**LiUNA Headquarters Expansion Building Re-Design: Combining Old-World Heavy Timber Techniques with Modern Engineered Wood as a New Structural Solution**

**Literature Review**
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**AE 481 W Honors Thesis**
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As part of the requirements for completing the integrated BAE/MAE program while completing the requirements of the Schreyer Honors College, this literature review provides an overview of the topic of heavy timber construction. Topics discussed are the structural properties of timber design, strength and serviceability design of CLT systems, design of the charring method of fire protection, and moment-resisting connection details in heavy timber.

## Industry-Published Design Aids and Manuals

### ***The Timber Construction Manual*** **by the American Institute of Timber Construction**

The industry guide to heavy timber construction, The Timber Construction Manual moves beyond the scope of stick-frame applications and the NDS Design Guide to focus on heavy civil and commercial building applications. Recognizing that longer spans are often required, chapter 15 focuses on the design of moment splices at inflection points. Following an elastic analysis of the uncut section, a combination of tension straps, compression plates, and shear plates are used to complete the connection. Additional resources provide guidance on the design of glulam members for camber, spandrel beams, and glulam deck panels.

### ***CLT Handbook*** **by FP Innovations**

Originally developed in Austria during the 1990's, Cross-Laminated Timber or CLT has seen an increase in usage in the North American construction industry recently. In response to the increasing need for a unified design reference manual, FP Innovations with the Forest Product Laboratory, American Wood Council, APA, and Wood Products Council wrote the first edition of the CLT Handbook in 2013 based on current research in the fields of manufacturing methods, structural and performance design, material properties, and constructability of CLT systems.

Within the field of structural design, Ross, Gagnon, and Keith review the application of the "Shear Analogy" method developed by Kreuzinger for the analysis of shear and bending stresses in solid panels with perpendicular cross layers. Kreuzinger's method summarizes the effects of the individual cross layers into two "beams" A and B along the top and bottom faces of the panel being analyzed. Through the summation of the individual contributions of each CLT layer's stiffness in a particular direction, the net effect of all layers working to resist stresses can be quantified and used to size the member accordingly. The design equations used are integrally written with the NDS.

### ***ANSI/APA PRG 320-2012 Standard for Performance-Rated Cross Laminated Timber*** **by APA – The Engineered Wood Association**

The standards for testing and material strength specifications for CLT products is published for use by professional engineers in design. The majority of the text focuses on the individual components, requirements, and qualifications of different CLT materials from a manufacturing perspective. Appendix A lists the mandatory design properties of products meeting the ANSI/APA PRG – 320 CLT standard.

***National Design Specification (NDS) for Wood Construction 2015 Edition* by the American Wood Council**

The 2015 NDS provides the industry standard for the design of solid-sawn, glulam, and CLT wood members for both strength and serviceability states. Within the field of connections, the NDS provides direction on the properties of bolts, nails, and screws and the yield limit equations applicable when these connectors are used in single and double shear conditions. However, the NDS is silent on the topic of moment-resistance connections. Therefore, additional research must be done to find a design criteria applicable to the moment resistance required by the project at-hand.

## Additional Design References and Textbooks

**"CLT Floor Design: Strength, Deflection, and Vibrations" by Scott Breneman**

Three criteria govern the design of CLT floor design: strength, deflection, and vibration limitations. In his presentation, Breneman discusses the composition of CLT panels and the effect of varying properties between the minor and major axis on design. Through the assumption of one-way flexural action, panels can be designed according to the flexural capacity $F'_bS_{eff}$ found within ANSI/APA PRG-320. Deflections can be found assuming one-way or two-way behavior. Vibration performance can be quantified by evaluating the natural frequency of the floor system to be greater than 9.0 Hz and the floor span being less that that prescribed.

***Design of Wood Structures ASD/LRFD* by Donald E. Breyer, Kelly E. Cobeen, Kenneth J. Fridley, and David G. Pollock**

Breyer's text is designed to be the accompanying narrative of the usage and capabilities of the NDS. Covering the application of the equations provided in the NDS, Breyer presents a clear guide for the design of wood structures for both strength and serviceability criteria using ASD and LRFD methodologies. Many of these topics are also covered at larger scale in the American Institute of Timber Construction Design Guide. Unfortunately, the Breyer text is also silent on the topic of moment resisting connections, therefore requiring further investigation in search of design aids.

***Timber Engineering* edited by Sven Thelandersson and Hans J. Larsen**

Utilizing an emphasis on finite element analysis and testing data, Thelandersson and Laresen provide a detailed discussion of wood connection elements in Part Three: Joint and Structural Assemblies. In order to achieve ductile failure, the European Yield Model supported by Johansen theory is presented for dowel fasteners.

***Multistory Timber Buildings Seismic Design Guide, 6$^{th}$ Edition* by M.P. Newcombe**

While Newcombe discusses many aspect of seismic analysis and wood design, his explanation of the design of moment-resisting steel gusset plate, expoxied rod connections, and post-tensioned connections for both strength and serviceability proves to be the most complete and recent design aid available.

***Timber Bridges* by Christopher J. Mettem**

Published by the Timber Reseach and Development Association (TRADA), Mettem's overview of the design, construction, and testing of timber bridges across the world discusses the various types of structural materials and design methods that might be used to support modern bridge loading requirements. Beyond the typical scope of glulam and LVL materials, Mettem introduces various bridge deck framing schemes including LVL built-up decks, CLT decks, stressed-laminated glulam decks, and timber-concrete composite decks.

## Moment-Resisting Connections and Lateral Design

**"Basic Design Issues in Timber Frame Engineering II" by Tom Nehil and Amy Warren**

In the investigation of raking forces in timber frames utilizing knee-brace construction, Nehil and Warren found that the traditional method of using braces at the intersection of the beam and columns was less effective than the use of braces at the intersection of the columns and base. The idealized infinite rigidty provided by the foundation provides more resistance to the axial forces transmitted by the knee braces, and therefore helps impose a condition more similar to a fixed connection at the upwind column base. Nehil and Warren do recognize, however, that the combination of shear wall or additional lateral force resisting systems are best suited for higher loads or multistory construction.

**"Behavior of Traditional Timber Frame Structures Subjected to Lateral Load" by Robert G. Erikson and Richard J. Schmidt**

In traditional timber-frames, knee braces with pegged mortise and tendon joinery provide lateral resistance. Typically used in residential, light commercial, or industrial applications, knee braces have been traditionally designed using rules of thumb without testing done to determine what stiffness is provided by the complete assembly. Erikson and Schmidt tested five (5) single story, single frame and four (4) two story, two frame knee brace configurations for response to a lateral load determined using assumptions based on the ASCE Wind Loading provisions.

The authors most commonly observed failure of the peg members located at the mortise and tendon joints rather than failure in the members themselves. Cyclic loading of varying duration was applied on the frame both with and without Structural Insulated Panels (SIPS). Erikson and Schmidt found that the stiffness provided by all knee brace configurations was not adequate to provide the required resistance to a lateral displacement of height/400 but was capable of providing adequate strength to resist lateral load. Therefore, the authors concluded that knee braces in conjunction with SIPs or additional lateral resistance is necessary in timber framing construction.

**"Development of Moment Connections in Glued-Laminated Alberta Spruce and Pine Timber" by Peter Hattar and J.J. Rodger Cheng**

The majority of the research surrounding wood moment connections is aimed at light commercial and residential applications. In order to make glulam framing systems more competitive, Hattar and Cheng looked to utilize rivet moment joints, shear plate joints, and circular bolted patterns for resisting rotation. Through a total of 15 different configurations, the properties of rivet connections versus bolted connections, butt joints versus lap joints, member thickness versus instantaneous center of rotation, and bottom and top bracing brackets versus none were studied.

The timber riveted connections performed better than the bolted connections. While the circular bolt patterns provided better results than the rectangular bolt patterns, a greater ultimate rotation angle was observed than that in the timber riveted connection. Splitting along the side grain at the rivets furthest from the I.C. was the primary mode of failure. The inclusion of a bottom and top bracket increased the stiffness at the joint, increased the ultimate moment capacity, and helped reduced wood crushing failure at the bottom inside corner of the beam and top inside corner of the column. A positive correlation between the increased spacing and reduced number of rivets along the side plates was observed.

Using the Hankinson Formula and an assumed behavior similar to that of eccentrically loaded bolt groups as presented by AISC, the authors conservatively predicted the ultimate moment capacity of the joints utilizing the circular bolted connections and timber riveted connections. These assumptions can be used to predict moment capacity, but further research is required to analyze the effects of additional components such as the bottom and top braces utilized in the later stages of testing.

**“Seismic Design of Glulam Structures” by A.H. Buchanan and R.H. Fairweather**

Commercial office spaces require open floor plans with limited possibilities for interruption with shear walls and large bracing elements. In order for an office building to be made out of wood, there must be a solution for lateral force resistance that does not impact space. In order to accomplish this goal, moment-resisting connections are preferred.

Several different types of moment connections in wood design are available. Although glued, nailed, and doweled connections are all available, Buchanan and Fairweather focused on the application of epoxied steel bars. Their requirements for ductile connections in the seismic region of New Zealand influenced this choice, but in a wind-governed design, stiffer connections would be acceptable.

Using reversed cyclic loading, Buchanan and Fairweather found that the most successful connections typically had a ductility factory between 1.5 and 3 with an ideal value of 2.0. This methodology prevents failure of the wood members while the connection members fail. While designs for single-story frames were investigated, four multi-story beam column connections were investigated. Three of the connections experienced brittle fracture in the column, the type of sudden failure within the structural member that is hopefully avoided in seismic loading. The fourth design featured steel brackets and nailon plates in addition to the threaded rods used before. The hysteresis loops exhibited a displacement ductility factor of approximately +/- 8.0, ensuring that ductile failure could occur.

Through their research, Buchanan and Fairweather show that ductile moment connections in heavy timber construction are possible when the lead design intent is to prevent brittle failure within the members and ensure ductile failure in the connecting elements. Through the use of a combination of steel plates and epoxied steel rods, this design intent can be achieved.

**“Moment Resistance of Bolted Timber Connections with Perpendicular to Grain Reinforcements” by Frank Lam, Michael Schulte-Wrede, C.C. Yao, James J. Gu.**

Hidden-plate connections are a popular choice among designers for their clean appearance and embedded fire protection of the steel plate within the wood. These connections, however, are not typically utilized for moment resistance. The authors used self-tapping wood screws to provide perpendicular-to-grain reinforcement based on the research from Blaß and Bejka. Using both monotonic and cyclic loading testing, the reinforced connections were found to have an increase in streght of 1.7 to 2.0 times that of their unreinforced counterparts. The both the unreinforced and reinforced connections utilized 11 3/8" x 5 1/8" beam and column members with ¾" bolts. The unreinforced connection had an ultimate moment of 26 Kip-feet while the reinforced connection had an ultimate moment of 46 Kip-feet. In order to increase strength and ductility, the inclusion of self-tapping screws perpendicular to grain is recommended.

## Fire Protection and Charring Design

***Technical Report No. 10, Calculating the Fire Resistance of Exposed Wood Members*** **by the American Wood Council**

Since the 1960s, research has been conducted to determine the fire-resistive properties of wood members using the charring method. The charring method assumes that in a fire-damage event, the outside edges of the member will char and render this component of the section modulus inadequate to carry structural load, but this charring will prevent the fire from damaging the rest of the interior cross section.

Based on independent tests of flexural, compressive, tensile-loaded members, the American Wood Council has published design procedures for wood members. The strength provided by a member is directly affected by the loss of section modulus over time due to charring. Therefore, the effective char rate and char layer thickness for 1, 1.5, and 2 hour assemblies should be used to evaluate the remaining section modulus. Using the prescribed process, the member can be evaluated for expected gravity loads before and after the event.

In order to make fire-resistive design accessible, the American Wood Council provides guidance in two additional locations. First, within their "Design for Code Acceptance" Series, the AWC provides design guide *Design of Fire-Resistive Exposed Wood Members* formatted to accompany the NDS. Second, the NDS itself features an introductory design guide for typical prismatic sections and CLT members.