Bowstring Trusses “Fail” to Meet Current Code Requirements

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Introduction

The timber bowstring trusses found in many local buildings have been affected by a series of changes that have rendered them as “dangerous members” as defined by the International Existing Building Code (IEBC). These trusses have been in use for more than seventy years to provide economical, unobstructed spaces in commercial and industrial buildings, gymnasiums, airplane hangers, etc. From the 1940s through the 1960s they were a dominant roof structural type. In fact, Timber Structures, Inc. of Portland, Oregon claimed to have manufactured so many bowstring trusses that if laid end to end, they would stretch around the world four times. There are many buildings still in use today that use this type of roof structure.

Bowstring trusses are made with a curved top chord and a straight bottom chord. The top chords were originally made with multiple leaf chords where the curvature was cut into the solid sawn chord members. A second style of bowstring truss used glued-laminated chords. The top chord in these trusses was curved in the laminating process.

While these trusses have carried the roof load for decades, it is not uncommon to receive calls regarding broken trusses following a heavy snow event. Fortunately, the breaks seldom lead to a total roof collapse if the trusses can be properly shored and repaired quickly.

Three factors, including a series of code changes, refinements in analysis methods and revisions to allowable timber stresses, have resulted in these trusses now being significantly overstressed. The IEBC defines a dangerous member as one where, “the stress in a member or portion thereof due to all factored dead and live loads is more than one and one third the nominal strength allowed in the *International Building Code…*” Increases in loading and decreases in allowable stresses alone render most of these trusses dangerous.

The application of unbalanced snow loads as prescribed in ASCE 7 results in a localized increase in forces for many truss members and is significantly more severe than the original design loading. The use of computer-assisted frame analysis identifies secondary moments that the original classical determinate truss analysis ignored. Finally the allowable timber stresses were reduced in the late 1980s.

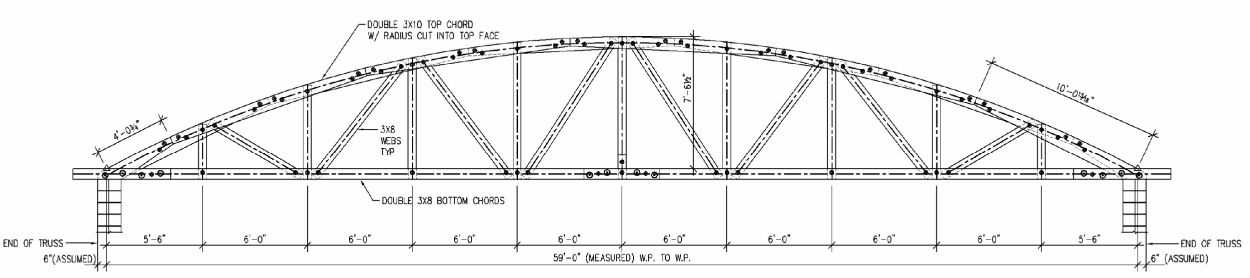
However, these trusses can be retrofitted to remedy these problems and to increase the load capacity to meet the current code requirements. This is accomplished by first analyzing the trusses using frame analysis software with the current code-required loading and then upgrading each member and connection as required to meet the design requirements.

Bowstring Truss Configurations.

The trusses existing in most buildings today have one of two dominant configurations. The first configuration is referred to as a TECO truss. TECO trusses were fabricated using multiple leaf chords and single webs. The top chords were made by using wide solid sawn members where the roof curvature was cut into the top of each piece of wood. The members are lapped from side to side so that the splices in the top chord members do not occur at the same location from one side to another. These splices are also located so that they fall in between truss panel points.

The bottom chords were made of two solid sawn members and were spliced between web members using wood splice blocks between the chord members and on the outside of the chords. The splices were usually made up of multiple split ring connections.

The web members are connected to the chords with a single bolt with split rings. The centerlines of the webs do not intersect at the centerline of the chords so there is some eccentricity to the connections. This eccentricity induces shear forces and bending moments into the chord members but these were not accounted for in the original design. Shown below is a typical layout of a TECO bowstring truss.



TRUSS PROFILE

The second configuration used single glued-laminated chords. The top chord was curved in the manufacturing process. This type of bowstring truss (as manufactured by Timber Structures, Inc.) was known as a Tim Truss. The webs were often solid sawn members. The web to chord connections were made with steel plates and angles, bolted to the timber members, and arranged so that the web centerlines intersected at the chord centerline.

In both configurations, the most economical truss was obtained by using a top chord radius equal to the truss span. This relationship yields a 30° spring angle at the truss heel.

Changes in Loading Considerations

The basic roof snow load has increased in many jurisdictions since the time the trusses were designed and installed. For example, the snow load was increased from 20 psf to 25 psf in the Portland area following a large snowstorm in the late 1960s that caused many roofs to collapse. Additionally, the building codes in effect during the design of these trusses required a dead load plus ½ snow load plus wind load combination. Recognizing that some of the truss members experienced a reversal of forces under unbalanced loading, it was common to apply the ½ snow load to one side of the truss and leave the other side unloaded. While this may have changed the force in some web members from compression to tension or from tension to compression, it seldom changed the absolute value of the member force and therefore did not change the member size or the connection.

In ASCE 7, section 7.6.2, the unbalanced snow load varies from ½ at the crown to 2 times the roof snow load at a slope of 30°. (This is located at the eave for common bowstring trusses.) The application of this loading condition greatly increases the load in the web members and drives more of the members into stress reversal. It is not uncommon for this loading condition to cause the longer web members to become compression members with very high L/d ratios resulting in the members being significantly overstressed.

Changes in Structural Analysis Methodology

The design of both of these types of trusses was accomplished using a graphical force diagram. This analysis method provides an accurate means of determining the member axial forces. In the TECO truss analysis, the eccentricity of the web connections and the continuity of the members at the joints were ignored.

In the Tim Truss analysis, the continuity of the top chords was accounted for by treating the member as a three-span beam to determine the primary bending moments. An additional bending moment was determined by multiplying the axial load by the offset due to the curvature of the member.

The shortcoming of these methods is that the secondary moments produced by the continuity of the members at the joints were not accounted for. These secondary moments can be quite large. The graphical methods also do not account for the shears and moments introduced by the joint eccentricity of the TECO trusses. Additionally, these methods cannot account for the effects of the relative stiffness of the members. Since the trusses are statically indeterminate, the relative stiffness of the members must be accounted for to accurately determine the internal forces.

Today, with the use of general-purpose frame analysis methods, it is easy to account for the actual geometry of the truss configurations, the continuity and the relative stiffness of the truss members.

Changes in Allowable Timber Stresses

In the 1980s, the timber industry completed an extensive testing program to evaluate the allowable stresses of full-size timber members. This program was referred to as the “In-grade Testing Program.” Before this program, allowable stresses for timber members were determined by multiplying the stresses obtained by testing small clear samples with a series of factors that accounted for naturally-occurring, strength-reducing defects, duration of load, drying, safety factors, etc. The In-grade Testing Program demonstrated that the testing of these small clear samples failed to accurately determine the appropriate allowable stresses for full-size members.

With the In-grade Testing Program, full-size members for each grade of each species were tested to failure. This extensive testing program resulted in the reduction of the allowable stresses for timber members for many grades and load conditions. This reduction affects the capacity of TECO bowstring trusses because the tension values for the bottom chord members were significantly reduced for many sizes. For example, prior to 1982, the NDS supplement listed the allowable tensile stress of a 3 x 10, Douglas Fir-Larch #1 bottom chord member as 1000 psi. In 1982, the application of footnote 3 reduced this value to 600 psi. In the current NDS, the value is 675*1.1 = 742.5 psi.

Effect of These Changes on Existing Bowstring Trusses

The combination of the three factors (changes to loading, analysis methods and timber stresses) results in an overstressed condition for most bowstring trusses. In a recent example, the maintenance personnel at the Salem-Keizer School District in Salem, Oregon noticed that the pilasters of a gymnasium were cracking. The district called Youngman Locke Engineers of Salem to inspect the building. The inspection uncovered several broken chord members in the trusses. Youngman Locke Engineers prepared a design-build specification for the analysis, design and repair of the trusses on this building and three other buildings. One of these buildings was the district’s Technical and Information Services Building. Western Wood Structures, Inc. of Tualatin, Oregon was awarded the contract to complete this work. The TECO trusses on this building are 78 feet long and are spaced at 17 feet on center. The top chords were made using two 3 x 14 members with the roof curvature saw cut into the top of the members. The bottom chords were made using two 3 x 10 members and the webs were single 3 x 6 and 4 x 6 members.

The analysis using current code load requirements and allowable timber stresses resulted in the top chords being overstressed in combined bending and compression by 36 percent. The bottom chords were overstressed on combined bending and tension by 94 percent. Several of the web members originally designed as tension members became compression members and violated the limit of 50 for L/d ratio. Other web members were overstressed by 63 percent.

Upgrade Techniques

The good news is that these trusses can be upgraded to meet the current code requirements for lower cost than replacing the roof structure. The trusses at the Salem-Keizer School District were retrofitted to increase their load-carrying capacity. To accomplish this, the trusses were first fully shored to remove the dead load stresses from the members. The compression members in the top chord and webs were upgraded by epoxying and screwing timber side members to the existing member. The addition of the side members reduces the L/d ratio and increases the section size. The upgraded members are analyzed using a transformed section of the new member to account for differences in stiffness.

The bottom chord was upgraded by adding post-tensioning elements. The addition of these post-tensioning elements applies an initial compressive stress to the bottom chord. The trusses on this building had an applied ceiling installed that provided lateral support for the bottom chord along its length. The initial compressive force is calculated so that the total tensile force in the bottom chord is less than the allowable load after the roof load is applied.

Conclusions

Bowstring trusses in existing buildings built before 1980 most likely will not meet current code requirements for load capacity. Recognizing this, the city of Portland, Oregon requires existing bowstring trusses to be upgraded to current code when a change to the building occupancy occurs. Using modern frame analysis methods, these trusses can be accurately analyzed, and by applying specific repair techniques, the members can be upgraded to meet the current code requirements.