Seismic Design of Glulam Arches

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Structural glued laminated timber (glulam) arches continue to be popular for use in large open structures such as churches and gymnasiums for many reasons which include their structural performance, inherent fire resistance, and aesthetic appeal. This structural system has been used successfully in North America since its debut in the 1930s. Until recently, there has only been limited guidance for design of arches to resist seismic loads, leaving the choice of seismic design coefficients to the discretion of the design engineer and local building official.

Seismic Coefficients for Glulam Arches

Seismic design coefficients for glulam arches shown in *Table 1* are based on those presented in a paper titled "Special Requirements for Seismic Design of Structural Glued Laminated Timber (Glulam) Arch Members and Their Connections in Three-hinge Arch Systems" in Part 3 of the 2009 NEHRP (National Earthquake Hazard Reduction Program) *Recommended Seismic Provisions for New Buildings and Other Structures* (FEMA P750) and are intended for use with design provisions of *ASCE 7-05 Minimum Design Loads for Buildings and Other Structures* (ASCE7-05).

Seismic coefficients and detailing requirements proposed in the paper reflect a new approach and are included in Part 3 of the *NEHRP Provisions* to stimulate broad review, trial use, and/or additional study before integration into a national standard or model building code.

Both systems included in *Table 1* are assigned an R value less than the value of 2.8 associated with the *1997 Uniform Building Code* (UBC) system – heavy timber braced frames in a bearing wall system. A primary consideration in the recommendation for R was to approximate base shear from the 1997 UBC when provisions of ASCE 7-05 are used to determine seismic base shear. To account for changes in the base shear formula, a comparison of Zone 4 UBC base shear to ASCE 7-05 base shear (with mapped short period spectral response acceleration, S_s, equal to 1.5) was made. It was found that a value of R = 2.5 coupled with use of ASCE 7-05 provisions gives approximately the same base shear as derived from the 1997 UBC.

Table 1: Seismic Design Coefficients for Glulam Arches[a].

Seismic Force Resisting System	R	Ω	C_d
Special glulam arch	2.5	2.5	2.5
Glulam arch not specifically detailed for seismic resistance – limited to seismic design categories A, B and C	2.0	2.5	2.0

[a]Seismic coefficients are limited to one story.

Detailing Requirements for Special Glulam Arches

For timber structures, ductility is obtained through connection yield mechanisms, such as fastener bending and localized wood crushing at connections or points of bearing. Failure of timber members themselves is generally characterized as brittle. For a *special glulam arch* system, detailing requirements provide additional assurance that the timber components of an arch system will have greater strength relative to connections. This is done by sizing the member to resist over-strength load combinations of ASCE 7 or ensuring that members have capacity to develop the nominal strength of the connections. To promote yielding mechanisms, fasteners are designed to resist seismic loads without considering over-strength load combinations.

Seismic Load Distribution

A Tudor arch resists lateral and vertical loads primarily through bending. As such, distribution of loads throughout the arch affects the deflected shape and stress distribution in the arch. It is, therefore, not recommended to concentrate the seismic mass of the structure at a single location for design of the arch member; the load (mass) should be distributed as it occurs along the arch length.

Steps for Seismic Analysis

Assuming that the arch has already been designed to meet design criteria for loads other than seismic, application of new detailing concepts for seismic design of the special arch includes the following steps:

1) Apply seismic load combinations without over-strength factors and verify that the connection design capacity is adequate. At the base, also verify Mode III or Mode IV yielding for dowels or rivet yielding for timber rivets.
2) Determine the ratio of demand to capacity of the connection (D/C) where D is the demand and C is the nominal capacity of the connection (divided by 1.35 for allowable stress design (ASD)).
3) Verify that combined member stresses do not exceed 1.0 and that member failure modes at connections such as row and group tear-out and shear have capacity in excess of:
   a) Forces based on nominal connection capacities. Increasing arch loads by multiplying by 1/(D/C) can be used to establish design member forces limited by nominal connection capacities; or,
   b) Forces resulting from seismic load combinations with over-strength factors (ASCE 7-05, Section 12.4.3.2).
4) Apply load and resistance factor design (LRFD) seismic load combinations and check drift against applicable limits. (Seismic drift limits are associated with LRFD load levels, so LRFD load combinations must be used, even for ASD design).

Conclusion

Glulam arches have been used successfully for over 70 years in North America; however, guidance for seismic design has been limited. New techniques for design and detailing of a special glulam arch system are presented in a paper titled "Special Requirements for Seismic Design of Structural Glued Laminated Timber (Glulam) Arch Members and Their Connections in Three-hinge Arch Systems" in Part 3 of the *2009 NEHRP Recommended Provisions*. Special detailing provisions ensure that arch members have sufficient wood capacity to promote yielding mechanisms in connections. The response modification factor, R, produces approximately the same base shear used in prior codes recognizing that base shear formulas have changed between the 1997 UBC and ASCE 7-05.▪

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