Structural Testing

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Architectural Rendering – Exploded View.

New Cal Poly Laboratory

Showcasing Heavy Timber Braced Frames as a Practical Alternative to Steel

By Michelle Kam-Biron, P.E., S.E.

There is a common belief that, as far as structural materials are concerned, steel holds a monopoly on the braced-frame vertical lateral resistant system market. However, there is a growing niche for the use of Heavy Timber Braced Frames (HTBF) in non-residential applications. In addition to offering strength and excellent performance where issues such as seismic and fire safety are concerned, wood is aesthetically appealing while offering distinct advantages in terms of cost and sustainability.

The Simpson Strong-Tie (SST) Materials Demonstration Lab, recently constructed on the California Polytechnic State University's San Luis Obispo campus (Cal Poly), is one of the first HTBF buildings designed under the 2007 California Building Code (CBC) and ASCE 7-05 *Minimum Design Loads for Buildings and Other Structures*. The new, 5,000-square-foot facility serves as an interdisciplinary learning laboratory for all five departments in Cal Poly's College of Architecture and Environmental Design (CAED). HTBF was chosen for the lateral resisting system because of its performance and aesthetics. To showcase the structural materials, translucent panels were used in the building envelope. Students across the college's five departments will be able to use the lab to design, build, and test a variety of architectural and structural components. The lab will also provide vital support for four adjoining labs in

Michelle Kam-Biron, P.E., S.E. serves as technical director for WoodWorks – California, a program that provides education and technical assistance to help design and construction professionals integrate wood into non-residential projects. Michelle is also a Director of the Structural Engineers Association of Southern California. She can be reached at ***michelle@woodworks.org****.*

Interior View. Courtesy of Josef Kasperovich/Cal Poly College of Architecture and Environmental Design

Cal Poly's Construction Innovation Center. These departments include Architecture, Construction Management, Architectural Engineering, Landscape Architecture, and City and Regional Planning.

Why HTBF?

The building was originally envisioned as a concrete and steel structure, but was reconsidered to incorporate wood for the roof and lateral systems. The decision to use wood was largely based on budget, as wood proved to be a more cost-effective material when compared to both concrete and steel. However, other key factors were considered as well, including wood's durability, speed of construction and seismic performance. Sustainability was also considered during the design process, and the fact that wood is the only material that's renewable, sustainable, and recyclable was taken into account. According to Al Hauk, chair of the Cal Poly Construction Management Department, one of the goals in using timber framing was to incorporate environmentally conscientious materials.

Given that California is an area of high seismic activity, the design and construction of the SST Lab takes seismic performance into careful consideration. During the design development stage of the project, the prescriptive use of a HTBF system as a seismic vertical lateral resisting system was dropped from the 2006 *International Building Code*. The University was advised of the change and made aware of the option to pursue acceptance of an alternative system with the governing authority. The choice was made to continue with the use of HTBF as an alternative non-prescriptive lateral system, and seismic design criteria was subsequently accepted by the California State University (CSU) seismic peer reviewer. As designers know, if the ground motion is strong enough, it will move a building's foundation. However, inertia tends to keep the upper stories in their original position, causing buildings to distort. Since inertial forces increase with material weight, heavier buildings have greater potential for serious damage. The STS Lab is located in a Seismic Design Category D region and benefits from the fact that it has a relatively light roof structure compared to concrete or steel. Contrary to the connotation of its name, the heavy timber framing used on this project reduces the mass and therefore the inertial forces the building will experience during an earthquake.

Table 1: Equivalent Lateral Force Procedure Design Values

Importance Factor (ASCE 7-05, §11.5)	1.25
Response Modification Factor, R	3.0
Overstrength Factor, Ω_0–System	2.0
Overstrength Factor, Ω_0–Braces	2.5

Design Considerations

Project engineer Michael Parolini, S.E. of Lampman & Smith, understood that design of the braced frames needed to have a careful balance of strength, stiffness, and ductility of all components to provide a structurally efficient and sound system. Additionally, he understood that brace connections are typically the "weakest link" in the system and will govern inelastic behavior. Therefore, it was important that connections be designed to sustain nonlinear deformations to limit the force level in the braces.

Loads and Design Values

The building was designed using the Equivalent Lateral Force Procedure as outlined in ASCE 7-05 §12.8. In addition, a three-dimensional mass model was created by Parolini to verify the approximate period of the building in accordance with ASCE 7-05 §12.9. For a one-story building with a direct load path, it made engineering sense, both economically and theoretically, to employ the Equivalent Lateral Force Procedure. Ductility is the ability of a structure to yield and deform without fracturing. Typically, wood-framed structures gain ductility and damping not through the material itself, but by the sheer number of fasteners and connections that exist throughout the lateral load path. The fact that wood structures have numerous connections adds redundancy to the system and makes them more flexible. This also allows them to dissipate energy when subjected to the sudden loads of an earthquake. However, as a general rule, heavy timber systems contain fewer connections and fasteners with which to achieve the same level of ductility and damping provided in a light timber framing system. This fact led to use of a low Response Modification Factor (R) in seismic design of the HTBF systems (see *Table 1*).

By using a low R value, the assumption is a more elastic response during a design earthquake, not requiring excessive inelastic behavior from the lateral force resisting system or its connections. The intent was to align with an 'ordinary' performance level, therefore not allowing the building to undergo large inelastic deflections during a seismic event in excess of the design earthquake.

To protect the braces and ensure yielding at connections, the system employed two separate over-strength factors (see *Table 1*). The overstrength factor (Ω_0) for the system as a whole, including drags, drag connections, brace connections, and columns, was equal to 2.0. The Ω_0 for the braces was 25 percent higher at 2.5. Using R value of 3.0 in conjunction with an Ω_0 of 2.5 and the Importance Factor of 1.25 essentially means that the braces were designed for an $R_{equivalent} = (R/I)/W_o = (3.0/1.25)/2.5 = 0.96 \sim 1.0$. An R = 1.0 assumes no ductility in the system, therefore designing the system for strictly elastic force levels. This approach by Parolini, of applying a higher Ω_0 to the brace member itself and a lower value to the brace connection, is due to low ductile properties of wood. Parolini thought it was most critical to protect the brace from any inelastic force levels in compression or tension. Therefore, designing the brace for amplified seismic forces at a level assuming no ductility in the system provided the desired effect. In addition, it was not desirable for HTBF connections to be designed for the expected capacity of the member, only the amplified seismic loads, as ductility was designed to be introduced in yielding of the connection itself.

Connections

After consideration to prevention of buckling of the brace members, the most important design attribute for a building frame system of heavy timber is the connections themselves.

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SST with Heavy Timber Braced Frames at Dusk.

Interior View of Heavy Timber Roof.

A 2003 report documented a series of shake table tests conducted on single-story braced frame models with different connections. Diagonal braces with five different connection types were tested, four of which used bolts as fasteners, while one brace had timber rivet connections. It was found that the seismic response of the braced frames is highly influenced by the brace connections and their fastener geometry. The report states, "Braces with smaller diameter bolts … showed the most desirable seismic performance by dissipating the highest amount of seismic energy." (Popovski et. al., 2003). This concept was incorporated into the seismic design criteria by maximizing the slenderness of the bolts used in the connections. The minimum slenderness ratio of length to diameter in the approved seismic design criteria is 8.0. For the typical brace connection, the bolt slenderness ratio is greater than 8.0. Slender bolts are only useful if the bolts have the ability to deflect under load and the end distances are significant.

In an experiment conducted to determine the effect of end spacing on the wood splitting failure mechanism, single fastener joints were subjected to tensile loading for various end spacing, member thicknesses, and bolt diameters. The connections were tested under static conditions and results showed that fastener end distances "in current practice [are] adequate to conservative." (Rammer) Thus, required end distances for tension members as specified per the American Wood Council (AWC) *National Design Specification® for Wood Construction (NDS®)* is more than adequate. The addition of a 1-inch gap at the end of each brace allows bolts to deflect or yield in both tension and compression. The 1-inch gap and the proper end distance per the NDS provided the detailing for bolts to resist the assumed loads.

In addition to the configuration of the connection, more slender and therefore smaller diameter bolts were utilized, creating a connection with a greater number of fasteners rather than a connection using larger diameter and fewer bolts. This added ductility and more redundancy to the connections.

The connection design also considered the effects of local stresses around fasteners. According to NDS C10.1.2, "Where multiple fasteners are used, the capacity of the fastener group may be limited by wood failure at the net section or by tear-out around the fasteners caused by local stresses." The concentrated force at the fasteners was addressed as a group based on principals of mechanics as described in NDS Appendix E. The bolt tear-out and block shear allowable capacities of the connection were far greater than the demand of the amplified seismic loading.

Other Considerations

In addition to its seismic performance, several other factors contributed to the decision to use wood. Many designers believe that exposed wood enhances a building's aesthetics by creating a warm and inviting environment.

Life cycle assessment (LCA) studies also show that wood consistently outperforms steel and concrete in terms of embodied energy, air and water pollution, and other impact indicators. Wood products also contribute to a building's energy efficiency and indoor air quality. And using wood helps to reduce atmospheric levels of greenhouse gases because wood products continue to store carbon absorbed during the tree's growing cycle, and because of emissions avoided by not using steel and concrete.

In terms of fire protection, the SST Lab was categorized as an Occupancy Classification B and a Construction Classification of Type IIB, which is typically considered non-combustible and most architects would default to steel or concrete as the structure. However, per IBC Table 601 footnote d, the architect was able to incorporate a heavy timber roof system. Heavy timbers perform particularly well because they char on the outside while maintaining strength, slowing combustion and providing additional time to evacuate the building. In a controlled fire test sponsored by AWC (formerly the National Forest Products Association), researchers exposed comparable steel and glulam beams to the same fire conditions for the same length of time. After 30 minutes, the steel beam lost 90 percent of its strength and collapsed while the glulam beam lost just 25 percent and remained both straight and true.

Conclusion

With all of these factors in mind, the SST Lab is unique, both in its architectural and structural appeal. It combines three structural materials (concrete, steel, and wood) to fulfill architectural requirements, with heavy timber as its centerpiece. It is also aesthetically pleasing, as wood helps create an environment conducive to learning, and it is environmentally responsible while meeting all code requirements for seismic and fire protection.

Finally, the SST Lab, through its design, construction, and intended purpose, will help fulfill the educational needs of a highly respected university known for students who go on to become highly respected design professionals. Future generations of students will learn cutting-edge design within the walls of this building, just as they will learn through the building's own cutting-edge design.▪