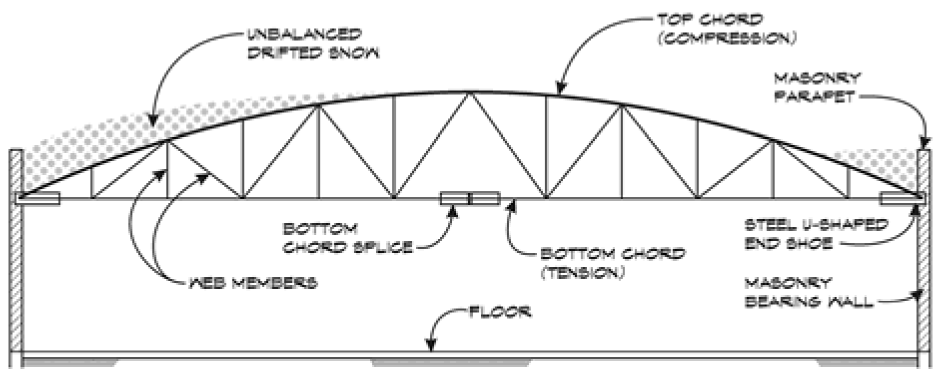
Vintage Timber Truss Roofs: Claims Waiting to Happen

By David B. Tigue and Kurt R. Hoigard

Buildings with heavy timber roof trusses can be found in many urban areas. Common in buildings constructed from the 1920s through the 1950s, timber roof trusses utilized large pieces of wood bolted together to form open spans, frequently longer than 70 feet. Timber roof trusses can be found in almost any kind of building, but were mostly used for single-story industrial and commercial buildings requiring large, open floor spaces. Examples include manufacturing facilities, warehouses, grocery stores, bowling alleys and roller rinks.



Today many of these buildings have been adapted for other uses as wide ranging as car dealerships, restaurants and video stores. While different in their uses, timber-truss-roofed buildings share several common attributes: large size; long, uninterrupted roof spans; and a propensity to sag or collapse under roof loads smaller than those prescribed by modern building codes. The authors find most timber roof truss failures are predictable, and fall into two general categories--those related to design issues and those related to long-term deterioration.

A variety of timber roof truss configurations have been used over the years. One of the most common types is the bowstring truss, so called because of its arched top chord profile (see Figure 1). Roofs constructed with bowstring trusses became popular in the late 1930s, and are readily identified by their curved shape. Although several systems were used in their manufacture, the most popular method was to construct both the top and bottom chords with two parallel members. In this arrangement, the web members were sandwiched between the chords and connected with bolts (see Figure 2).

The curved top chord members were made either by sawing straight lumber into curved shapes or laminating multiple smaller pieces bent over a jig to the desired shape. Bottom chord members were typically constructed with large, straight lumber members joined with either wood or metal bolted splice plates, located near mid-span, to achieve the required length. The top and bottom chord members were fastened together at the truss ends with U-shaped steel heels, or end shoes, bolted to both chord members (see Figure 3).

Design deficiency issues

The shortcomings in early heavy timber truss designs are rarely attributable to mistakes by the designer. Instead, they typically involve inaccuracies in the industry-accepted assumptions upon which the designs were based.

The most common deficiency in early truss designs involves inadequate bottom chord tensile strength. Early truss designs assumed wood tensile strength could be defined by bending tests of small, clear, straight-grained wood samples. Full-size lumber tests begun in the 1960s revealed that construction-grade lumber, with natural imperfections such as knots, checks and irregular grain, provides in-service tensile strength significantly less than that predicted by the earlier small scale, clear wood tests.

By 1968, lumber industry standards established a reduction factor of 0.55 to relate tensile strength to bending strength. Current building codes have increased this factor to 0.60, meaning the allowable tensile strength design values are only about 40 percent of those listed in the early codes. All trusses constructed prior to the late 1960s have a common code deficiency; the bottom chord members have inadequate tensile strength to support code-prescribed roof loads.

Another common truss design issue involves snow loads. Early building codes assumed roof snow accumulations were of uniform depth. In reality, wind frequently forms snow into drifts that can be significantly deeper than the average snow depth. Snow drifts behind raised building parapets, adjacent to higher portions of the same building, and on the leeward side of curved or sloping roofs can produce off-center or unbalanced roof loads far in excess of those predicted by the early codes.

This phenomenon was not specifically recognized in most building codes prior to the mid-1970s. The additional load, and its off-center location, can pose significant problems for older trusses by changing the distribution of forces in truss member components, resulting in their overload. Bowstring trusses, which behave principally as a tied arch under uniform loads, are particularly vulnerable to unbalanced loadings.

Roof overload can also occur due to later addition of loads that were not considered in the original design, such as an accumulation of roofing materials, heavier ceiling finishes and new mechanical equipment. The authors have investigated timber truss roof collapses involving 12 or more roofing layers, multiple ceiling levels, added sprinkler systems and roof-top HVAC units. The added weight from these items can exacerbate truss member overload conditions, particularly when combined with unbalanced snow loads and inadequate bottom chord tensile strength.

Two other factors contributing to timber truss failures involve the connections between the individual truss members. Truss joint design developments in the 1930s resulted in the use of multiple split-ring or bolted fasteners that inadvertently create semi-rigid connections. Semi-rigid connections have a low tolerance for joint eccentricity, joint rotation and wood drying shrinkage, which can occur for several years after the large timber truss pieces leave the saw mill.

Unfortunately, the analytical methods typically employed prior to the wide-spread availability of computerized structural analysis programs in the 1980s did not fully consider the effects of member continuity, connection eccentricity (the offset between theoretical member center lines and the actual connection points) and the semi-rigid nature of multiple-fastener connections. These conditions can combine to produce actual truss member stresses significantly higher than those anticipated by the original designer, and frequently result in connection splitting failures that ultimately endanger the entire truss (see Figure 4).

Long-term deterioration

Post-collapse review of vintage timber roof trusses reveals that design issues are not the only risk factor associated with their performance. Many collapses are the result of long-term environmental influences that weaken and deteriorate the wood components. These environmental influences include prolonged exposure to water from roof leaks, elevated temperatures in poorly ventilated roofs, deleterious fumes from various manufacturing processes and long-term, creep-induced distortion of the original truss geometry.

Bowstring roof trusses in many buildings were supported within pockets constructed integrally within exterior masonry bearing walls and pilasters. The exterior building walls were typically extended above the roof system to form a parapet, and drains to collect and dispel water from the roof were installed in the valleys formed at the interface of the curved roof surface and parapet wall. Over time deterioration of the roofing materials and improperly maintained drains can allow water to infiltrate into the masonry pockets supporting the truss ends, creating a moist, decay-promoting environment.

The end connections on bowstring trusses are critical to the overall truss performance. The bolted, steel, U-shaped end shoes at these locations transfer large thrust loads from the top chord members into the bottom chord. Rot and decay cause the wood to soften and lose strength, resulting in top-chord shortening from crushing against the steel shoe, localized sagging of the bottom chord, and elongation or splitting of the end shoe bolt holes (see Figure 5). Long-term deterioration of truss ends often results in failure of these connections and consequent loss of truss action. When the end connections deteriorate or fail, the outward thrust from the top chord is no longer resisted by the bottom chord. Instead, thrust loads push outward against the supporting masonry walls, resulting in bowing of the walls and--if left unchecked--complete collapse of the roof.

Early wood research indicated that strength of timber truss members would not be significantly affected unless exposed to prolonged temperatures above 150° F. More recent research indicates that reductions in strength begin at temperatures between 100° and 125° F, which are readily achieved in many attic spaces, particularly in spaces with poor ventilation. Poor ventilation of attic spaces in facilities that contain manufacturing processes involving certain chemicals can also result in a long-term reduction in strength of timber truss components from fume exposure.

Self weight and roof loads cause immediate and predictable deflections in all roof trusses, regardless of construction material. Timber trusses undergo additional deflections over time, due to a material property known as creep. Creep deformation is a natural phenomenon in which wood components undergo gradual, long-term length changes under prolonged loadings. These length changes (elongation from tension forces and shortening from compression forces) result in additional timber truss geometry changes over time. These long-term truss deformations are in addition to the previously mentioned immediate deflections at the time of construction.

Loosening of member connectors subjected to sustained service loads and restraint forces from drying shrinkage of the timber components will further increase truss deformations. The change in truss geometry due to long-term deflections can increase bottom chord tensile forces by up to 25 percent. These force increases are significant, particularly in conjunction with the previously discussed bottom chord tensile strength deficiencies inherent in all timber trusses built prior to the late 1960s.

Truss failure evaluation

Investigators tasked with evaluating the existing condition or cause of failure of heavy timber roof trusses face a formidable task. These structures are unique, specialty products that require the expertise of a licensed engineer having specialized experience in evaluating their structural integrity. One of the first steps in performing an evaluation is to locate all available plans showing the original construction and later building modifications and truss repairs. These drawings may provide information regarding the date of construction, the roof loads considered in the truss design and the roof construction materials supported by the trusses.

Buildings constructed prior to the mid-1960s will frequently be found to not comply with present building code requirements due to the unrealistically high tensile strength values assumed in the bottom chord member designs. Unbal-anced, drifting snow and concentrated loads from mechanical units may result in overloaded truss members and connections in earlier designs. Later building modifications, such as construction of additions having higher roofs or installation of updated mechanical equipment, may create conditions of drifting snow or new loads where none occurred before.

A proper evaluation of vintage, heavy timber roof truss roofs must include a comprehensive inspection of each truss to determine its condition. Actual truss member sizes, grades of wood and the physical condition of truss components, including defects, distress, abnormal behavior, rot and evidence of previous repairs, all should be documented.

Overall observations of sagging roof or ceiling lines, which may be accompanied by the presence of owner-attempted remedies (such as support posts), usually indicate structural distress that must be investigated immediately. Outward bowing of masonry bearing walls near the location of roof truss end supports is due to the outward thrust of a failing truss. Trusses accompanied by supplemental steel tie bars parallel to the bottom chord members require special review to assess the benefits derived from the added steel, which must act in concert with the wood bottom chord members.

Many truss failures are caused by deterioration of the truss ends. Each truss end must be visually examined for signs of rot or decay. This may require destructive openings in masonry-bearing wall pockets to expose the truss ends. Ceiling water stains, torn parapet flashings and multiple roof repairs are indicative of potentially damaging roof leaks. Evidence of deterioration at truss ends may include dark discoloration of the wood, crushing of the curved top chord member end against the steel shoe, elongation of bolt holes, splitting of chord members, visible reverse curvature of the top chord and visible, localized sagging of the bottom chord (see Figure 6).

Bottom chord members, splices and connections must be visually examined along the truss length to determine the presence of failed or split members. Kinks in the curvature of the top chord members are indications of member or connection distress. Trusses with multiple fasteners per connection deserve special attention because of the propensity for splitting caused by restraint from shrinkage, resulting from drying.

Web members must be examined at all visible surfaces, including ends that can be seen from between the bottom chord members. Bottom chord timber splice members often conceal the sides of the primary members at the connection bolt locations. Visible ends and edges must be carefully examined for signs of splitting or slippage of bolts in elongated holes. Members with large knots or unusual wood grain should also be carefully evaluated, because grain variations greater than 15 degrees can significantly reduce wood tensile capacity.

Trusses that exhibit excessive sag, deterioration and rot, or have failed and split members, must be immediately evaluated for safety and to determine the need for repair or replacement. A licenced engineer must be the sole judge in determining the appropriate actions for protecting the public in the event that the evaluation reveals significant safety issues. Temporary, emergency shoring may be required to provide a safe environment for building occupants and limit further damage to the structure.

Information drawn from an evaluation and structural analysis of a vintage timber roof structure can be used to assess the necessity and feasibility of repairs. Properly executed, a timber truss evaluation should provide sufficient information to understand the present roof condition and to make rational decisions regarding roof structure repair or replacement, considering project economics and future use.

Vintage timber roof trusses are unique products with a long history of failure. Design problems combined with susceptibility to long-term deterioration warrant paying particular attention when these roof structural systems are encountered. Prudent risk assessment starts with an understanding of their behavior and the typical failure causes. A licensed engineer with experience in old timber truss systems should be engaged to properly evaluate the condition of each truss by physically inspecting each truss for signs of previous repairs, sagging, distress and decay. Concealed truss components must be exposed to properly assess their condition, particularly at truss ends, connections and along the bottom chord.

When timber trusses are found to require strengthening repairs, building officials may require the costly upgrading of all of the trusses in the facility to meet current building code strength requirements. Local requirements for upgrading old trusses should be discussed with a local building official prior to undertaking repair work so that life-cycle repair costs for strengthening existing trusses can be compared with replacement costs using more modern, and frequently less costly, structural systems.

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