Physics of Aerials for Operations

The main concern that goes into any aerial design is that of safety. The goal is to design an aerial that meets a series of performance objectives while resisting catastrophic failure by integrating a proper level of safety factors along the design process. Once everyone realizes there are no perfect designs nor perfect materials and that real materials can and do wear out with time and usage, the prudent design engineer integrates appropriately chosen factors of safety into the design and establishes a realistic set of inspection and maintenance criteria.

Catastrophic failure can basically be traced to a number of generic conditions:

1. misuse / abuse
2. worn out materials
3. over loaded

In 1986, the NTSB got involved in the investigation of a number of accidents that involved fatalities dealing with emergency vehicles. Their conclusion was that in every case the vehicles showed deficiencies in their maintenance that contributed to the accidents, in most cases brakes. Following the NTSB’s report, a secondary report was produced that surveyed over 600 departments that concluded over 60% of the vehicles were not in compliance with OEM recommendations or DOT regulations. Essentially, the NTSB put pressure on the fire service indicating they had better upgrade their maintenance standards or be prepared to have the government get involved. To that end, starting in 1990, the NFPA had its “1901” committee start the process of generating a new “maintenance” standard. In 2000, NFPA 1915 was adopted and in 2007, the various standards dealing with maintenance, inspections, performance and refurbishment are folded together as a new combined standard NFPA 1911 – 2007.

To resolve the three conditions mentioned above, there are three avenues of action:

- The engineer needs to design to resist catastrophic failure using the knowledge of how materials fail, how columns fail and how stresses are transferred through the structure.
- Establish and follow the rules – that is, NFPA standards.
- Manuals from manufacturer that establish inspection, maintenance and testing criteria standards.
The role of the standards:

As much as both the manufacturers provide operational limitations with their aerials, i.e. load charts or elevation – inclination – extension – load relationships, and the individual fire departments establish Standard Operating Procedures (SOP’s), sometimes they are not mutually consistent. Certainly at times when there is a mixture of aerial apparatus within the department, it makes sense that some standards of operation need to be established, however, how each piece of apparatus and its associated limitations are addressed can become a real problem. Also, older apparatus manufactured before 1991 can have significantly different operating characteristics from newer pieces.

Case in point: An aerial is set up in accordance with the manufacturer’s recommendation. Say the load chart says that the tip of the aerial can safely support 500 lb at the tip at 0° and full extension in all directions when properly setup. If in an exercise addressing a second floor roof access with the truck properly setup according to the manufacturer’s recommendations and with the ladder perpendicular (at 90°) to the chassis, fully extended and at 45° inclination, with no one on the ladder, the stabilizer, on the opposite side from the side you are working on, comes off the ground. Should the operator stop and re-position or is it safe to continue lowering (not touching the roof) and placing people on the ladder?

So the question arises, what do the “rules” say? The first level rules in this case are the NFPA Standards. From the 2009 edition of NFPA 1901:

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AERIAL PHYSICS

Maximum weight at the tip can be reached very quickly. Two firefighters climbing close together and a victim is well beyond the rated 500 lb. capacity.

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AERIAL PHYSICS

In the new 2007 edition of NFPA 1911, the language says several things:

19.1.1 All inspections and tests specified in this standard except those specifically designated as nondestructive tests (NDT) shall be conducted at the following times:

(1) At least annually
(2) After major repairs or overhaul
(3) Following the use of the aerial device when the aerial device could have been subjected to unusual operating conditions of stress or load
(4) When there is reason to believe that usage has exceeded the manufacturer’s recommended aerial device operating procedures

Certainly the truck has not rolled over, but the question becomes, if the operator were to continue lowering the aerial, would conditions (3) or (4) be invoked?

Instability: (NFPA 1901) A condition of a mobile unit in which the sum of the moments tending to overturn the unit exceeds the sum of the moments tending to resist overturning.

Old “Stability” definition: The truck is considered to be stable when there is no sign of rollover) The lifting of a tire or stabilizer on the opposite side of the vehicle from the load does not necessarily indicate a condition of instability. Instability occurs when an aerial device can no longer support a given load and over turning is imminent.
Basically, the NFPA standards represent a “vanilla” version of what is determined to be a minimum “safe” level of operation.

The justice system uses the standards as the measure of “common sense”. The argument has two approaches, first, the justice system goes back to 1856 (Blyth vs Birmingham Water Works) defining the “Reasonable and Prudent Man” as:

Negligence is the omission to do something which a reasonable man, guided upon those considerations which ordinarily regulate the conduct of human affairs, would do, or do something which a prudent and reasonable man would not do.

The second argument is that the NFPA 1901 committee is composed of a diverse group of interested parties: of the 30 principal voting members, about 1/3 represent the fire service, about 1/3 represent the manufacturers and the last 1/3 represent others, like representatives from mechanics organizations, insurance companies, etc; the principal members span the breadth of climate, environment and geography – flat-landers, mountainous and coastal country, places with ice and snow and places hot enough to fry an egg on diamond-plate.
The NFPA collects recommendations for changes to the standards and the committee meets twice a year to
discuss and debate the requested changes for inclusion. Anyone can submit changes to the standards, just
fill out the form at the back of every NFPA standard, identifying who the submitter is, the standard and section
number of interest, the suggested changes and the justification for the suggested changes. In this way, the
public has access to the “standards” process. Altogether, the NFPA standards represent a process, diverse in
nature and interest with public accessibility, attempting to establish fair and reasonable measures of common
sense, safe, operating procedures.

From these perspectives, one has a “standard” to which everyone’s actions can be compared for the purpose
of determining “appropriateness” of decision making and actions taken.

The role of the design engineer:

The role of the design engineer is to design an aerial with specific performance criteria as objectives, i.e.
height, reach and rated capacity, while meeting the acceptable standards of factors of safety. To design to
resist catastrophic failure, one must know how aerials fail. The classic design of an aerial is best approxi-
mated as a column, and columns fail basically by Euler buckling. Euler (pronounced like “oiler”) was a mathe-
matician in the 19th century who solved the problem of how applied forces affect the structure of a column.
The main stresses applied to a column are tension and compression.
Tensile forces pull on bodies and tend to make them stretch and neck-down.

Compressive forces push on bodies and tend to make them shorter and thicker.

We easily discover that columns fail under compressive stresses. If we consider an aerial operating in a cantilever mode, that is supported at the base only, not at any other upper location, then the base rails are in compression and the top rails are in tension.

In order to resist compressive failure, base rails are strengthened (larger and thicker) but since top rails do not tend to fail in tension, they can be thinner and narrower. As a result of this understanding and design, engineers write operations manuals telling operators to not actually place aerials directly on roof tops or window sills. If the aerial is placed in such a “supported” position, the stresses are inverted and the top rails are put in compression and base rails in tension. Certainly the base rails can absorb the stresses with no problem (since they were designed to carry large forces in the first place) but the top rails were not designed to carry large stresses, and in this inverted configuration, the top rails can buckle!

The standards finally give the design engineer guidance as to how to characterize their aerials. In NFPA 1901, the standards define a number of performance specifications and minimum levels of performance, i.e. 250 lb rated capacity, rungs on 14” centers, top rails with a minimum width of 1” and height 12” above the rung centers, and a factor of safety of at least 2 to 1 in terms of yield strength of material. The manufacturers were given the responsibility of ensuring the designs were those required and the manufacturing process had appropriate levels of testing and inspections in the assembly process to meet the mandated safety specifications.

So we can see that design considerations implemented by the design engineer can have profound effects on the manner in which aerial operators are permitted to move and use their apparatus.
The role of manuals:

Manuals represent the formal way in which manufacturer informs the owner of how to operate, inspect and maintain their apparatus. The importance of these items is intuitively obvious just from normal everyday experience. First of all, it is obvious that for manufacturers to protect themselves, they need to inform the owner/operators of the apparatus and devices of “how” to properly operate their apparatus – surely, a single training session is not enough to ensure the complete learning of information; it acts as a reference guide in cases of uncertainty – to that end, it is critical to keep a copy of the owners manual in the cab at all times! MAKE SURE A COPY OF YOUR OPERATOR’S MANUALS ARE IN THE CAB!

Secondly, our everyday experience tells us that things wear out, i.e. tears and holes in clothing, boots that wear out, changing light bulbs and our hands get dirty, so we clean them. Similarly, hoses exposed to the UV sunlight age, become brittle and begin to crack, extension and retraction cables become cyclically bent back-and-forth as they travel around sheaves, like bending a wire coat hanger back-and-forth, they eventually break, and as slide blocks travel back-and-forth in guide channels, they slowly become dried out and start to wear, not to mention they drag bits of debris inside the guide channel, slowly scoring the metal surface.

Make sure you understand all the Quints operations and safety Guidelines
Besides the obvious visible wearing of material, microscopic cracking (both external and internal) occurs, leading to material failure at the atomic or very microscopic level. Just as scoring glass or concrete blocks can lead to crack that splits the material in two, microscopic cracks can lead, eventually, to catastrophic failures = breaks. In spite of material having a certain amount of flexibility, there are definable limits to this flexibility. Exceeding these limits of flexibility leads directly to definable material failure that is predictable. These microscopic defects are evaluated with techniques termed nondestructive testing, i.e. magna-flux, dye-penetrant, ultrasonic testing, and the such. The maximum permissible variations of the various measured characteristics are defined by the design engineer, based on initial design considerations and pre-determined factors of safety.

So as the design engineer establishes proper protocols for setup and operation of the aerial device and also establishes items to be inspected, the frequency of inspection and the manner of maintenance, the engineer’s and the manufacturer’s liability lie in the decision making that goes into the design and actual manufacture of the apparatus. To ensure they are covered, the engineer and manufacturer provide operation, inspection and maintenance manuals, detailing each step and then to make sure the recommendations are followed they ensure the standards committee include language specifying that the recommended operations, inspection, maintenance and testing are complied with by the owners of the apparatus in the standards that apply.

LA City 1970, One fireman died, two injured. Cause of the collapse was not determined immediately, but Fire Chief Raymond Hill said it was possible there was a hydraulic failure in one or both of the ground jacks, causing the snorkel unit to list and then topple.
In this way, the three sources of aerial failure are addressed: design, operation and inspections/maintenance and testing.

In spite of these precautions, however, as stated earlier, there are no perfect materials. All normally available materials, regardless of how carefully their manufacturing process is supervised, contain some localized internal defects at the microscopic level, i.e. atomic inclusions, grain boundaries, twinning. As well, the manufacturing process of assembly including welding, drilling and bolting produce other internal strains and stress concentrations result in a device with a number of potential problems, that are inherent in all manufactured structures. It is impossible to avoid these and that is one reason the design engineer must decide on the appropriate level of safety factors that need to be integrated in their design. Never-the-less, as with all manufactured devices, be they fire apparatus, light bulbs or DVD players, there exists a standard statistical failure curve.

Seattle; State, city and private investigators are examining a 20-year-old fire truck ladder that buckled during a blaze at an apartment building and injured a firefighter who fell to the ground.
If one plots the number of failures as a function of time, there are three distinct intervals in the lifetime of a structure: the break-in period, the service life and the end phase.

- In the break-in period, there are statistically a large number of failures, just due to the fact that there are no perfect materials or processes, and that a structure assembled from subcontracted components have a certain probability of not meeting performance specification (since quality control is in itself a statistical sampling of production), and these components have some chance of failing. This break-in period is compensated for by a “warranty” period, where everyone involved understands this statistical probability exists, even when everyone in the chain employs a quality control program.

- A service life is the usable interval of time for the device when it operates as it is supposed to. The amount of “down” time is a function of the quality of the design, the quality of the components, the quality of the assembly and a combination of work environment and maintenance.

- The end phase is marked by an increase of “down” time with an associated increase in cost of repair. At some point, the device nickels-and-dimes you to death. Short of replacing every single component, at some astronomical cost, it becomes time to retire the device. Basically, the material just wears out.

So no matter how well an aerial is designed and built, eventually it will fail. The trick is to retire the apparatus before the catastrophic failure occurs and some gets hurt!
AERIAL PHYSICS

Training:

As part of either ISO ratings or especially for self-insured cities, a comprehensive training process is critical. More and more cities and fire districts are discovering that some sort of “formal” training reduces the risk of either personnel becoming injured or of apparatus being damaged. Even departments using volunteers have discovered that it is better to require some sort of training before people are permitted to operate and aerial, or even be part of a truck company.

Some departments have used as little as 2 hours of hands-on training to operate aerials (or to qualify for auxiliary assignments on apparatus, other than the aerial apparatus to which they have been previously assigned) to requiring 2 weeks of more comprehensive training that includes the knowledge to inspect and do simple maintenance, like grease zerk fittings, inspect and lube the cables (when required) as well as sufficiently demonstrate their ability to properly setup and operate the aerial. In some cases this may require documentation to be generated that goes into a training file as well as the operator’s file showing proper training.
AERIAL PHYSICS

A short history of aerials:

The history of aerials, in the opinion of the author, can be characterized as falling into three eras:

1. Pre-1988
2. the interval of time between 1988 and 1991
3. After 1991

1. Pre-1988

Certainly this generalization does not apply to all aerials manufactured in this early era, but to many it does. By and-large, the aerials were characterized qualitatively as light, medium and heavy duty; exactly what that meant was as varied as the person you spoke with. Many of the light duty aerials could not even “pick themselves up” from a 0°, fully extended position. In those cases either the ladders had to be supported while in the horizontal position and assisted with pike poles to either retract or lift themselves up. The manufacturers clearly showed load charts with “forbidden rotation” areas marked off on the load charts. In order to operate at these low angles, some of the aerials had to be retracted in as the inclination came down.

Note: There is nothing wrong with this as the ladders were not designed to operate at low inclinations and operators who tried to use them at such low angles inappropriately were operating against manufacturer recommended procedures!
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They often had load charts with rated capacities as, in the old vernacular, “1-man at the tip” with an inclination (at full extension) of a minimum of 65°. The ladders occasionally gave two load ratings whether the ladders were “supported” or “unsupported”.

In the “old” days, the lifting cylinders were single acting, that is, they hydraulically raised the ladder, but gravity brought it back down. So when the ladder was rested against a roof or parapet, once the ladder rested on the roof, the ladder stopped coming down. Accordingly, when the ladders were put in the cradle in travel mode, “cradle locks” would hold the ladders in the cradle so they wouldn’t bounce and cold work and harden the steel, which would lead to cracking.
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Ladders constructed now a days have double acting cylinders which hydraulically lift the ladders out of the cradle and then hydraulically lower the ladder. In the bedded position, in order to keep the ladder from bouncing in the cradle, the ladders are powered against the pressure relief valve to ensure the ladder is held in place, making cradle locks unnecessary.

Firefighters being unfamiliar with the controls on the newly purchased aerial platform truck, training in a "high risk" scenario before becoming familiar with new equipment, failure to use fall restraints, the design of the platform railing and integrated doors and the location of the lifting eyes underneath the platform which contributed to the platform snagging on the building's parapet wall.
The problem that arises now is that operators have the ability to power the ladder onto a roof or parapet. Where as in the bedded position, the torque generated from the hydraulic force from the lifting cylinders is significantly smaller because of the short moment arm from the lifting cylinders to the cradle, as compared to longer moment arm from the lifting cylinders to the tip of the ladder resting on the roof generating a greater torque. The greater torque generated with the ladder resting on the roof in this inverted situation leads to the ability to exceed the compressive limit on the top rails (which they are not designed to sustain) and potentially buckle. Therefore, just about every manufacturer stipulates that their aerial is designed to be operated in cantilever and should not be directly placed directly on the roof. Instead, the ladder should be positioned such that about a 4” gap should exist between the ladder and the roof before personnel start to climb. If at this time, the ladder touches the roof or parapet, there should not be force created by personnel to create any damage.
The third characteristic of these “older” ladders is in the diagonal supports for the rungs. In some of the older ladders, there would be a gusset welded in the corner of a rung every so often, every 4th or 5th rung, later, as time approached 1988, every rung would have a gusset, both sides. The purpose was to “stiffen” the ladder and be less likely to twist.

Between 1988 and 1991

The NFPA 1901 committee agreed the failure process for many of the aerials was due to twisting that led to buckling. The ladders being built had great strength as long as the loads were applied perpendicular to the plane of the rungs, but when loads had a lateral component (except when applied at the neutral axis), a twisting torque results that can lead to a buckling condition. With metal shelves, like the ones that are sold at hardware stores, remove the twisting weakness by installing diagonals, like shear plates in building construction, to reinforce the structure and strengthen it. So in 1988, the committee decided to mandate K-Bracing between the rungs for reinforcement. Some manufacturers were already incorporating K-braces in their designs before 1988, however, other manufacturers had to re-design their stabilizer systems to adequately handle the extra weight provided by the additional metal.
Post 1991:

Following the mandate for K-bracing in 1988, the NFPA 1901 committee began looking toward substantial changes in the criteria for designing and manufacturing aerials. The new standard called for:

a) Tip loads to be reclassified as **rated capacity**, with quantities to be stated in pounds, i.e. 250 lb minimum (NFPA had for years assumed for design purposes that the average firefighter weighed 200 lb for the purpose of chassis cab design + 50 lb turnouts and air pack). And since personnel populate aerials in integral numbers, loads in excess of the 250 lb would be increased in intervals of 250 lb.

b) The rated capacity would be defined for ladders at 0° inclination and at full extension.

c) While maintaining a minimum structural factor of safety of 2-to-1. Gone was the mandate for K-bracing, instead the NFPA required theoretical analysis and prototype testing to verify the various designs met the 2-to-1 structural safety factor.

d) And the aerials had to maintain a stability factor of safety of 1.5-to-1 against rollover in any permissible orientation with the rated capacity.

**Rated Capacity**: (NFPA 1901) The total amount of weight of all personnel and equipment that can be safely supported at the outermost rung of an aerial ladder or on the platform of an elevating platform with the waterway uncharged.

This chart found on the aerial turntable.

Weights are per section, do not total the weights and apply to only one section. This will cause the ladder to fail.

NFPA Guidelines stated in 250 lb. increments, weight given to average firefighter in full turnouts.
New terms were created:

**Dead Load:** (NFPA 1901) The weight of the aerial device structure and all materials, components, mechanisms, or equipment permanently fastened thereto.

**Live Load:** (NFPA 1901) Forces acting on the aerial device from personnel, portable equipment, water, and nozzle reaction.

And new standards were developed for NFPA 1901, dealing with the design and construction of aerials: (for the 2009 edition)

19.3.1 The rated capacity of the aerial ladder shall be a minimum load of 250 lb carried on the outermost rung of the outermost fly section with the aerial ladder placed in the horizontal position at maximum extension. *(that is, at 0° and full extension)*

19.3.3 Rated capacities in excess of 250 lb shall be stated in increments of 250 lb and shall be in addition to any fire-fighting equipment installed on the aerial ladder by the manufacturer.

The NFPA also defines a 2-to-1 structural factor of safety;

19.20.1 All structural load supporting elements of the aerial device that are made of a ductile material shall have a design stress of not more than 50 percent of the minimum yield strength of the material based on the combination of the rated capacity and the dead load. This is equivalent to a 2:1 safety factor
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And stability:

19.21.2 The aerial device shall be capable of sustaining a static load 1½ times its rated capacity in every position in which the aerial device can be placed when the apparatus is on a firm and level surface.

In the past, arguments erupted over which is better: steel or aluminum? Ladders or platforms? Maybe we don’t need an aerial, maybe all we need is a water-tower?

At least the issue of steel versus aluminum can be put to rest. According to NFPA 1901, as long as the designs meet the specifications for structural and stability factors of safety, it doesn’t matter which is used! Certainly, the specific designs must be different to take into account the differences in the material, but from an academic standpoint, either material is acceptable.

Ladders (“sticks”) versus platforms is a needs analysis decision. Is the aerial to be used for rescue, from high rises or used as an anchor point for confined space or cliff rescue? This is where those decisions belong and become integrated into the performance specification for the bid process.
**Structure of aerials** In order to resist catastrophic structural failure one needs to understand the basic failure mechanism, which is Euler Buckling. The failure process is the result of three types of stresses being applied: tension, compression and twisting.

As a first approximation, an aerial is basically a column. For a column, being operated in cantilever, which defined as a projecting beam or other structure supported only at one end, the top (hand) rails are in tension and the bottom rails are in compression.

**Forces in ladder in Cantilever and Supported Operating Modes**
AERIAL PHYSICS

For any column there exists a line known as the neutral-axis, such that any force applied through the neutral axis results in only axial displacements (no twisting about the axis), otherwise any force not passing through the neutral axis results in some twisting.

The twisting failure occurred in the lower right bed section, collapsing the ladder to the right side.
Euler buckling is dependent on the material used, the cross-sectional area and the length.

“Stiffness of material” is the tensile strength of the material, “cross-sectional area” is actually a parameter known as the Moment of Inertia which evaluates the resistance to twisting for a column, which depends on not only the physical dimension of the column, but also the dimensions and wall thicknesses of the individual members that compose the structure and length is simply the length of the aerial.

As the aerials become longer, they become intrinsically weaker (less resistant) to buckling, regardless of what they made of or their cross sectional area.

It is the length of an aerial that becomes its greatest liability when it comes to strength, for example, if a column is doubled in length (like 50 ft to 100 ft) the column has only ¼ the resistance to buckling it originally had, that is $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$, therefore only ¼ as strong. The opposite is true also, as the aerial becomes shorter, length decreases, the aerial becomes stronger – not only does the column become stronger, but the centre of gravity comes in closer to the rotation axis!

**Sequence of Events Leading to a New York City Ladder Collapse**

1. Ladder is placed with the tip of the Left beam on the window sill. One firefighter ascends to the tip to initiate rescues.

2. Two adults and two small children evacuate onto the tip of the ladder. Their weight causes the tip of the ladder to slip off the window sill.

3. The weight causes bending stress in the ladder. Contact with the wall adds twisting component.

4. The bending creates tension forces in the handrails and compression forces in the beams of the ladder. The bending stress increases from the unsupported tip of the ladder.

5. Ladder fails just above the base
Higher tensile strength metals resist twisting and buckling better than lower tensile strength, ductile metals. When comparing steel to aluminum, steel has a greater tensile strength than aluminum and so has a greater strength, however, the steel also weighs more! As well, there is a variety of steels with different tensile strengths. As a design engineer decides which steel he might use, he needs to also take into account that higher tensile steels also are more brittle, that is less flexible and more susceptible to cracking when suffering an impact. So as usual, there are trade-offs. Do you want a lighter weight (because it needs less of the higher strength metal) steel ladder that is more susceptible to developing cracks, or a heavier ladder (because it needs more steel of a lower tensile strength to have the same overall strength) but be more tolerant to impacts?

New York City Ladder Collapse

Prior to the collapse, the tip of the left rail rested on the window sill. The weight of the occupants caused a twisting force to the unsupported right side.
19.1.1 All inspections and tests specified in this standard except those specifically designated as nondestructive tests (NDT) shall be conducted at the following times:

(1) At least annually

(2) After major repairs or overhaul

(3) Following the use of the aerial device when the aerial device could have been subjected to unusual operating conditions of stress or load

(4) When there is reason to believe that usage has exceeded the manufacturer’s recommended aerial device operating procedures.

Parts (3) and (4) address the issues of the operators being aware of how much load is being applied to the aerial and if it exceeds the load chart or the equivalent load gauge’s values and if the aerial has been operated outside the limitation of operations as recommended by the manufacturer. *Hint: the statement, “I didn’t know……!” is not a defense!*
AERIAL PHYSICS

Loads on Aerials

a. Static – quasi-static = weight

b. Dynamic

- Hits/collisions/impacts
- Crane
- Nozzle reaction
- Rappelling
- Rescue

At first inspection, the idea of load seems simple enough, but in reality it can be quite complicated; a person on a ladder is one thing, but at night, wind blowing, flowing water at some angle while the temperature is below freezing creates a whole different scenario. Or the aerial is being used to either stabilize vehicles after an accident or there is some sort of confined space rescue, things get complicated. The purpose of this section is to delve into the issue of loads, how are they figured and to look at some examples.

Two firefighters were hurt when an aerial ladder collapsed during a commercial fire in Monongahela, Pennsylvania.

In the old days, aerials were rated qualitatively, as mentioned earlier, as light duty, medium duty and heavy duty, whatever those things meant, and how would those get translated to usage in examples stated just above? Who clearly knows? Be certain, the typical analysis always concluded that the people at the bottom of the food chain were most vulnerable, “operator error” or “improper maintenance” was the source of the mistake, that is go after the fire fighters or the mechanics, obviously, they were the last to touch the aerial!
One of the best things that have precipitated from the change in the 1901 standard in 1991 was the inclusion of language mandating the clearly defined safety factors, design and performance criteria and quantitative ratings! Now, regardless of the longevity of the manufacturer, the playing field has been leveled. Departments and districts purchasing “new” apparatus, now can feel confident in purchasing any NFPA 1901 compliant aerial, in terms of its performance and credibility.

The “down” side to the new standard is that now the operators are being held accountable for “knowing” both the limitations of their aerial (load versus extension, rotation and inclination) and what their actual load is at any moment of time! For example, some ladders come with tie-off rings with plates attached that say the maximum load on each ring is 200 lb, so the question becomes “How do you know when the applied force reaches 200lb?” The operator is being held accountable, but how do they know?

The two basic definitions of load are found in NFPA 1901:

**Live Load:** (NFPA 1901) Forces acting on the aerial device from personnel, portable equipment, water, and nozzle reaction.
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**Rated Capacity**: (NFPA 1901) The total amount of weight of all personnel and equipment that can be safely supported at the outermost rung of an aerial ladder or on the platform of an elevating platform with the waterway uncharged.

On one hand it seems intuitive to simply say that rated capacity is the maximum live load permitted, but there is more to it than that. Basically, live load is the measure of whatever forces are being applied to the aerial device.

Forces come in two types, static and dynamic (or shock) loads. Static (or quasi-static) forces are those which represent forces from and on things that are not moving (stationary) or forces that are applied slowly, the “weight” of an object represents a static force. A person’s weight requires the person to be standing still; stepping on, off, or doing deep knee bends while standing on the scale would not be actions that provide an accurate weight of a person.

The definition of rated capacity states that it represents the “total amount of weight” that can be safely supported. This definition has imbedded in it the concept that a design engineer chooses a performance objective, i.e. a rated capacity of 500 lb, which he is able to synthesize in his computer program and prototype test by simply applying a single weight hanger of 500 lb.

For the operator of the aerial, it means the maximum static-equivalent load cannot exceed 500 lb; a 250 lb person jumping down from some height can also create a 500 lb reaction force, depending on how he lands on the aerial. If one attaches a dynamometer to an aerial and to it a weight is suspended, initially the weight “bobs” up and down applying a range of weights, the maximum deflection of the dynamometer needle indicates that maximum applied force, which is greater than the weight of the suspended body! So 500 lb loads can be intermittently applied by individual weight bodies less that 500 lb!
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Both the old 1914 standard and the new 1911 standard requires action to be taken if the aerial devices have had loads in excess of the rated capacity applied to them; without a dynamometer, how is one to know?

From physics, Newton’s laws of force give us a way to predict or calculate forces applied. Newton’s second law stipulates that:

Force = Mass x Acceleration.

Weight = Mass x Acceleration of Gravity

Because the acceleration of gravity is a constant, we can speak of weight like we speak about mass – it makes discussion easier. Acceleration is the time rate of change of velocity, going faster or slower or changing direction; in most of our discussion, we will deal with speeding up or slowing down. Newton stated that only external forces from outside a body can affect a change in its motion. So if a body speeds up or slows down, there is some external influence acting on the body, there is no internal mechanism that can make it change; Newton’s first law states that without any external influences, a body will travel in a straight line at constant speed, forever, or until some external force is applied.

With 2 firefighters and charged hose this aerial is now beyond the max tip load.
Impacts: consider an object colliding with another object. The force of impact depends on the mass (or weight) of the body times its acceleration. Consider the effect of a brick on a person's bare foot:

a) just resting the brick on your foot,
b) dropping the brick from 6" in the air, and letting it hit your foot,
c) dropping the brick from 12" in the air, and letting it hit your foot,
d) dropping the brick from 24" in the air, and letting it hit your foot, and
e) dropping the brick from 36" in the air, and letting it hit your foot.

Certainly the effect of the same brick on your foot is not the same each time! As the brick accelerates for greater distances, its speed is becoming faster and faster, so as it collides with your foot and stops, effectively the stopping distance is the same, so the deceleration becomes greater and greater and the force of impact becomes greater. That is, even though the weight (or mass) of the body remains a constant, different accelerations result in different amounts of force. The net force on a body is not only dependent upon the mass or weight of a body, but also how the impact happens!

Some departments advocate using the tip to break out windows. How do you calculate the stress absorbed by the aerial?

So it is clear that impacts are difficult to analyze without actual kinematical data, i.e. speeds and collision intervals, but without a doubt can generate quite large forces. Keep in mind that even though these forces may be generated for only short intervals of time, they can be sufficient to momentarily exceed the yield strength of the material and produce a localized defect that starts the creep and "crack propagation" process!
Yonkers, New York aerial ladder failed during ladder pipe operations.
Use as a crane: Virtually every manufacturer states that their aerial should NOT be used as a crane! On the other hand, they provide “tie-off” rings on platforms or on plates that are mounted between base rails. The manufacturers usually either state in the manual or place a plate near these rings stating the maximum amount of force allowed to be applied to the rings. So what’s the deal? There are several things to keep in mind.

An operator might say what is the difference between having 250 lb on the ladder and having 250 lb suspended below the ladder? The obvious answer is that First is “how” the load is applied, is it applied through the width of the rope or cable, or is it distributed over a broad area (pressure comes into play which equals “stress” – as in the stress-strain curve). Secondly, is the load “centered”? If not properly applied, twisting the ladder results, which is more likely when loads are suspended by ropes or cables, rather than by placing the load on top of the aerial. Thirdly, if you lift a 250 lb object which is attached by some sort of rope or cable, the elastic nature of the rope or cable comes into play, not to mention the acceleration of the object. Realize, that to lift a 250 lb object by a rope or cable requires a tensile force of more than 250 lb (a tensile force of 250 lb simply “balances” the weight, to lift up requires more) and the rate the load is accelerated amplifies the effect. And finally, the elastic nature of the rope or cable adds its own acceleration component. Because many of these items are not really controllable by the operator and can result in substantial increases in the forces acting on the aerial, the engineers at the manufacturers insist that the loads are not applied inappropriately and so ensure the statements are included in the operator’s manual.

Keep in mind the placards that identify the “ratings” on the tie-off rings represent the maximum permissible static equivalent applied forces, not just the “dead load” or “weight”!

Another consideration is that OSHA does not consider that fire personnel need to be crane certified as operators because manufacturers do not permit their aerials to be operated as a crane! A new consideration is that if the aerial is being used to lift people or something like a Stokes basket, with people inside, the aerial may now be being used as a crane, depending if the aerial is simply an anchor point or if it is being used to physically lift the basket! If an accident occurs, be prepared!
**AERIAL PHYSICS**

**Nozzle Reaction:** When water leaves the nozzle effectively pressure is converted to velocity and the acceleration of the water results in a reaction force (Newton’s Third Law of dynamics – for every action, there is an equal and opposite reaction). There are a variety of hydraulic equations that everyone learns in hydraulic classes, but everyone forgets after passing the test. On one hand, basic hydraulics shows that a Nozzle Reaction force for a smooth bore nozzle can be calculated from:

\[ NR = 1.57 D^2 P \]

With \( NR \) in pounds, \( D \) = diameter of the bore in inches and \( P \) = discharge pressure in psi. However, this is a little cumbersome on the fire scene. An easier calculation, that is a good 1st order approximation, is:

at 100 psi tip pressure, \( NR = \frac{1}{2} \) (GPM),

where \( NR \) is in pounds and \( GPM \) = gallon per minute flow. For example, if a nozzle is flowing 1,000 GPM, then it has an approximate nozzle reaction on the order of 500 lbs.

The critical concern in these cases is if the discharge pressure varies. A variable discharge pressure results in “water hammer”. If either basic pressure varies, or if the switch from tank to hydrant is not smooth or if there was compressed air in the hydrants, fairly large water hammer can occur. In one major city, it was found that compressed air in the hydrants resulted in water hammer from factors of 2 to factors as high as 7! Imagine a nozzle flowing 1,000 GPM having a normal reaction force of ~ 500 lbs, then compressed air in the hydrant momentarily results in a factor of 3 in water hammer, would yield a transient reaction force on the order of 3 x 500 lbs = 1500 lbs!
**Rappelling:** Typically manufacturers avoid the whole topic basically because they cannot provide a “verifiable” process for carrying out the procedure safely. The general question posed is that if a person rappels down a rope at constant speed, then the force they apply to the rope is simply equal to their weight, and if the person does not exceed the rated capacity, then isn’t the load okay? And the answer to the question is “Yes”. The problem arises in real life!

The starting and stopping of the person results in dynamic loads associated with their accelerations. Either the excitement at the time or the “hot dogging”, “showing off” or “stupidity” can easily result in forces that are double the weight of the person. If a person free-falls a few feet and then tightens back up on the rope can effectively double their applied weight.

Due to these possibilities that bring potentially large reaction forces lead manufacturers to refrain from condoning the rappelling activity. Although some departments still persist, for legitimate reasons, the activity carries some dangerous potential for damage and the activity should be carefully considered before being employed.
AERIAL PHYSICS

Use as an anchor point: A standard technique in high angle or confined space rescue is to use the aerial as an anchor point. As with use as a crane, the problem that arises is that it is the tensile force through the connecting straps, ropes or cables that deliver the force to the aerial, not the connected load itself.

In the case of hanging a pulley below the aerial and passing a rope of some sort over the pulley to use to lift a load, like a Stokes basket, the pulley provides only a change of direction, but no mechanical advantage.

Consider a strap attached to both base rails, slung under the aerial with a self-centering pulley, as shown: Imagine a Stokes basket with a combined weight of 240 lbs (basket, person and block & tackle). A single rope attached to the Stokes, passes up and over the pulley and down the other side. To support the 240 lb load, the tension in the rope must be 240 lbs, so as it passes over the pulley, the rope pulls down on both sides of the pulley with 240 lbs, with a maximum net force of 480 lbs (if both ropes are parallel, certainly the net value decrease slightly as the angle between the two ropes increases – these are vector sums, not scalar sums). If the Stokes is to be raised, the overcoming friction in the pulley system requires a force greater than the 480 lbs.
Firefighters in Mundelein, Illinois were practicing a stokes basket evolution when their aerial ladder failed just above the bed section. The firefighters had run a rope through pulleys attached to the tip and the front tow hook (seen below), and were attempting to raise the basket when the collapse occurred.

Maintaining the “pulling” rope as parallel to the aerial as possible will reduce the effect of the force pulling downward.
With the use of a 2-to-1 block and tackle concept:

The rope is initially attached to the upper pulley, passes around the lower pulley at the Stokes, then passes back over the upper pulley and travels back to the ground and the rescue workers.

Each rope on the Stokes around the lower pulley must carry a tension of 120 lb in order to support the 240 lb Stokes basket. The upper pulley now has three ropes pulling down at 120 lb each resulting in a net downward force of 3x120 lb = 360 lb. Then overcoming friction, the net pull must be somewhere between 400 lb and 450 lb, depending on the manner in which the rope is pulled.
In a third scenario, a pulley (or “roller”) is attached between the base rails at the tip so the rope from the Stokes can pass up and over the pulley and then pass down the ladder, parallel to the ladder. In this last scenario, the rope that passes down parallel to the ladder tends to compress the ladder along its length, not pull down. The cross section of the ladder is designed to absorb those compressive stresses, so those stresses do not represent a major problem.

This photo shows a close-up view of the point of failure just above the bed section in the Mundelein incident. Ladder failures often occur at this point in the ladder.
In each of these cases, the force applied to the aerial is greater than the weight of the “dead load”. Dynamic forces are variable; they can be theoretically determined given a discrete and well defined set of circumstances and precise operations, however, after the fact, actually evaluating the effect of an action given anecdotal information is very difficult. And be sure, in case of an accident or incident, theoreticians, in opposition, will try paint the worst possible scenario to make the operator liable, so always be aware of the consequences of your actions.

Cross section of the main beam of the Mundelein ladder after it was cut to remove the damaged sections. The beam is assembled from several section of flat steel strips which are bent to form the flanges and then welded together to create the I-beam shape. The interior of the beam is hollow.
Aerial Truck

There are two perspectives to keep in mind when calculating forces and torques on aerial devices: (1) the aerials in an elevated condition are nothing more than large crow bars, and (2) the same relationships that apply to a ground ladder equally apply to the aerial devices.

For vertical equilibrium, operators must be careful that their trucks not sink into the ground. Not only is dead weight important, but as the aerial devices are positioned into different orientations, the force/weight transfers due to torques can result in extra large forces being exerted at specific vehicle support points in excess of those forces sustained with the dead weight. Cal Trans (California Department of Transportation) recommends city and state roads be built to support compression pressures of 500 psi (pressure = force/area). Private roads, shopping center grounds, school grounds and apartment parking lots may not necessarily be built to these specifications.

NFPA 1901 - 2009, section 19.21.4.2.1, states that the maximum pressure exerted by any stabilizer not exceed 75 psi.

The compression pressures can be calculated simply by knowing the weight on the various axles, and hence the wheels, of a truck and dividing the weight on each wheel by the contact area (in square inches). The weights on the wheels/axles is given on the GVW tag on the truck for the front and rear axles. To determine these weights independently, agencies can either go to public scales or place some portable scales under the wheels. In the case of weight transfers, portable scales can be placed under the wheels and the stabilizers. Carefully monitor the scales as the aerial device is positioned in different orientations. For stabilizers, use the area of the plate that goes under the stabilizer pads. These compression calculations should give a fairly reliable sense of how much force is being generated by a truck on the ground, and hence a sense of intrinsic stability. (The older NFPA Standard required the minimum size of stabilizer shoes and pads, but starting with the 1991 edition, the Standards Committee opted for a performance criterion rather than a fixed dimension.)

Weights exerted on the ground by a vehicle are determined by:

- the total weight of the vehicle
- the number and positions of the axles
- the position of the centre of gravity of the vehicle.

For horizontal equilibrium, unless the truck is on an incline, there is no general concern. However, even slight inclines can be of concern and dangerous. Trucks have been known to vibrate off their stabilizer plates. Inclines can also contribute to rotational instability, i.e. roll-overs. If a stabilizer sinks into the ground, then the truck will tilt and slide or potentially roll-over.
**AERIAL PHYSICS**

**Model ladder** – forces on stabilizers

Several items must be considered:

1. The total upward force through the wheels and/or stabilizers (some aerial manufacturers recommend that the jacks and stabilizers be lowered so to lift the truck to take the bubble out of the tires and others to lift the tires totally off the ground) must equal the total weight of truck chassis, aerial device, water, firefighters and equipment.

2. In an ideal situation there will be no incline, so we will not have to worry about horizontal forces along the ground.

3. Torques. Basically the torque generated by the three parts of the aerial: the boom itself, the firefighter and the axe at the tip must be balanced by the supporting torque of stabilizers. Torque is determined by taking the pivot at the base of the aerial. Torque is downward weight times the horizontal distance from the pivot to where the weight force crosses that line.

4. There are several ways of looking at the rotational equilibrium of the truck. One view could be that the sums of the torques from the ladder itself, the firefighter and the axe are on one side of the stabilizer planted on the ground, and the truck then acts as a “counter-weight” on the other side. This approach unfortunately only gives us the weight of the chassis, which is basically already known, so nothing new is discovered. A different approach is to let the “pivot” point be the centre-line of the chassis. In this case the ladder and weights act to roll the truck over as though it acted counter-clockwise through the centre-line, and the stabilizer under the ladder would act as a clockwise torque, also acting about the centre-line. In this second case, what is discovered is the force that acts through the stabilizer. This value can be measured with portable truck scales placed under the stabilizers.

\[
\begin{align*}
F_1 &= \text{weight of firefighter + axe}, \\
F_2 &= \text{dead load of ladder}, \\
F_4 &= \text{force through stabilizer}
\end{align*}
\]

To determine the forces on the stabilizers we assume the ladder is fully extended and rotated to 90° to the chassis. In this calculation, it will be assumed that there is only one set of stabilizers on each side. From the diagram, the sum of the moments tending to overturn the truck includes the ladder, the firefighter and the axe:

- For the ladder, \( T = R_f F_2 \)
- For the firefighter, \( T = R_f F_{FF} \)
- For the axe, \( T = R_f F_{	ext{axe}} \)
AERIAL PHYSICS

Sum of moments tending to overturn the truck = sum of the torques.

To resist overturning, assuming the rear wheels have been taken off the ground, all the downward force in the rear passes through the stabilizers. The “stabilizing” torque equals,

\[ T = Rf4 \times F(\text{stabilizer}). \]

These calculations assume a dead load weight of 10,000 lbs for the ladder with a center of gravity at a point 32 feet up from the heel pin (since the ladders are not uniform in dimension, with the base heavier than the fly means the centre of gravity is closer to the base). Representing a rated 100 ft ladder, the boom length is taken to be 100 ft, even though a 100 ft ladder is not actually 100 ft long. A 100 ft determination is measured from the tip of the ladder at full extension and elevation to the ground, which takes into account the base of the ladder starting 8 ft (or so) in the air because of its mounting on top of the truck. From these two numbers, any other aerial devices can be scaled up or down in size by changing the factors, such as 10,000 lbs and the 100 ft. We will assume a firefighter of 250 lbs and an axe of weight 10 lbs.

Take the aerial to be inclined 60° up from the horizontal. This is chosen because for older ladders, at full extension with “one man” at the tip, unsupported, the minimum elevation is around 60°, and at this angle there are simple geometrical relationships. Given an equilateral triangle where each side has the same length and the three angles are 60°, if the triangle is bisected, the right side of the triangle has angles 30°, 60°, 90°. One of the halves of the bisected equilateral triangle is a right triangle with a 60° angle. It is clear that if the hypotenuse has a length, \( x \), the projected length along the base is \( \frac{1}{2} x \). This relationship makes the calculations at 60° elevation more simple.
At 60° elevation, the centre of gravity 32 ft up the ladder projects to 16 ft horizontally from the heel pin and the firefighter and axe, 100 ft up from the heel pin project to be 50 ft horizontally from the heel pin.

The torques acting on the aerial are then: \( T = MA \times \text{force} \)

\[ T_{\text{ladder}} = 16 \text{ ft} \times 10,000 \text{ lb} = 160,000 \text{ ft lb} \]

\[ T_{\text{FF}} = 50 \text{ ft} \times 250 \text{ lb} = 12,500 \text{ ft lb} \]

\[ T_{\text{axe}} = 50 \text{ ft} \times 10 \text{ lb} = 500 \text{ ft lb} \]

For a sum of moments = 173,000 ft lb

To resist overturning, a counter torque is generated through the stabilizers, such that in this case, the torque through the stabilizer must equal 173,000 ft lbs.

\[ T_{\text{stabilizer}} = MA \times F_{\text{stabilizer}}. \]
There are two ways to determine the moment arm of the stabilizers: one is to fully deploy the stabilizers and measure from centre to centre for the stabilizers across the truck and divide by 2. The other way is to assume most trucks are 8 ft wide, so half way from centre of the chassis to the edge of the chassis is 4 ft, and then add the distance the stabilizer sticks out from the chassis to the 4 ft (this isn’t as precise, but it’s a quick good first order approximation). For this calculation a moment arm (from the centre of the chassis to the centre of the stabilizer) of 8 ft will be used.

\[ 173,000 \text{ ft lb} = 8 \text{ ft} \times F_{\text{stabilizer}}. \]

Divide by 8 ft and \( F_{\text{stabilizer}} = 21,625 \text{ lb} \).

Note: due to the “crow-bar” effect, a total applied weight of 10,260 lbs (\( = 10,000 + 250 + 10 \)) generates a total of 21,625 lbs!

To determine the pressure acting on the ground, \( P = F/A = \text{lb/in}^2 = \text{psi} \), the areas of the shoes and pads must be determined. In the old standard, NFPA gave guidance to manufacturers; NFPA stipulated prior to the year 1991 that shoes should have a minimum area of 140 in\(^2\) (~12” x 12”) and pads should have a minimum of 575 in\(^2\) (~24” x 24”). Starting with the 1991 standard, as noted previously, the NFPA stated that no pressures generated on the ground should exceed 75 psi. However, simple observation shows that the common values of sizes of shoes and pads remain at about these dimensions, with a few variations of course. To compare the effective pressures generated through shoes and pads, for the two dimensions will suffice. Remember: since shoes and pads are layered, the net force through each remains the same, only the pressure changes.

\[
\begin{align*}
P_{\text{shoe}} &= \frac{21,625 \text{ lb}}{140 \text{ in}^2} = \sim 154 \text{ psi}, \quad \text{and} \\
P_{\text{pad}} &= \frac{21,625 \text{ lb}}{575 \text{ in}^2} = \sim 38 \text{ psi},
\end{align*}
\]

which meet the intent of NFPA.

Now if the ladder is permitted to be lowered from 60° to 0°, things can change significantly.

Basically, as the ladder is lowered, the centre of gravity of the ladder itself as well as the weights of the firefighter and the axe move out farther from the centre of the heel pin, and when the ladder is rotated off to the side of the chassis, the moment arm creating the overturning torque (and stress on the aerial components) increases.
The moment arm of the cg of the ladder changes from being 16 ft to 32 ft and the moment arms for the fire fighter and axe change from 50 ft to 100 ft, so the moment are doubled. Doubling the moment arms results in the doubling of the applied torques. To accommodate this effect, all manufacturers are required to provide load versus extension and inclination capabilities:

**NFPA 1901 – 2003:**
20.4.2 A system that is lighted and marked with labels shall be visible from the operator’s position to indicate the elevation, extension and rated capacities.

As the ladder is lowered from 60° to 0°, the torque from:

The ladder changes from 160,000 ft lb → 320,000 ft lb
The fire fighter changes from 12,500 ft lb → 25,000 ft lb, and
The axe changes from 500 ft lb → 1,000 ft lb

So the sum of moments changes from 173,000 ft lb → 346,000 ft lb

The force on the stabilizers changes from 21,625 lb → 43,250 lb, and

The pressure on the shoe changes from 154 psi → 308 psi

With the pressure on the pad changing from 38 psi → 76 psi, which is too large to meet the NFPA performance specification!... Time to change the model!
The point of this result is that if an aerial is set-up in a way such that a combination of poor decisions are made: over-loaded tip, too low an inclination, people climbing on/off the tip or flowing water, using the aerial as a battering ram, not placing the stabilizers out all the way, or not placing the plates under the stabilizer shoes, then the operator is courting disaster.

The purpose of the stabilizers is to prevent the aerial device from rolling over while the aerial is in operation. Obviously, if the aerial is short-jacked, a shorter moment arm will occur resulting in (1) greater force applied up through the stabilizer, or (2) instability and subsequent rollover.

When operating the aerial take the time to calculate the loads, this will save someone's life.