure 7
"Flex test" of wood dining chair. By applying forces on the seat front and upper backrest, the inspector can mimic the occupant loading on a rear corner junction for a residential (250-pound weight capacity) and commercial (300-pound weight capacity) chair.

As shown in **Figure 7**, the flex test is performed by leaning the chair on the rear legs, placing one hand on a corner of the back rest and the other hand on the front seat corner, and slowly applying force to observe any gapping or movement in the corner junction for that side of the chair. Leaning the chair on the rear legs will give the inspector greater leverage to use his own weight in applying a force on the order of 45 pounds for residential chairs and 55 pounds or greater for commercial chairs (300 pounds or greater occupant weight). The use of an accurate household weight scale or similar force measuring device under the rear corner junction and leg being tested may be helpful to the inspector while performing this test. Compare both sides of the chair and any other similar model chairs to help decide when a chair has joint or leg movement but no visible signs of gapping between parts or external damage. Not all the chairs in a group will wear out at the same rate. Consult a furniture repair professional for additional inspection and repairs if any gapping or excessive movement in the backrest, corner junction, or legs are noticed. Remove and discard any damaged chairs that cannot be repaired back to their original condition.

In conclusion, several chair failures have been discussed, and inspection procedures based on industry safety standards and manufacturer guidelines proposed. Forensic engineers are hired to investigate the mechanism of failure, the length of time prior to the accident that the hazardous condition existed, and if the owner or customer were aware of the impending failure. Chair failures are primarily due to abuse, design, or manufacturing defects — or improper maintenance by the owner. Chair failures and injuries will continue to occur. However, by purchasing quality chairs from manufacturers who design to safety standards and provide detailed care and maintenance guidelines and implementing a proper inspection program, owners can reduce the risk of injury in the future.

References

1. "National Electronic Injury Surveillance System (NEISS)," CPSC.gov, 8-Aug-2018. [Online]. Available: https://www.cpsc.gov/Research--Statistics/NEISS-Injury-Data. [Accessed: 16-May-2019].

2. R. O. Ritchie, "Mechanisms of fatigue-crack propagation in ductile and brittle solids," International Journal of Fracture, vol. 100, pp. 55–83, 1999.

3. Standard Performance Requirements for Plastic Chairs for Outdoor Use. ASTM International Standard F1561 (1996)

4. J. Leffler, "Forensic Engineering Investigation of an Alleged Plastic Chair Failure," Journal of the National Academy of Forensic Engineers, vol. 27, no. 2, pp. 55-64, 2012.

5. M. Philip, J. Attwood, A. Hulme, G. Williams and P. Shipton, "Evaluation of Weathering in Mixed Polyethylene and Polypropylene Products," The Waste & Resources Action Programme, Banbury (UK), 2004.

6. Official Florida statutes. Tallahassee: State of Florida, 2017, s. 768.0755.

7. "BIFMA Standards Overview," BIFMA. [Online]. Available: http://www.bifma.org/?page=standardsoverview. [Accessed: 10-Oct-2017].

8. General Purpose Office Chairs-Tests, ANSI/BIFMA Standard X5.1 (2011)

9. Safety of Machinery - General Requirements and Risk Assessment, ANSI Standard B11.0 (2010)

10. "FALCON Care and Maintenance Guide" Falcon Products. [Online]. Available from: www.falconproducts.com [Accessed 12-Oct. 2017]

11. Shelby Williams-CFGroup (2013) Handle with Care: Appropriate Care Ensures a Solid Return on Investment [Brochure]. https://www.shelbywilliams.com/files/docs/brochure-shelbywilliams-white-paper-care-4171.pdf.

12. Friedrich v. Fetterman and Associates, P.A., SC11-2188, (Fla. 2013)

13. L. Hu, O. Tor, J. Zhang, B. Tackett, and X. Yu, "Analysis of Back Forces While Sitting Down, Seated, and Rising from a Stationary Chair in Subjects Weighing 136–186 kg," Advances in Ergonomics Modeling, Usability & Special Populations Advances in Intelligent Systems and Computing, pp. 39–49, Mar. 2016.