Analysis of a 100 ft. Aerial Ladder Collapse

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Abstract
While being used in fire fighting operations, a 100′ aerial ladder collapsed, resulting in the injury of a firefighter. The ladder consisted of four nested sections mounted atop a fire truck. The main beams of the ladder were built from sections of formed steel sheet, electric resistance spot welded along their length to form a modified I-beam. The remainder of the ladder was mainly constructed from welded steel tubing. An investigation into the cause of the collapse was initiated. Examination of the ladder showed that the primary failure occurred in the second section, slightly above its overlap with the base section. As part of the investigation, a finite element model was built and analyzed using ABAQUS/Standard. The finite element model was used to confirm the failure mode and address the possibility of defects and/or maintenance issues playing a role in the collapse. The lowest two sections of the ladder were modeled using shell elements, allowing analysis of localized stresses and buckling modes, while the upper two sections of the ladder were modeled with beam elements. The ladder was analyzed in various positions, including the most likely position and loading at the time of the accident. Both stress and elastic buckling analyses were run. The model confirmed that the observed ladder failure was likely under the applied loading, absent any defects, malfunctions or unreported loading. The model also showed that during normal service, the ladder, which was an older design, operated at factors of safety which were much lower than expected.

Introduction
While in service at a fire scene, a 100′ aerial ladder collapsed, resulting in the injury of a firefighter. Engineering Systems, Inc. (ESI) was asked to complete an independent evaluation of the cause of the collapse. The investigation had three main phases; a visual inspection, metallurgical evaluation and testing, and a finite-element-based structural analysis using ABAQUS/Standard. Although each portion of the investigation was of importance, this paper will focus mainly on the structural analysis.

Background
The steel ladder consisted of four sections, a base, an inner-mid, an outer-mid and a fly (listed from the ladder base toward the tip). Each section was nested within the previous section with rollers to allow for extension and retraction of the ladder. General construction of the sections consisted of main rails with (roughly) an I cross-section built-up from welded steel sheet, and handrails of welded, rectangular steel tubing. The ladder steps were made of circular tubing, with some steps gusseted by steel sheet. A view of the general ladder construction is shown in Figure 1.
At the time of the collapse, the ladder was fully extended at an angle of 23° above the horizontal, with the tip unsupported. A single firefighter, weighing 275 lbs (with equipment), was near the end of the fly section to untie a full, 1-¾” water hose attached along the ladder’s right side. The hose was apparently not in use at the time. Winds were reportedly calm at the time of the collapse.

Of note was the fact that the loading, extension, and angle of the ladder exceeded the limits specified by the manufacturer for this ladder. Despite this, investigators were still interested in eliminating the possibility that any defects, damage, inadequate maintenance, etc. contributed to the accident. As the investigation progressed, the overall strength of the ladder, even under normal use, became of interest.

Visual Inspection
Inspection of the subject ladder showed that the primary failure occurred in the main rail on the right side of the inner-mid section. The failure resulted from local buckling/crippling of the rail, approximately 104 inches from the inboard end of the inner-mid section. This location matched the expected end of the overlap between the inner-mid section and the base section with the ladder fully extended. Inspection of the primary failure area revealed no pre-existing damage or defects. See Figures 2, 3, and 4 for details.

Metallurgical Investigation
Since no material properties were available for the ladder, sections were cut from both the left and right main rails for tension testing in accordance with ASTM E8-00. The mechanical properties of the main rail were found to be unexpectedly low, with an average yield strength of 25 ksi (172 MPa) and an average tensile strength of 55.7 ksi (384 MPa).

Hardness measurements and chemical analyses, per ASTM E415-99, were also performed in order to classify the subject steel. Based upon these analyses and the tension tests, the ladder material was classified as an SAE 1008 steel, aluminum killed. This material has good formability, but is not high in strength.

Structural Analysis
A finite element analysis model was constructed in order to investigate the stresses present in the ladder at the time of the collapse. In order to assist in ruling out the possibility of maintenance issues or other deficiencies in the ladder, it was important for this investigation to determine the most probable failure mode of the ladder under the known loading condition. As the investigation progressed, the strength of the ladder, even under less severe loading conditions, also warranted investigation. The FEA model was constructed based upon dimensions taken directly from the subject ladder and an undamaged, sister ladder. This information was supplemented by photographs and ESI’s previous experience with aerial ladders of this type. Construction of the model was done using the pre/post-processor HyperMesh, and the analyses were performed using ABAQUS/Standard.

Because of the higher bending moments nearest the ladder’s base under the given loading, the most critical sections of the ladder for this analysis were the base and inner-mid. These sections were primarily modeled using first order shell and brick elements (types S3R, S4R and C3D8R were used), allowing for the more refined investigation of both stress and buckling modes in these sections. The outer-mid and fly sections were predominately modeled using beam elements (type B31), resulting in both a reduction in modeling time and model degrees of freedom without a loss in the usefulness of the model. Overall and detailed views of the finite element model are shown in Figures 5 and 6. The total number of degrees of freedom in the final model was 427,968.

Although elastic/plastic material properties were available from the tension tests, it was determined that results suitable for this investigation could likely be obtained using only linear elastic material properties. This also minimized the amount of metallurgical testing required, as it is common for ladders of this type to utilize slightly different material strengths in different components of the ladder. As reported above, this information was unavailable for use in the investigation.

The ladder model was held at the ladder pivot points and tilt cylinder connections. Each section was connected to the next with rigid elements at the roller positions on the actual ladder. There was no evidence of the ladder sections shifting with respect to one another during the failure, so this simplification was deemed acceptable. Loads were applied to the ladder through the use of gravity loads acting on both the ladder itself and mass elements positioned on the ladder to represent the firefighter and the fire hose. A mass element representing the firefighter was placed between the third and fourth rung from the end of the
fly and slightly off center to the right, in deference to reports the firefighter was untying a hose on that side. The full 1-¾” hose was found to weigh 162 lbs. Masses were spaced evenly along the right side of the ladder to represent the hose. No dynamic amplification was assumed for these analyses.

Two different loading scenarios were analyzed:
- The loading present at the time of collapse (ladder fully extended at 23° above the horizontal with no tip support);
- The ladder loaded as at the collapse, but at a 65° angle (the minimum angle specified in the manual for the ladder at full extension with no tip support and a user on the fly section).

Both these loading scenarios were analyzed for both stress and elastic stability (eigenvalue buckling), resulting in four separate runs.

Results and Discussion

Accident Scenario
Under the subject loading scenario, analysis showed that there were multiple areas with stresses in excess of the as-tested average yield strength. The handrail of the base section, in the area of the tilt cylinder connection, was found from testing to be in tension at the average yield strength of 25 ksi (172 Mpa). Stresses at the average yield were found in compression in the base section at the overlap of the base section and inner-mid. Although these areas of stresses in the vicinity of the yield strength are of concern, the highest stresses in the model under this loading scenario occurred in the inner-mid, right main rail, just beyond its overlap with the base. This area sustained compressive stresses as high as 51 ksi (352 MPa), calculated using von Mises equivalent stresses. The left main rail of the inner-mid sustained similar, but slightly lower, stresses in this same area. Recall that only linear elastic material properties were used in this analysis, so no load redistribution resulting from plasticity was accounted for during the analysis. This load redistribution would result in overall stresses lower than the reported 51 ksi (352 MPa). Despite this, it is clear that the entire lower main rail flange in this area would yield in compression under the given load, and failure would be expected. This result was consistent with the visual inspection of the ladder, which identified a buckling/crippling failure resulting from compressive overload in this area. Selected plots from this analysis are shown in Figures 7 and 8.

Buckling analysis of the ladder under this scenario showed that an elastic buckling failure as the initial failure mode was unlikely, even with significant dynamic amplification of the load (which was not explicitly accounted for). The first elastic buckling mode, a lateral buckling of the base section, was predicted to occur at loading more than six times that present at the time of the collapse. The first buckling mode is shown in Figure 9.

65° Angle
Stress results from this scenario showed a reduction in stresses to below the average yield in all areas of the ladder. One of the more highly stressed areas of the ladder was, once again, the inner-mid main rail, just beyond the end of its overlap with the base section. Again, this area was loaded in compression. In this case, the highest linear elastic von Mises stress was 23.8 ksi (164 MPa), roughly 95% of the measured average yield strength. With consideration of the possibility of dynamic effects (not modeled), it is clear that there is a minimal factor of safety present in this ladder design and the ladder could be over-stressed when loaded with a firefighter and water hose. Results from the elastic buckling analysis in this configuration showed elastic buckling was not a concern as the first five buckling load factors were large and negative.

Conclusions
- The fully extended ladder was being used at an extremely low angle with the tip unsupported at the time of collapse.
- Inspection showed that the primary failure was due to compressive yielding and crippling of the inner-mid right main rail, just beyond the base overlap.
- Material used for construction of the inner-mid main rail had an average yield strength of 25 ksi (172 MPa) and an average ultimate strength of 55.7 ksi (384 MPa).
• Structural analysis showed that, under the loading present at the time of the collapse, failure due to crippling would be expected on the inner-mid right main rail, just beyond the base section overlap.
• Even at ladder angles specified in the ladder limitations (65°), there was a minimal factor of safety under the given loading.
• The metallurgical and structural investigations showed that, under the loading known to be present at the time of collapse, failure of the ladder was expected to occur in the absence of any defects or damage in the ladder.

References
Figures

Figure 1. General view of ladder construction.

Figure 2. Post-accident view of the subject ladder.
Figure 3. Post-accident of the primary failure area of the inner-mid as viewed from the left side of the ladder.

Figure 4. Primary failure area as viewed from right side. The tip of the ladder would be toward the right of the photo.
Figure 5. Overall view of ladder model.
Figure 6. Model details of the base and inner-mid sections.
Figure 7. General location of highest stresses in the inner-mid.
Figure 8. Von Mises stress contour plot for ladder loaded per accident scenario.
Figure 9. First buckling mode shape for ladder loaded per accident scenario. The buckling load factor is more than six.