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A Forensic Engineering Investigation of a Ladder Failure

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Abstract

A worker (Plaintiff) fell from a step-ladder and was injured. The purpose of the Forensic Engineering investigation was to determine the cause(s) of the incident, and in particular, if the incident was caused by a ladder defect. The incident ladder and a representative incident scene were inspected. Various discovery documents and the applicable American National Standards Institute (ANSI) standard were reviewed. A critique from the opposing (Defendant's) expert is presented and addressed. The cause of the Plaintiff's fall from the ladder was determined to be its sudden instability due to the failure of a rivet that secured the top cap to the left-front rail. The failed rivet was not recovered. Further analysis indicated that the cause of the rivet failure was its defective design coupled with its reduction in shear load capacity from normal and improper use of the ladder. The determination of the defective design of the rivet was confirmed by subsequent design improvements of the ladder. The relevance of the analysis performed is discussed. Various noteworthy points are presented for consideration for Forensic Engineers of various technical disciplines.

Keywords

Ladder, Rivet, Shear, Safety Factor, Adherence, Design, ANSI, Fatigue, Work Hardening

Ladder Description and Inspection

The incident ladder was an eight foot aluminum step-ladder with a duty rating of 225 lbs. The change in elevation between each step was one foot. An overall view of the ladder is shown in Figure 1. A label affixed to the ladder referenced ANSI A14.2-1981.

Figure 1
Overall View of the Ladder

The overall condition of the ladder was poor. Various scratches, abrasions, deformations, wear marks, etc., indicate that the ladder was used, at times improperly, relatively frequently since it was placed in service. Two rivets secure each of the front rails to the top cap, and one rivet secures each of the rear rails to the top cap. The rear rivet that secures the left-front rail to the top cap was missing (see Figures 2 and 3), and was not recovered. Also shown in Figure 2 are gouge

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marks on the left-rear rail that appeared to be relatively fresh and consistent with an impact from the top-rear edge of the left-front rail. Several other ladder rivets were loose and/or distressed. The foot of the left-rear rail was missing (see Figure 4). The other ladder feet were significantly worn to the point that the metal foot clamps would contact the ground surface when the ladder was in use. The wear on the feet of the front rails was most severe toward the front of the ladder (see Figures 5 and 6). Additional areas of noteworthy damage to the ladder were the downward deformation of the center portion of its top cap and bent diagonal braces that support the first step of the ladder and the lowest cross brace between the rear rails.

It is possible that some of the damage to the ladder occurred as a result of the incident. Nonetheless, it is reasonable to conclude that the pre-incident condition of the ladder warranted it being taken out of service and discarded.

Figure 2
Missing Top Cap Rivet (Arrow 2) and Rail Gouge Marks (Arrow 1)

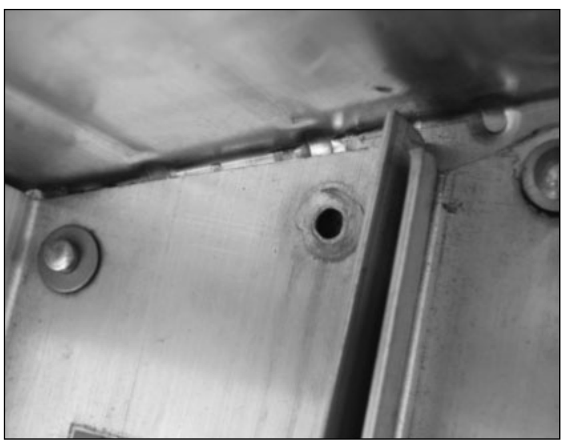

Figure 3
Inboard Side of the Ladder at the Failed Rivet Location

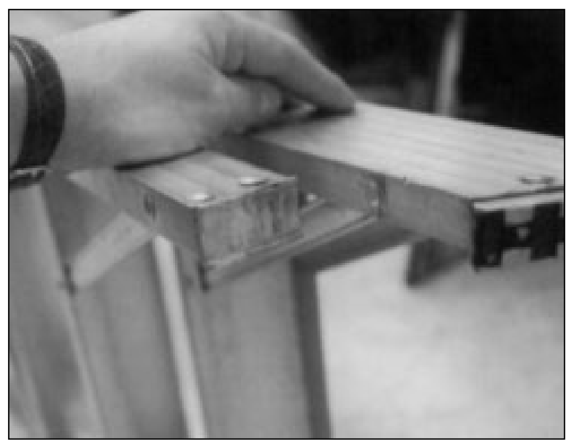

Figure 4
Missing Foot from Left-Rear Rail

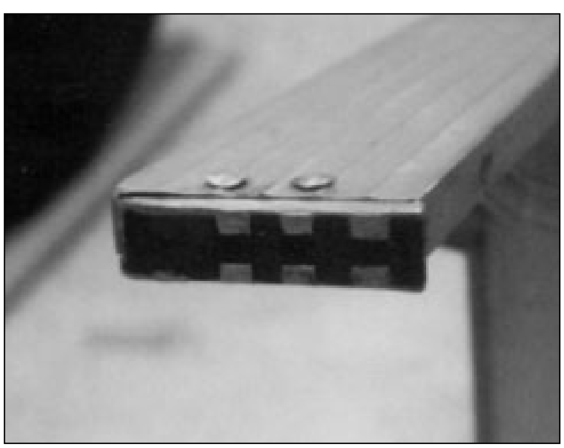

Figure 5
Wear of Right-Front Rail Foot

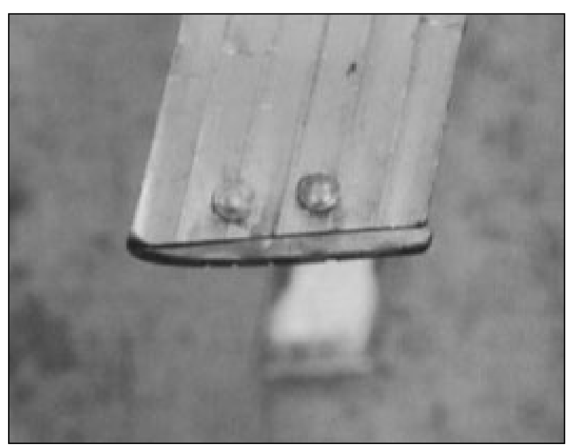

Figure 6
Profile of Right-Front Rail Foot Wear

Incident Description

The following pertinent information was contained in the Plaintiff's deposition transcript regarding his fall from the ladder:

- The Plaintiff was using the ladder to place 3 feet by 2 feet (other dimension not specified) boxes of bed pillows on the top shelf of a set of storage racks (see Figure 7). The top shelf was between 10 and 12 feet above the floor. The incident occurred at 1:30 pm. The Plaintiff first used the ladder at 1:00 pm that day.
- The Plaintiff locked the ladder spreader bars and made sure that all four of its feet were in contact with the concrete floor. The ladder was stable during his ascent of the ladder and at all times prior to the incident.
- At the time of the incident, the Plaintiff had been waiting for another pallet of pillow boxes while standing on the fifth or sixth step of the ladder for a couple of minutes. He was between the front rails of the ladder, facing the ladder, and motionless.

Figure 7
Representative Pre-Incident Position of Plaintiff

- While in this position, the ladder suddenly became unstable. The Plaintiff indicated that it felt like the ladder twisted as he fell from it.
- The Plaintiff was 5'11" and 200 lbs., at the time of the incident.

Cause of Plaintiff's Fall from the Ladder

During the inspection of the ladder, its lower steps were carefully ascended. The stability of the ladder significantly decreased with each ascending step. The origin of this instability was at the location of the aforementioned missing rivet that previously secured the top cap to the left-front rail. Fresh gouge marks on the left-rear rail are consistent with an impact from the top-rear corner of the left-front rail as a result of the rivet failure. It is therefore reasonable to conclude that the missing rivet was in place immediately before the incident, and that its failure caused the ladder to become unstable and the Plaintiff to fall from it.

The above analysis was not challenged by the Defendant. The task then became to determine the cause of the rivet failure. Of course it is very difficult to determine if the rivet failed due to a material or manufacturing defect without the rivet, which was not recovered. The remaining option was to determine if the design of the rivet was defective.

Applicable Industry Standard

The following excerpts are from the American National Standard Safety Requirements for Portable Metal Ladders (ANSI A14.2-1981), which is an applicable industry standard for the incident ladder:

- *1.1 Scope. This standard prescribes rules governing the safe construction, design, testing, care and use of portable metal ladders…*

Interpretation: If the ladder does not meet the ANSI A14.2-1981 requirements, it is defective.

- *1.2 Purpose…It is not the purpose of this standard to specify all the details of construction of portable metal ladders. The limitations imposed are for the purpose of providing adequate general requirements and testing methods.…*

Interpretation: Meeting the ANSI A14.2-1981 requirements, although necessary, is not sufficient proof that the ladder is not defective.

Various design verification tests are specified in ANSI A14.2-1981, which were performed on sample ladders by Underwriters Laboratories (UL). The test that is most relevant to the incident is the Step-to-Side-Rail Shear Strength Test. The magnitude of the load for this test was 900 lbs. Since the duty rating of the ladder is 225 lbs., the respective minimum factor of safety associated with this test is 4.0. It is reasonable to extend this factor of safety (i.e., design factor) requirement to the failed rivet. The justification for doing so will be discussed in the *Opposing Expert's Critique* section of this paper.

Ladder Design Analysis

The following methodology was used to determine if the design of the failed rivet was defective:

- Determine the maximum loading of the rivet when the ladder is used within the manufacturer's limits (design scenario).
- Determine the resulting shear stress in the rivet.
- Determine the shear strength of the rivet material.
- Determine the factor of safety by dividing the rivet shear strength by the resulting stress in the rivet.
- If the factor of safety is four or greater, the rivet design is adequate for shear loading. If the factor of safety is less than four, the rivet design is defective.

Rivet Design Loading

A "Danger" label was affixed to the seventh step of the ladder that read, "DO NOT STAND ON OR ABOVE THIS STEP." Therefore, a 225 lb. load distributed over a length of 3.5 inches (representative of the width of a human foot and per ANSI A14.2-1981) on the sixth step next to the left rail was used as the design scenario for the loading of the failed rivet. This loading scenario resulted in a shear load in the failed rivet of approximately 160 lbs.

Resulting Shear Stress in the Failed Rivet

Average shear stress is determined by dividing the shear load by the shear area (i.e., τ=V/A). Although this approach is often used for the design of rivets, bolts and other fasteners, a more in-depth analysis is warranted. The equation for the maximum direct shear stress in a beam of circular cross-section, is τ=1.33V/A, which occurs at its neutral axis (i.e., horizontal diameter). An even more elaborate analysis shows that the shear stress varies from 1.23V/A at the ends of the neutral axis to 1.38V/A at the midpoint of the neutral axis for a circular cross section.

Measurements of the rivet hole and discovery documents provided by the Defense indicated that the diameter of the failed rivet was 3/16 inch. Considering a shear load 160 lbs., and a direct shear stress formula of τ=1.33V/A, the resulting shear stress in the rivet is approximately 7,700 psi.

Rivet Strength

The material noted for the failed rivet in the discovery documents provided by the Defendant is "ALUM 1100-H18." Some of the mechanical properties of this grade and temper of aluminum alloy are:

- Ultimate Strength – 24,000 psi
- Yield Strength – 22,800 psi
- Shear Strength – 13,000 psi
- Elongation – 15%

Failed Rivet Design Adequacy

The resulting factor of safety of the failed rivet for the design loading scenario noted above is approximately 1.7 (i.e., 13,000psi/7,700psi). Since this value is substantially less than four, the design of the failed rivet can be deemed defective. However, a factor of safety of 1.7 itself will not result in a failure. Theoretically, a failure will occur when the factor of safety is less than 1. Further, the Plaintiff weighed 200 lbs., at the time of the incident and was standing on the ladder in a way that would have generated considerably less shear stress in the failed rivet (i.e., he was not standing on one foot at the left end of the sixth step). Therefore, the actual factor of safety of an undamaged rivet for shear loading immediately before the incident was significantly greater than 1.7.

Actual Rivet Shear Load Capacity

Of the observed pre-incident damage to the ladder, the wear pattern on the feet of the front rails was one of the more relevant factors with respect to the failure of the missing rivet (see Figures 5 and 6). The wear of these feet is more severe toward the front of the ladder. This indicates that the ladder was moved on numerous occasions by pulling and dragging it by one of its upper steps. The associated vibrations would have resulted in dynamic and cyclical loading of the failed rivet. This loading and that from regular usage likely weakened the rivet prior to its failure.

Opinion

Based on the above information and analysis, the writer opined that the cause of the Plaintiff's fall from the ladder was its sudden instability due to the failure of the rear rivet that previously secured the left-front rail to the top cap.

The cause of the rivet failure was twofold:

1) The design of the failed rivet was defective. Calculations show that at least one loading scenario of the ladder, within the manufacturer's acceptable usage limits, would have resulted in a factor of safety of less than 2.0. The minimum factor of safety associated with a related design verification test in the applicable American National Standard Safety Requirements for Portable Metal Ladders (ANSI A14.2-1981) is 4.0, and

2) The weakened condition of the rivet from dynamic and cyclical loading, as a result of improper (i.e., dragging it numerous times) and regular usage.

Opposing Expert's Critique

The Defendant's expert had experience investigating numerous ladder failures. He also served on and chaired various ANSI ladder standard subcommittees. The following are some of the more relevant points of his critique of the writer's methodology and opinions noted above:

- Misapplication of ANSI A14.2-1981
- Irrelevant Loading Scenario
- Improper Shear Stress Formula
- Rivet did not Fail when Loaded to a Factor of Safety of Less than 1
- Greater Actual Rivet Strength Due to Work Hardening during the Setting of the Rivet

Application of ANSI A14.2-1981

The opposing expert stated that the writer's, "assumptions regarding the ANSI standard and how it should be applied to the rivet are not reasonable. The subject ladder design passed all of the test requirements of ANSI A14.2." During the writer's deposition, Defendant's counsel inquired about the validity of extending an implied factor of safety from one of ANSI's design verification tests to the failed rivet.

A duty rating of 225 lbs., and a design verification load of 900 lbs., for the step-to-side-rail shear strength test results in a minimum required factor of safety of 4.0 for the shear loading of the step-to-side-rail rivets where the test load was applied. ANSI A14.2-1981 states, "The test load shall be applied on the longest braced and unbraced steps of the ladder with the least fastening." For the incident ladder these are the first and fourth steps, respectively.

The potential for harm is greater for falls from steps at higher elevations. Therefore, the factor of safety for shear loading for the rivets that secure the higher steps to the front rails should be no less than that of those for lower steps (e.g., the factor of safety for the fifth step rivets should be greater than that for the fourth step rivets, sixth greater than the fifth, etc.). The loading of the failed rivet increases as the ladder is ascended, as the support for the loading on the steps is transferred from the ladder front feet to the top cap. Therefore, the failed rivet is more susceptible to a shear failure when one is standing on the left end of sixth step of the ladder compared to standing at the left end of the fourth step. For this reason a factor of safety of no less than 4.0 should be applicable to the failed rivet for shear loading.

Design Loading Scenario

The opposing expert made a point that the design loading scenario described above (i.e., 225 lbs., distributed over a 3.5 inch width at the left end of the sixth step) was not relevant since the Plaintiff did not impart such a load on the ladder at the time of the incident.

The duty rating of the ladder is 225 lbs. This load distributed over a 3.5 inch width at the left edge of the sixth step of the ladder results in the maximum shear loading of the failed rivet while using the ladder properly (i.e., standing on one foot anywhere below the seventh step of the ladder). It would therefore be proper to use this loading scenario to evaluate the design adequacy of the failed rivet. The fact that this was not the loading scenario at the time of the incident has no bearing on the design adequacy of the rivet. However, it does raise the question of to what degree the defective design of the failed rivet contributed to its failure. Although the loading of the rivet at the time of the incident was most likely substantially less than that from its design loading scenario, the defective design of the rivet was a significant contributing factor to its failure.

Rivet Shear Stress Formula

The opposing expert indicated that the appropriate formula for shear stress in the rivet is τ=V/A. The writer's basis for using τ=1.33V/A is noted in the *Resulting Shear Stress in the Failed Rivet* section above. To gain further insight into the shear stress distribution in the failed rivet from the design loading scenario, two finite element analysis (FEA) shear stress approximation plots were generated. The first plot was generated by uniformly distributing the shear load over the rivet bearing surfaces in contact with the top cap and left rail (see Figure 8). The second plot was generated by concentrating the loads from the top cap and the left rail at the top and bottom of the rivet (see Figure 9). It is expected that the actual loading distribution would be non-uniform and closer to the concentrated loading scenario.

The FEA shear stress plots shown in Figures 8 and 9 are near the axial mid-point of the rivet. Recall that the calculated maximum shear stress in the rivet using the τ=1.33V/A formula was approximately 7,700 psi., which is reasonably close to the maximum shear stress of 7,758 psi shown in Figure 8 (uniform distributed loading). The maximum shear stress shown in Figure 9 (concentrated loading) of 8,662 psi is approximately equal to 1.5V/A. It is expected that a more elaborate analysis utilizing a more realistic non-uniform distributed loading (i.e., greatest loading at the top and bottom of the rivet that diminishes rapidly toward the ends of the neutral axis) would result in a maximum shear stress near 7,900 psi (i.e., τ~1.38V/A) at the mid-point of the neutral axis as noted above. Using the average shear stress equation (i.e., τ=V/A) yields a shear stress value of approximately 5,800 psi. Selected locations of this average shear stress value are shown in Figures 8 and 9.

The FEA shear stress plots show a shear stress distribution that is generally consistent with near zero shear stress at the top and bottom of the rivet and the maximum shear stress at the neutral axis that is reasonably close to the calculated value. Although an approximation by nature, the FEA stress plots tend to confirm that τ=1.33V/A would be a more appropriate equation to determine the maximum shear stress in the rivet than τ=V/A.

Another type of stress in the failed rivet that warrants consideration is bearing stress. Two additional FEA plots were generated showing the equivalent (i.e., von Mises) stress in the failed rivet from bearing and shear loading. These plots were of sections of the rivet directly below a bearing surface. The range of stress levels in the rivet again varies greatly. As expected, the greatest stress was at the bearing surface at the top of the rivet, which was greater than the ultimate strength of the rivet. However, the actual stress at this location was likely less as the surfaces of the failed rivet holes in the top cap and left rail were deformed, resulting in larger bearing surfaces.

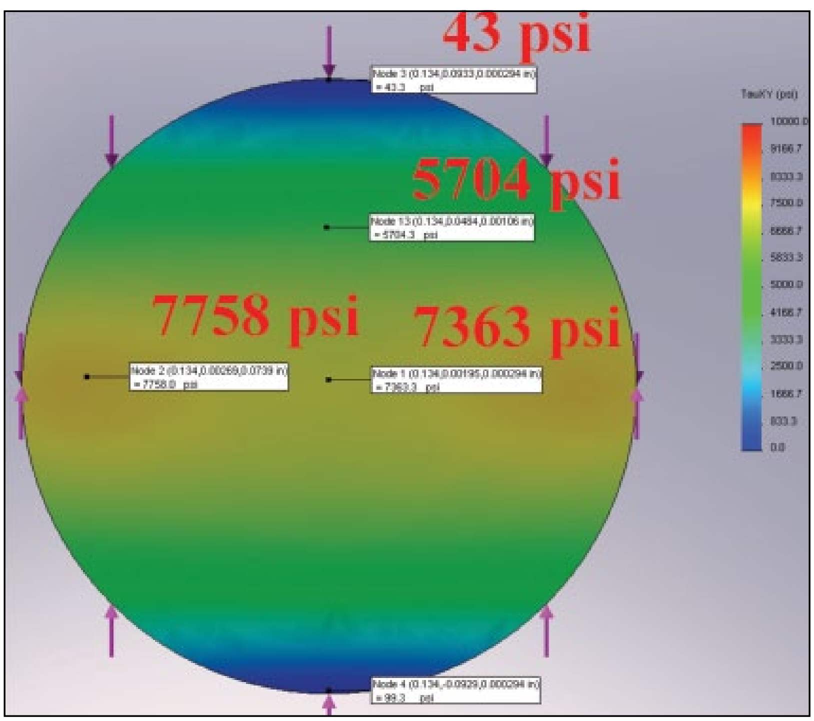

Figure 8
FEA Shear Stress Approximation – Uniform Distributed Load

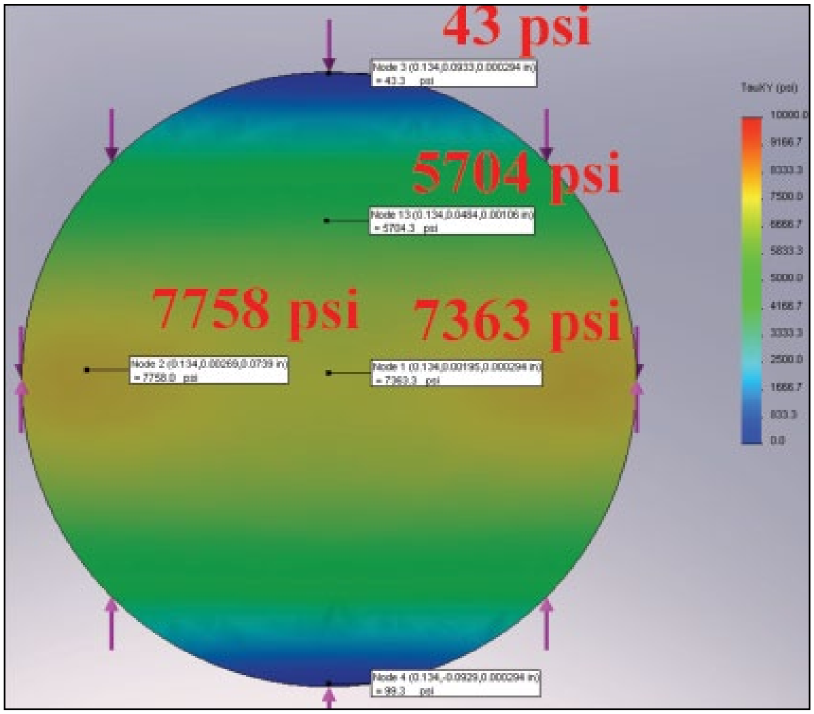

Figure 9
FEA Shear Stress Approximation – Concentrated Load

Rivet did not Fail when Loaded to a Factor of Safety of Less than 1

Employing the same methodology described above, the placement of a 225 lb., load at the left edge of the fourth step will result in a factor of safety in the failed rivet of about 2.3. Therefore, placing a 900 lb., load at this location (per ANSI's step-to-side-rail shear strength test) will result in a factor of safety of about 0.6. A question raised by the opposing expert was why did the rivet not fail during this design verification test performed by Underwriters Laboratories?

This is an excellent question. It was not asked during the writer's deposition, but almost surely would have been asked during cross-examination at trial. A complete answer to this question requires an analysis beyond the scope of this paper. Nonetheless, the non-failure of the rivet at the location of the incident rivet during UL's step-to-side-rail shear test was likely due, at least in part, to one or more of the following factors:

Static equilibrium analysis of the entire ladder and ladder components was performed to determine the shear loading of the failed rivet during the design scenario. This analysis was performed based on the assumption that the ladder behaved like a rigid body, which for most of the ladder components is reasonable. However, while the top cap has some rigidity from its front to rear edges, it is significantly less rigid from its left to right edges. This will result in the top cap more readily transferring loads between the rails on either side of the ladder (i.e., left-front to left-rear, and right-front to right-rear) than from the left rails to the right rails. Therefore, the actual shear loading of the rivet was likely somewhat less than that calculated based on the rigid body assumption.

In a new (i.e., UL test) condition, there was likely significantly more clamping force from the rivets that connected the top cap to the side rails compared that in a used ladder. The resulting higher frictional force in the test ladders between the top cap and front ladder rails would have resulted in a lower shear loading of the rivets at the failed rivet location.

The shear stress distribution within the rivet varies from a maximum at the center of the neutral axis to zero at the top and bottom of the rivet cross-section. Based on this and the above factors, the shear stress in the rivets at the failed rivet location during UL's tests may have exceeded their shear strength only near the central portion of its neutral axis, which would not necessarily result in a complete shear failure of the rivet. However, this would result in localized work hardening and resulting non-uniform mechanical properties across the rivet cross-section, making it more susceptible to a fatigue failure.

Published material strength data are typically minimum expected values. The actual shear strength of the rivet was likely somewhat greater than 13,000 psi.

It is noted that the above factors would have effectively resulted in a greater factor of safety in the rivet. However, it would be inappropriate to incorporate these factors when designing the rivet, as their effects are difficult to quantify, can change during the life and use of the ladder, and doing so would not be considered a conservative design approach.

Greater Actual Rivet Strength Due to Work Hardening during Setting of Rivet

Figure 3 shows the inboard side of the rear rail where the failed rivet was installed. The other rivet that secured the top cap to the left-front rail was likely set in the same manner as the failed rivet. That is, the tenon of a rivet with a head on one end was inserted through corresponding holes in the top cap and rail from the outboard side of the ladder. A washer was then placed over the tenon. A blunt axial force was applied to the end of the tenon to expand its diameter and secure the washer and thereby the rivet.

Work hardening of a metal occurs when it is cold worked and plastically (i.e., permanently) deformed. While this occurred at the end of the tenon of similar remaining rivets, there was likely minimal plastic deformation in the portion of the rivet tenons that was subject to maximum shear loading.

Design Alternatives

Although a manufacturer's subsequent design improvements may not be admissible in court, they often provide insight for design alternatives, and their existence can validate a defective design claim. Information contained in the Defendant's discovery documents indicated the following design improvements were made to subsequent ladders.

- The diameter of the rivet was increased from 3/16 inch to ¼ inch.
- The spacing between the rivet at issue and the other rivet that secured the front rails to the top cap was increased. This increased moment arm between these two rivets and thereby decreased the shear force in the rivet at issue.
- The material of rivet was changed to a steel alloy that was nearly three times as strong as the failed aluminum rivet.

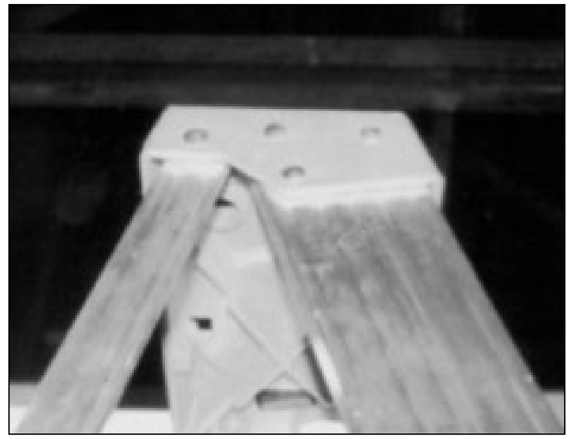

Figure 10
Exemplar Ladder –
Two Rivets at the Failed Rivet Location

These three factors increased the calculated factor of safety from 1.7 to nearly 10.0. Further, many ladders use two rivets at the location of the failed rivet (see Figure 10). This will further reduce the stress in the rivets that secure the top cap to the front ladder rails and add redundancy at a critical location.

Analysis Relevance

Although the analysis presented above proved to be helpful in resolving the case at hand, it may have been of limited relevance regarding the actual rivet failure. Figure 11 shows a close-up view of the prominent markings on the rail surface from the rivet washer, along with a predominately vertical elongation of the rivet hole in the rail. Therefore, the rivet may have failed as a result of a shear failure or its washer being pulled from its tenon. However, attempting to prove the same and the potential associated defects without the rivet or the washer would not have been a worthwhile endeavor.

Figure 11
Close-up view of the inboard surface of the rail where the rivet was located.
Refer to Figure 3

Conclusion

The case settled favorably for the Plaintiff shortly before trial. The Defendant's expert correctly stated that, "Any conscientious examination of the ladder would indicate that it should have been removed from service." Nonetheless, despite various uncertainties associated with the writer's analysis of the ladder failure, it was difficult to prove that the rivet design was not defective.

The following noteworthy points related to this incident may be of use to Forensic Engineers of various technical disciplines:

- Non-adherence to an applicable standard, code, etc., is sufficient to prove the existence of a defect. However, adherence to an applicable standard, code, etc., is not sufficient to prove that a defect does not exist. Many standards and codes include introductory language indicating the same.

- An appropriate factor of safety for a given component should be directly related to the potential for harm from the failure of that component.
- The condition of a new device during design verification testing may not be representative of its condition during its useful life.
- The determination of the actual stress in, and strength of, a component can be very complex. As such, one should always maintain an awareness of the limitations of the selected method of analysis, and the accuracy and preciseness of material property data.

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