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Structural Collapse Under Fire Conditions

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Most fire service personnel learn basic building construction early in their careers but little on how to predict structural collapse. However, the newer materials and construction techniques used today, particularly truss systems, are more likely to collapse faster in a fire than traditional materials, thus making it all the more crucial to possess the knowledge to predict structural collapse at an incident scene.

EVOLUTION OF CONSTRUCTION METHODS AND MATERIALS

Over the past 30 years, construction methods have transitioned from heavy timber, larger steel, and concrete sections to smaller, lighter sections. The wood construction industry transitioned from using heavy timber sections (approximately 12 inches × 30 inches), to rough-sawn lumber, to dimensional lumber, and now to engineered lumber. Engineered lumber is presented in several ways, which may include larger pieces of laminated veneer lumber (LVL), I-joists, and wood trusses. Connection methods vary from glues to metal plate connectors. The larger LVLs and structural glue-laminated timber (known as "glulams") perform similarly to heavy timber. Wood I-joists are constructed of smaller laminated veneer flanges and an oriented strand board (OSB) web.

The structural and economic advantages of the truss products have led to a significant increase in their use, especially in residential and light commercial buildings. It is common to find lightweight steel or wood framing in virtually all smaller structures such as nursing homes, hotels, apartments, schools, single-family homes, daycare centers, and small business offices. The Wood Truss Council of America reports that wood truss roof systems are used in more than 60 percent of all new buildings constructed in the United States. When properly installed and unaltered, truss systems are among the strongest structural systems. However, the performance of truss systems is less predictable under fire conditions.

FIRE RESISTANCE RATINGS

To understand how structural systems perform under fire loading, let's examine how the fire resistance rating is obtained. The most common test in the United States is the American Society for Testing and Materials (ASTM) E119. This test is recognized by fire and building officials as "standard test methods for fire tests of building construction and materials." ASTM E119 prescribes a standard exposing fire of controlled extent and severity. The material's performance is defined as the period of resistance to standard exposure before the first critical point or failure of the system. Critical points may include the following:

- The transmission of heat through the material, raising the average temperature on the unexposed

side more than 250°F;
- allowing the passage of flame and gases; or
- failure of the assembly under load.

This standard measures and describes the response of materials, products, and assemblies to heat and flame under controlled conditions but does not incorporate all factors required for fire hazard or fire risk assessment under actual fire conditions. ASTM E119 testing is conducted with weight loads that are static and not equivalent to the dynamic load of multiple firefighters, tools, hose, and flowing water. There are also concerns that the time/temperature curves do not reflect the newer materials present in today's fires, including the amount of plastics and synthetics found in today's consumer products, which burn much faster and with higher temperatures.

To determine the fire resistance rating, you must understand the rate of char for wood structural members and subsequent loss of mass and cross-sectional area of a structural member. The fire endurance of a given structural member depends on the performance of any protective membranes, the extent of charring, and the load-carrying capacity of the uncharred cross section. Burning wood undergoes pyrolysis, which reduces density by changing the wood to gases and char. The rate at which this occurs depends on the type of wood, moisture content, chemical composition, permeability, and density. On average, wood will burn at approximately 1½ inches per hour or faster. (Note: This rate of char development is not a hard and fast rule; it depends on wood type and moisture content, among other things. Never use char depth, for example, to determine specific durations of "burning time" in a fire investigation.) As wood burns, a char layer is formed that provides a level of protection to the structural member. A protective membrane may also add protection to the system, depending on its material. A single layer of 3⁄8-inch Douglas fir plywood provides five minutes of protection, and a double layer of ½-inch gypsum board provides 50 minutes of protection. A standard, unprotected wood floor or roof joist, 16 inches on center, will contribute 10 minutes to an assembly; an unprotected wood roof or floor truss assembly, 24 inches on center, will contribute five minutes to an assembly. Figure 1 compares failure times between dimensional lumber and engineered lumber.

Figure 1. Lumber Failure Times

Material	Spacing (on center)	Assembly Rating	Structural Failure	Loading (per square foot)
2 × 10	16 inches	9 min 0 sec	> 13 min	31
I-Joist	24 inches	4 min 40 sec	4 min 40 sec	31
Metal Plate Connected Truss	24 inches	9 min 0 sec	15 min 45 sec	31
TJL (Truss Joist)	24 inches	6 min 50 sec	9 min 45 sec	31

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Another critical factor in determining the ability of a structural system to react under fire conditions is the existing loading. As the loading nears the design capacity, the ability to withstand a fire load decreases. The failure of structural elements and the subsequent structural collapse are affected by the loading, protection, fire intensity, and fire duration. A 51⁄8-inch × 21-inch unprotected wood beam exposed to fire on three sides and loaded to 50 percent of its allowable load will have a fire resistance rating of approximately 64 minutes. At 75 percent of its allowable load, it will have a fire resistance rating of approximately 54 minutes, and the same beam loaded to 100 percent of its allowable load will have a fire resistance rating of approximately 49 minutes.

Although the load-carrying characteristics of various construction materials may be similar, the cross-sectional size directly affects their ability to remain intact under fire conditions. The newer, lighter-weight materials with less cross-sectional area have less ability to retain their designed load-carrying capacity in a fire. A heavy timber section has significant cross-sectional area and mass to resist the impact of fire for longer durations. Dimensional lumber sections provide a small cross-sectional area and contribute only about 10 minutes to an assembly rating. Wooden I-joists and trusses have a significantly lower cross-sectional area compared with dimensional lumber and laminated veneer lumbers.

TRUSS SYSTEM PERFORMANCE UNDER FIRE CONDITIONS

Truss system manufacturers and public safety officials have debated the performance of truss systems under real-life fire conditions for some time. Literature reviews and case studies show the need for additional research to provide the ability to effectively evaluate collapse potential. Engineering shows the fire performance of these systems under controlled conditions. Exposed truss members fail in as little as five to 10 minutes. Protected truss members show fire resistance ratings of one to two hours. Since actual fire conditions are an uncontrolled environment, truss system failure becomes less predictable.

Few indicators of imminent structural failure are available to firefighters and incident commanders. Building construction is a small part of the basic firefighting course curriculum; this usually includes the differences between structural loads (live loads, dead loads, impact loads), different construction types (fire resistive, noncombustible, ordinary, heavy timber, wood frame), construction materials (wood, concrete, steel), and a brief section on building collapse. Most firefighting textbooks identify collapse indicators as the following:

- Bowed or leaning walls.
- Prolonged fire exposure to structural components.
- Distorted structural members.
- Sagging or spongy roofs and floors.
- Loose or falling sections of a building.
- Cracks or separations in building components.
- Unusual noises.

Firefighter education on lightweight steel and wood framing in truss systems is usually limited to identifying these materials and techniques as "the most serious hazard facing today's fire service." Some resources recommend an estimated failure time of five to 10 minutes when these lightweight structural members are exposed to fire. They teach that many, if not all, of the typical collapse indicators are absent with lightweight construction. One of the only indicators of imminent truss system collapse is the characteristic sponginess of the floor or roof.

WHY FIREFIGHTERS CARE ABOUT STRUCTURAL COLLAPSE

Reports indicate that between 1979 and 2002, there were more than 180 firefighter structural collapse fatalities. The United States Fire Administration (USFA) reports that from 1990 to 2000, structural fires and explosions accounted for 46.1 percent of firefighter fatalities. The USFA report further states that during the same period, nearly 28 percent of firefighter fatalities and injuries occurred in residential properties (which, as indicated earlier, makes significant use of truss systems and products). Fifteen separate incidents investigated by the National Institute for Occupational Safety and Health (NIOSH) identified at least 20 fatalities and 12 injuries from 1998 to 2003 that occurred during firefighting operations in buildings containing truss systems. Collapse fatalities resulted from being caught or trapped in the structure (60 percent) or being struck by a piece of falling structure (40 percent).

Fire that impacts unprotected trusses puts emergency responders at an unnecessary risk. Until these lightweight systems are required to be protected through gypsum assemblies and the installation of automatic sprinkler systems, firefighters must be aware of their limits. Preincident planning, early detection, and constant awareness and monitoring are crucial to a safer fire scene involving any structure but are especially critical if the structure involves truss systems.

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