The Philosophy of Modern-Day Fire Resistance and the Lightweight Parallel-Chord Steel Truss

by Captain John P. Flynn, P.E.

Firefighting response has remained essentially the same over a period of many years--despite new threats that parallel the evolution of building materials and construction methodology. In a general sense, all Firefighters recognize new threats to their safety and well-being posed by modern, "engineered" materials and methods of construction. However, a true beginning point in the attempt to fully realize the threat posed by these "engineered" products is understanding the philosophy of modern-day fire resistance.

Once this philosophy is realized, the specific characteristics of the engineered structural elements may be analyzed to further increase awareness. This article will describe the modern design philosophy and then concentrate on the hazards specific to one of the greatest threats Firefighters face--the lightweight parallel-chord steel truss.

Philosophy

The benefits associated with the use of engineered materials and components are widely known to the engineering profession and the construction industry. These materials and components are permitted under current building codes and their use is growing, based on many undeniable tangible benefits. Articles in firefighting publications repeatedly decry the hazards posed by these structural elements. However, this information is not readily available to the engineers, architects and code writers, who truly dictate the nature of modern-day construction.

More importantly and critical with regard to future Firefighter safety, is the recognition that such arguments all too often would fall on deaf ears. This is because the current state of design practice is founded upon three fundamental assumptions:

1. Modern codes and design procedures adequately protect structural elements from heat and flame.
2. The structure will be constructed exactly as designed.
3. The structure will remain in the "constructed" condition throughout its existence.

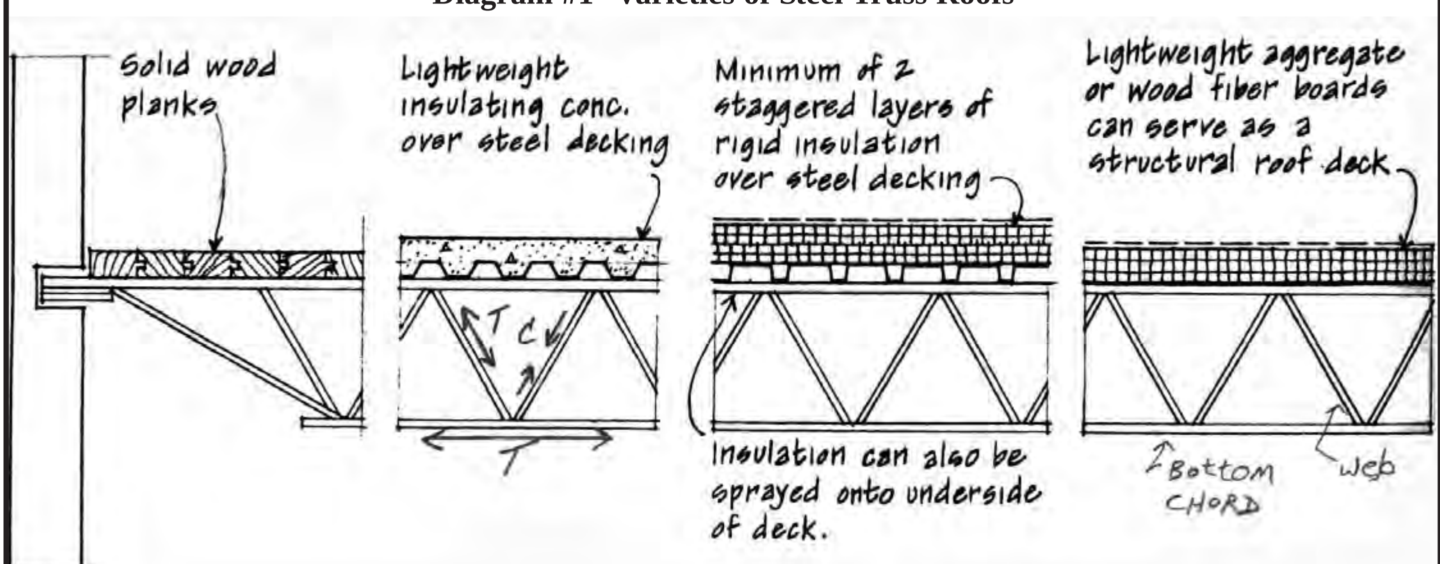
It would be difficult for the firefighting community to contest the first assumption. It is a fact that modern-day code provisions, materials and practices truly provide a level of structural fire resistance unseen in the history of mankind. At face value, therefore, Firefighters are safer from fire than ever before. This realization permits the code developer and engineer to sleep at night, satisfied that they have provided a safe and efficient product to the public.

The Firefighter, however, must look deeper and recognize that the two remaining assumptions are not consistent with reality. The absence of the recognition of real-world occurrences that reduce the integrity of fire resistance is a puzzling, but irrefutable, truth that Firefighters must not forget. The building *may not* be constructed as designed and it *may be* subject to misuse, deterioration and neglect over time.

With these real-world developments, the products, methods and materials of modern-day construction ironically transform into the greatest challenges ever faced by the Firefighter. In a sense, it boils down to an *all or nothing* design philosophy: As long as the structure exists *as designed*, it is safe. Minor instances of compromise, however, can result in an exponential increase in danger.

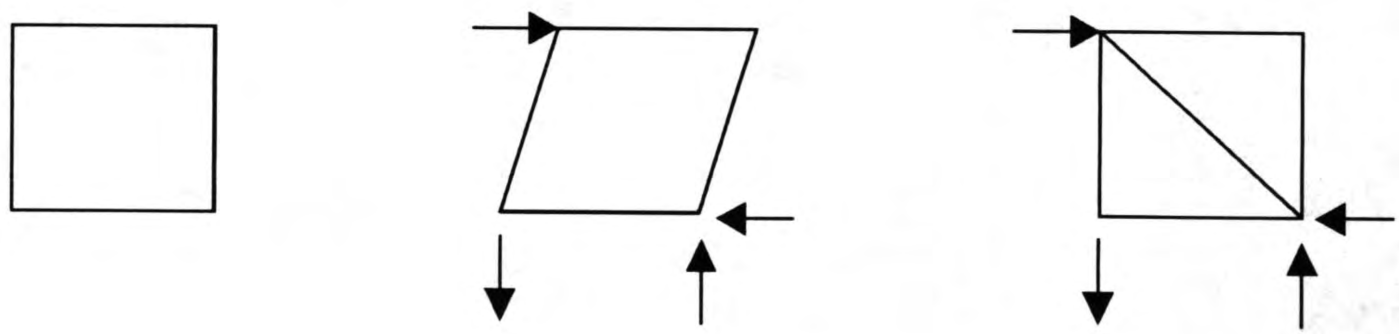
The relative newness of these methods and materials has resulted in a decrease in the number of fire-related threats. Instances of compromise, however, have caused an increase in the

Diagram #1--Varieties of Steel Truss Roofs



taken from Building Construction Illustrated, *by Francis Ching*

Diagram #2--Stability Through Triangulation



(Left)--A square is structurally unstable. (Middle)--When a force is applied, a square will distort. (Right)--A member can be added to form two inter-related triangles, which are structurally stable.

variety of ways in which Firefighters are injured or killed and an increase in the potential for multiple Firefighter fatalities. It must be remembered, however--particularly within the ranks of younger Firefighters--that with age, the number of fire incidents can be expected to climb with a commensurate increase in the potential for injury and death.

Engineered structural elements include lightweight parallel-chord steel trusses, lightweight wooden trusses, modular construction systems, light-gauge steel framing systems, laminated veneer lumber beams, wooden "I"-shaped joists and fiber-reinforced composites. This article now will focus on the characteristics and hazards associated with the lightweight parallel-chord steel truss, common to commercial structures, but also used in residential structures of many shapes and sizes in New York City.

The lightweight steel truss

Lightweight parallel-chord, open-web steel joists (aka bar joists) now are a staple of the construction industry. (See Photo #1.) These trusses are used in virtually all types of occupancies, including multiple-family residential, light commercial and high-rise office buildings. They possess unique characteristics that must be fully appreciated by the firefighting community to ensure safe response.

A review of fire-related publications during the past 20 years indicates that the fire service is familiar with the general hazards posed by various types of trusses under typical structural fire conditions--so much so that the truss is largely considered a nemesis. A similar review of publications associated with the engineering profession and the construction industry, however, indicates that most people employed in those professions are *unfamiliar* with the susceptibilities associated with lightweight truss-based design.

This may come as a surprise to many Firefighters. However, discussions with structural engineers and a review of the subject matter taught at engineering schools reveals a virtually complete absence of fire as a consideration in the structural design process. Furthermore, distinct administrative boundaries between fire and building departments result in marginal communication regarding the implications of the use of lightweight steel elements in construction.

Periodic disasters involving lightweight trusses--most notably the collapse of the World Trade Center towers--highlight the need to spread the word to the people who make decisions regarding the fire-related behavior of the components of structures. In many cases, a prohibition on the use of trusses is justified--and would be supported by well-meaning design professionals--if these decision-makers were more aware of the inherent hazards.

The factors of concern include the following: design characteristics, material, geometry, location within the building system and potential fire exposure. Experience indicates that each factor alone is problematic and potentially hazardous for Firefighters and civilians. Factors in combination can cause a synergistic effect. It is up to the fire service--the most concerned stakeholder--to enlighten the various entities involved in the design/build process and influence code-writing to the greatest extent possible. Concerned Firefighters must be intimately familiar with the weaknesses of the lightweight steel truss so they never underestimate the threat it represents.

In an effort to further increase awareness, the following concerns specific to lightweight steel trusses are provided:

Photo #1--Typical bar joist construction.

all photos by Captain John P. Flynn, P.E., unless stated otherwise

Photo #2--Trusses may be constructed with bars or, as shown here, cold-formed steel sheets.

Photo #3--Another type of lightweight truss consists of wooden chords and tubular steel webs.

Design Characteristics

- The benefits of truss construction derive from the ability of the truss to replace *mass* with *geometry*. Conventional beams respond to external vertical loads by developing internal resistance in the form of shear and bending--both inefficient response mechanisms that depend on mass. The truss manages to resist external loads by using triangulation to cause only direct stresses (compression and tension)--stresses that are resisted efficiently by most construction materials. (See Diagram #2.) In this manner, lightweight, slender directional components are effectively used to provide a much lighter element relative to conventional beams. The end result is a more efficient member under normal loading conditions; i.e., a light truss versus the heavier "I"-shaped beam seen in "ordinary" steel framing. Inexpensive lightweight trusses are easily transported, lifted into place and fastened to the structure by relatively non-skilled individuals. The unfortunate result of structural efficiency is that the mass of the load-carrying member is significantly reduced, while the surface area is significantly increased. This results in a member that is more susceptible to rapid heating with a shortened onset of the deleterious effects associated with heating. The effectiveness of extinguishment by the Fire Department is predicated upon a response that eliminates the fire during the incipient stage when the contents are burning and the structure is intact. A rapid onset of heat-related effects to the structure prior to extinguishment--a susceptibility of the lightweight truss--reduces the factor of safety for the responding Firefighters. This is particularly true at the upper reaches of high-rise structures and deep within warehouse areas, due to the unavoidable delay in reaching the fire location.
- The narrow cross-section and slenderness of the truss components provide a much smaller area in which to provide fixation to supporting elements. Fewer fasteners and fasteners of reduced size result in a greater tendency for premature failure during extreme events such as uncontrolled fire. This tendency proved to be a contributory factor in the collapse of the World Trade Center towers and other structures in which Firefighters have perished.
- The greatest single benefit derived from the use of trusses is the creation of large floor areas without the need for intermediate supports (columns and walls). These vertical support elements are considered by owners, occupants and real estate professionals to be unsightly and reduce usable floor space. Headroom is maximized due to the ability to run ducts within the truss web area above the ceiling. The fire load within an enclosure is proportional to the area of the enclosure and the heating effects can increase non-linearly due to increased air supply to larger spaces. The lightweight truss is, therefore, exposed to critical temperatures earlier and for longer periods of time than "ordinary" steel-framed structural elements. Trusses typically vary in depth from approximately eight to 36 inches; the span will not exceed 24 times the joist depth, a figure that may be used as a rule of thumb in determining expected span. The maximum span to be expected in standard usage is approximately 60 feet. Special deep lightweight joists can span up to 144 feet.

Material

- The open-web truss used in commercial applications is almost invariably constructed with structural steel. "Bar joist" may be a misnomer. Often, the truss elements are constructed with thin steel pieces that are "bent" into shape or otherwise inexpensively cold-formed. (See Photo #2.) They also may be composite in nature (wood and steel). (See photo #3.) In any event, the design is based upon the truss sustaining a maximum loading that results in the steel being stressed to a pre-determined percentage of the yield stress (the stress at which the material elongates under load without the ability to return to its original dimensions). At temperatures readily achieved in the average structural fire, this yield stress is reduced by as much as 50 percent, reducing or eliminating any safety factors that exist in normal usage. The relatively small mass and large surface area of the truss causes its members to reach these critical temperatures rapidly. FDNY experience with lightweight steel trusses indicates that when directly exposed to fire, these elements fail in as little as five minutes. Fire operations on roofs determined to have exposed steel truss support must be aborted immediately and the roof evacuated. Similar controls must be considered for floors supported by steel trusses that are similarly exposed. Photo #4 illustrates a steel truss roof failure that resulted in Firefighter fatalities at the August 2, 1978, Waldbaum's supermarket fire on Ocean Avenue in Brooklyn.

• Steel expands significantly when heated. Minor increases in temperature result in lengthening of the steel truss. Restrained expansion, as experienced when the truss is welded to a girder or abuts a wall, will result in one of two failure modes:
1. Buckling of the compression chord (top chord) of the truss, followed by collapse. Restrained expansion is no different than overloading a truss in compression along its axis; the truss fails in a manner similar to an overloaded column. This failure is sudden, complete and without warning.
2. Failure of the element providing restraint. Such would occur in the form of a parapet wall being pushed outward or a girder being bent out of shape. This failure may occur gradually with the possibility of a warning.

In the event that failure of the truss or support does not occur due to inherent "forgiveness," under continued heating, the truss will lose strength and sag into a tension structure. This loading condition is foreign to the truss and its connections and failure likely will be gradual in nature. This effect has been identified as a major factor in the demise of the World Trade Center towers. Grossly sagging trusses pulled portions of the exterior columns inward by as much as six feet, causing an instability-induced collapse of the columns.

NIOSH photo

Photo #4--This truss-supported roof collapsed due to fire.

Geometry
• The slenderness of the typical truss component reduces the effective adherence of sprayed-on fireproofing. It is extremely difficult to consistently apply a 3/4-inch layer of fireproofing to a 3/4-inch-diameter truss web. Recent studies have indicated that minor localized imperfections in fireproofing can result in disproportionate heating with exaggerated effects. The inherent absence of redundancy within a truss element causes a localized failure of a component to compromise the entire truss. The lack of redundancy within a truss system causes a single truss failure to compromise the entire floor or roof support system.
• The open-web configuration of the truss eliminates the capability for "built-in" firestopping, which is inherent in other types of floor and roof construction. Heat and fire gases are liberated throughout the void space, affecting large expanses of structural framing simultaneously and igniting combustibles therein.
• The relatively weak bond between the lightweight, sprayed-on fireproofing material and the slender truss components is susceptible to damage from air pressure, fragmentation and blast over-pressures--phenomena often associated with fire. The loss of fireproofing leaves the truss vulnerable to direct fire exposure and rapid heat absorption.
• The slender truss cannot stand on its own as a structural element. It depends entirely upon lateral support from other trusses and the decking above it. It is a system part and cannot exist independent of that system; conversely and ironically, the system cannot exist in the absence of even a single truss. This interdependence results in a veritable "house of cards" that is not considered by the designer who assumes that each and every component will always be intact and present. Firefighters must be very careful in removing any element of the system, including cutting ventilation holes in the decking and removing lateral braces. A surprising number of trusses fail during construction due to instability; more fail in use as a result of overload, corrosion or misuse. (See Photo #5.)

Location
• The truss most commonly is used for floor and roof construction, two locations of critical importance to Firefighters conducting initial firefighting operations. The buoyancy of heated fire gases results in a positive pressure on the underside of ceiling assemblies, which causes the gases to seek out imperfections and gaps, thereby penetrating the membrane, entering the ceiling space and exposing the truss assemblies to direct heat.
• The nature of truss construction in multi-story buildings is typically a repetitive design used on successive floors. The failure of the floor system on a single story will result in impact loads on the story below. This impacted floor possesses joists spanning wide areas with minimal connections, as described previously. The lack of redundancy inherent in this construction will increase the potential for a rapid, global, progressive failure of the structure.

Photo #5--Trusses often collapse under normal loading conditions in the absence of fire. Here, snow was the culprit.

Photo #6--Trusses may be unprotected over areas housing significant fire loads.

Fire Exposure

- The truss is employed in many applications, including those in which fireproofing and fire protection are not required. (See Photo #6.) The effects of heat on exposed lightweight steel are remarkable and rapid, resulting in loss of structural integrity within minutes. A fire in such a location will prove especially hazardous to responding Firefighters who employ the strategy of interior attack, as in the New York City Fire Department.
- Buildings under construction that experience a fire prior to or during the application of fireproofing will be subject to the same immediate effects as those that are not required to be fireproofed.

The lightweight steel truss system is a relative newcomer to the building construction industry in New York City. As such at this time, an accurate history of performance under fire loads is limited. In concert with the law of averages, most fires to date have occurred in the well-compartmentalized buildings conforming to the pre-1968 building code. This code required more substantial fireproofing and the use of larger, steel "I"-shaped columns and beams in steel-framed structures (i.e., One New York Plaza, 1972, and 299 Park Avenue, 1979).

Despite these fateful advantages, significant damage to even these "ordinary framed" steel structures often has occurred (i.e., One New York Plaza, 1972; One Meridian Plaza, Philadelphia, 1991; and the Bankers Trust Building, 1993). The substitution of lightweight steel trusses for conventional framing introduces the distinct potential for fire-induced failure and progressive collapse.

The knowledge of the many hazards associated with the use of steel trusses is useless without the ability to recognize their presence. This is a difficult skill developed over time with experience, education, increased awareness and the development of recognition capabilities. It is particularly difficult in a finished building or in a heavy smoke condition. All responders must be on the lookout for the following tell-tale signs that may indicate the presence of steel trusses:

Age--The steel truss has been incorporated in New York City buildings for more than 50 years, but the past 20 years has seen a dramatic increase in their usage. Newer structures are more likely to incorporate steel trusses than older ones.

Large open floor areas--Part of a Firefighter's size-up must include an evaluation of the occupancy regarding size and floor plan. Probably the most useful and obvious clues are large, open, continuous spaces without intermediate columns or walls. Drop ceilings with acoustical tiles often are suspended below truss construction in order to achieve a fire rating as an assembly. Note, however, that gypsum board also is used to serve this purpose.

Flat roof--It is generally uneconomical for an owner to construct a pitched roof over a truss system. The truss thus serves as a support system for both roof and ceiling.

Smoke emitting from various sides of the building at ceiling level or pushing down at multiple locations within the occupancy--These conditions coincide with the existence of a large, unobstructed, open area above the ceiling level.

A galvanized steel, pan-type roof or floor deck is discovered to exist--These decks commonly are corrugated and often associated with steel joist support systems. They are used to support concrete, plywood sheathing and insulation boards. Their presence may be detected from above or below. (See Diagram #1 and Photos #3 and #4.)

CIDS--This is the only pro-active, systematic, protective measure available to New York City Firefighters. All members must be inquisitive regarding the nature of new structures within their response areas and mindful of their capability and obligation to convey critical information to future generations of Firefighters.

The signs of steel truss construction rarely will be clear-cut in nature. When in doubt, it is best to assume a worst-case scenario and proceed accordingly. Once their presence is determined at an operation, immediate communication of their existence may prove to be the difference between a safe operation and an avoidable disaster.

In summary, all Firefighters--particularly Officers and Incident Commanders--must be mindful of the philosophy of design that serves as the unseen enemy of safe firefighting. Additionally, the specific hazards of each of the engineered products must be known and respected, including the widely used and potentially deadly open-web lightweight steel truss.

Members are urged to read the following:

- "CIDS Again Proves its Worth at Queens Fourth Alarm," by then-Deputy Chief Stanley Dawe, in the 2nd/2001 issue of *WNYF*.
- "CIDS to the Rescue in Staten Island" and "Three Little Characters and CIDS," by Deputy Chief Theodore Goldfarb, in the 2nd/2005 issue of *WNYF*.
- "Company Drill Proves Critical to Firefighter Safety," by Battalion Chief Robert J. Strong, on page 2 of this issue of *WNYF*.
- *Collapse of Burning Buildings*, by Vincent Dunn.
- *Building Construction for the Fire Service*, by Francis Brannigan.
- "Risk Management and Lightweight Truss Construction," by Deputy Chief Vincent Dunn, in the 1st/98 issue of *WNYF*.
- "Three Kinds of Timber Truss Roof Collapse," by Deputy Chief Vincent Dunn, in the 4th/98 issue of *WNYF*.
- "Multiple Dwellings with Wood Truss Floor Joists," by Battalion Chief Charles Ditta, in the 3rd/99 issue of *WNYF*.
- "Construction Hazard Safety Tip #1, Lightweight Wood Truss Construction," by Captain Joseph Russo, in the 3rd/99 issue of *WNYF*.

About the Author...

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