Structural Glued Laminated Timber Arches

By Jeff Linville

Structural glued laminated timber (glulam) has many advantages including its ability to be manufactured in a variety of shapes from straight beams and columns to graceful, curved arches. Members can be manufactured with constant cross section along the length, or with taper to meet architectural requirements. The glulam arch fully takes advantage of the unique properties of laminated timber construction.

Since their U.S. debut in 1934, in a school gymnasium in Peshtigo, Wisconsin, glulam arches have been successfully used in a variety of structures including churches, schools, warehouses, barns, aircraft hangars, and others. Several of the early U.S. glulam arch structures, including the original gymnasium are still in use today (Rhude 1996).

Glulam arches continue to be popular for use in large open structures such as churches and gymnasiums because of their excellent structural performance, inherent fire resistance, and beautiful appearance. Laminated timber arches are also used for vehicle and pedestrian bridges.

Figure 1 illustrates a number of common arch configurations. Arches may be of either two- or three-hinged design. The AITC *Timber Construction Manual* (TCM) indicates that tudor arches can be used economically for spans of up to 120 feet and that parabolic and radial arches can be used economically for spans of up to 250 feet (AITC 2004, p. 6).

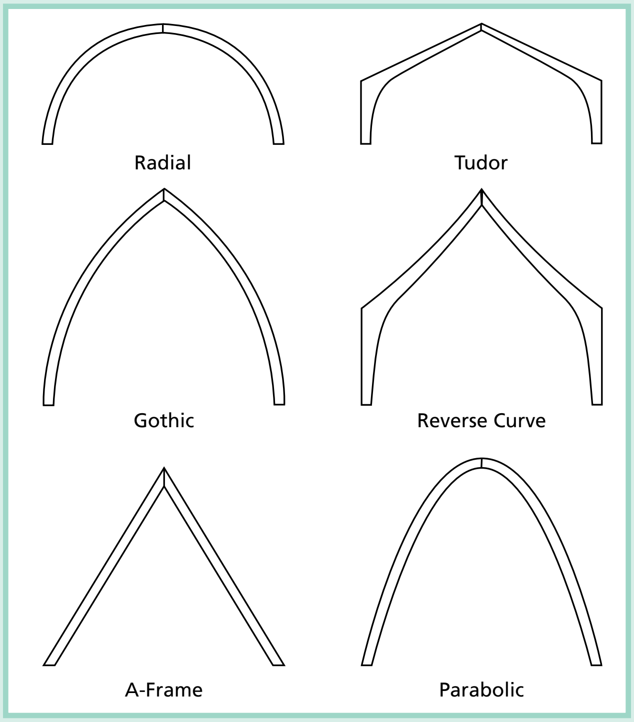

Figure 1: Common arch configurations

The length of arch segments is generally limited by transportation and erection constraints. Properly designed moment splices may be used in long span arches to facilitate shipping (AITC 2004, pp. 280-288).

The most popular arch configuration in use, today, is the three-hinged tudor arch. It provides a vertical wall frame and a sloping roof that is commonly used for modern structures. Its appearance is also pleasing to most people. Because of its popularity, the three-hinged tudor arch is the focus of this article; however, similar methods can be used to design other types of glulam arches.

Arch Design

The procedure presented herein is an overview of one method of designing a three-hinged tudor arch. Other methods, which have been validated through tests, extensive experience, or analyses based on recognized theory, can also be used. Manufacturers of structural glued laminated timber arches and engineering firms specializing in laminated timber design may have proprietary methods for design. Finite element modeling and other numerical methods may also be used to compute member forces and deflections under load.

Aesthetic Considerations

Because structural glued laminated timber arches are typically exposed to view, the aesthetic appeal of the arch is an important design consideration, in addition to its structural performance. The building designer and owner should verify that the final geometry meets the aesthetic requirements and any other architectural requirements for the design. Because of the numerous material and geometric parameters involved in arch design, multiple geometries can be utilized to meet the same structural requirements.

Structural Design

The design of arches is a trial and error process. Experience will lead to fewer design iterations. Design checks should be made at several sections along the arch. Because the number of calculations required is large, the use of a spreadsheet is recommended for arch design and analysis.

The basic design procedure includes the following steps:

1. *Determine all applicable loads and load combinations.* Roof and wall loads can typically be assumed to be uniform if decking is applied directly to the arch (or if purlins are closely spaced), or they may be concentrated at purlin points. Appropriate loads and load combinations can be obtained from the applicable building code or from the building official having jurisdiction.
2. *Determine a trial geometry*. The outside geometry (wall heights, peak height, outside span) of the arch is typically dictated by architectural constraints of the building. To complete a trial geometry, the designer must choose a width, end depths, radius, and angles of taper for the wall leg and roof arm. Critical geometric features of a tudor arch are shown in *Figure 2*. Any suitable method may be used for determining a trial arch geometry.

The base and crown sections of the arch must be adequately sized to resist shear loads at those locations and to accommodate required fasteners. Typical connection details are shown in AITC 104 (AITC 2003). All other sections must be sized to resist bending moment, axial forces, and shear forces and the combined effect of these when appropriate.

3. *Divide the arch into segments, locate sections of interest, and calculate their section properties.* Because of the complex geometry of the arch and the variability of loading conditions, deflections are typically estimated using the principle of virtual work. Additionally, the critical cross section for stress analysis will not be obvious. Therefore, several sections, taken perpendicular to the laminations, should be chosen for evaluation along the length of the arch. To minimize calculations, the same sections chosen for analysis of stresses can be used for virtual work calculations.

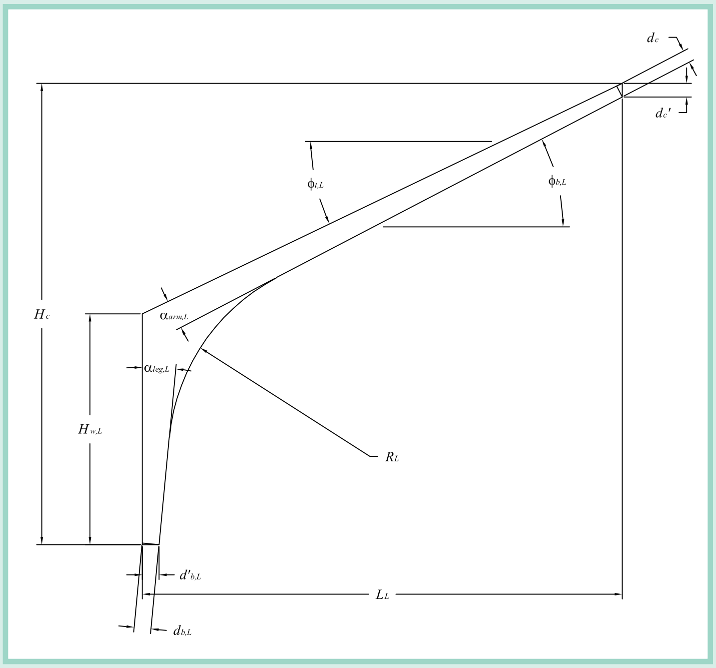

Figure 2: Arch geometry. (Only left half shown for clarity)

4. *Determine the adjusted design values (allowable stresses) for each section.* Allowable stresses in compression, bending, and shear must be determined for each of the sections chosen for evaluation. Reference design values must be adjusted by all appropriate adjustment factors specified in the *National Design Specification® (NDS®) for Wood Construction*.

In addition to the factors described in the NDS, the stress interaction factor, C_I, described in the AITC *Timber Construction Manual* (TCM) (5th Ed., p. 108) should be applied for sections taken through the straight-tapered segments of the arch.

Out-of-plane buckling of arches should be considered between points of lateral support through application of the column stability factor, C^P. Localized, in-plane buckling of the straight segments of the arch should also be considered through application of the column stability factor, C^P. These segments can be analyzed as tapered columns modeling the large end as fixed and the small end as pinned.

It is not necessary to evaluate in-plane buckling in the curved segment of tudor arches, because secondary moments due to the eccentricity caused by buckling will generally be small compared to the bending moment due to the curved shape. Therefore, for in-plane buckling in the curved segment, the column stability factor is equal to unity (C^P=1.0).

5. *Determine forces and moments and corresponding stresses on each section.* The bending moment, shear force, and axial force must be determined for each section of interest. These forces and moments can be determined using free-body diagrams at the sections of interest or structural analysis software.
6. *Calculate combined stresses on each section.* Arches simultaneously support both axial and flexural members, so stress interactions must be considered. The combined effect of axial and flexural stresses at each section must satisfy the NDS interaction formulas. Combined flexure and compression are usually critical; however, for some loading conditions, flexure and axial tension may be developed in some sections.

Furthermore, the abrupt change in section at the haunch of a tudor arch causes stress concentrations that can be accounted for by multiplying the stresses calculated by the flexure formula for that segment by the following factor:

$$K_{\theta,haunch} = 1 + 2.7\tan\left(\frac{180° - \theta}{2}\right)$$

where: θ = the included angle between the outer faces of the wall leg and roof arm

The factor, $K_{\theta,haunch}$, should be applied to the stresses calculated by the flexure formula prior to checking the section for combined stress interaction.

7. *Evaluate radial stresses in the curved segment.* Loads that result in an increase in the radius of curvature cause radial tension stresses in the curved segment of the arch. Loads causing a decreased radius of curvature result in radial compression stresses. These stresses may be calculated using the following equation.

$$f_r = K_r \frac{6M}{bd^2_{haunch}}$$

where:

$$K_r = 0.36\tan^{1.2}\left(\frac{180° - \theta}{2}\right)$$

8. *Use the principal of virtual work to calculate arch deflections for each load combination.* Because of the complex and varied geometry of tudor arches, deflections are generally determined using approximate analysis methods, such as by using the principle of virtual work. By using the same sections chosen for stress calculations, the number of calculations can be reduced.
9. *Iterate until an acceptable design is obtained.* Because it is unlikely that an optimum design will be obtained on the first try, iteration will be necessary until a satisfactory solution is reached. As stated previously, the use of a spreadsheet for design calculations will facilitate the design process.

Conclusion

Structural glued laminated timber arches can be used to create dramatic architecture while acting as the main structural system of a building. They can also be used to span long distances without intermediate supports, making them ideal for industrial applications such as warehouses. The basic steps required for design of arches have been discussed briefly in this article. AITC is currently developing a new technical note for the design of arches that will expand on these steps. The technical note is expected to be available in Summer 2007. Further work is being done to develop coefficients for use in earthquake design of arches.

Coming Soon

Since 1952, the American Institute of Timber Construction (AITC) has been the voice of the structural glued laminated timber industry, providing design guidance to engineers and architects with published technical notes and standards. Continuing this tradition, the AITC technical committee is currently working to develop a new technical note on arch design. It is expected to be available by Summer 2007. This note will include specific formulas for defining geometric parameters of the arch, locating sections of interest, and determining the stresses on a chosen section. Examples of arch design will also be included.

Additionally, AITC is working with the American Forest & Paper Association (AF&PA) to develop design coefficients for use in the seismic design of glulam arch systems. It is anticipated that this information will be included in the AITC technical note on arch design.▪

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