Simpson Strong-Tie Materials Demonstration Laboratory California Polytechnic State University, San Luis Obispo

Heavy Timber Braced Frames A Non-prescriptive Seismic Load Resisting System Solution for a High Seismic Area Project

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Abstract

It is a common misconception that steel, as a structural material, possesses a monopoly on the braced frame vertical lateral resisting system market, especially for projects located in high seismic areas. On the contrary, there is a niche for the use of Heavy Timber Braced Frames (HTBF) in non-residential applications. Wood is a beautiful, sustainable, cost-effective material and, when folded into the architectural design as exposed structure, it can create innovative projects that bring warmth and aesthetic appeal to the occupants and end users.

Such is the case with the Simpson Strong-Tie Materials Demonstration Laboratory being constructed at California Polytechnic State University's San Luis Obispo campus (Cal Poly), one of the first HTBF buildings (if not the only one so far) designed and approved under the *2007 California Building Code* (CBC) and ASCE 7-05. The project architect chose to showcase the structural materials in the design of the building envelope through the use of translucent panels over the HTBF structure. HTBF was chosen for the major lateral system not only for aesthetics, but also as a nod to the building's namesake.

The project began design development prior to the January 1, 2008 adoption of the 2007 CBC. At that time, the prescriptive use of a HTBF system as a seismic vertical lateral resisting system was dropped from the model 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 established and accepted by the California State University (CSU) seismic peer reviewer.

This case study will present the project as a whole, but specifically focus on the non-prescriptive seismic design criteria and special detailing requirements for using a HTBF system in a high seismic area. The study will also address other peripheral issues relating to fire rating, sustainability, building location, site constraints and foundation design.

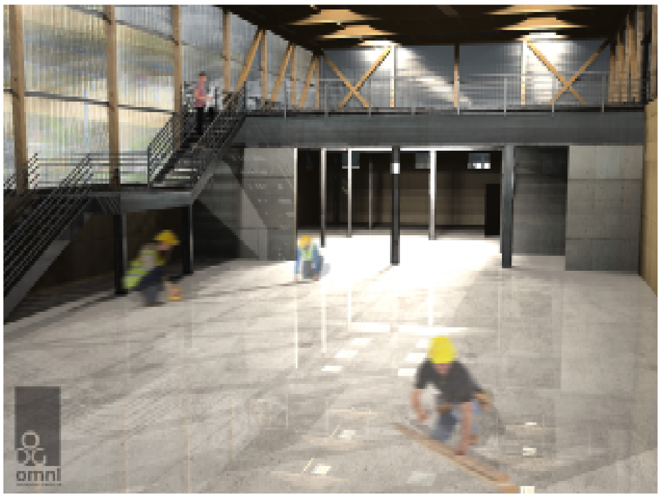
Exterior North-west view;
Rendering courtesy of Omni Design Group

As previously stated, the project is currently under construction and is slated for completion in the fall of 2010. A live webcam is available at the Cal Poly Construction Management Department's website: http://cm.calpoly.edu.

Introduction

The Simpson Strong-Tie Materials Demonstration Laboratory (SSTMDL) is an approximately 5,300-square-foot facility with a 2,500-square-foot mezzanine situated at the core of the California Polytechnic State University, San Luis Obispo campus. The building has an Occupancy Classification of B and a Construction Classification of Type IIB, fully sprinklered. As the building is on a CSU campus it is owned by the State of California; however, the project is managed and will be operated by the Cal Poly Facilities Department.

The SSTMDL is intended to serve the interactive teaching needs of all five departments in the College of Architecture and Environmental Design: Architecture, Architectural Engineering, City and Regional Planning, Construction Management, and Landscape Architecture. The design, engineering, and installation of different materials in the built environment is one of the key unifying subject areas that brings all five of these departments together; therefore, this building will provide working spaces where students can work on full-scale models and building components applicable to both indoor and outdoor environments, investigate components and assemblies of materials, and demonstrate static and interactive displays of materials and building components.



Interior west view; rendering courtesy of Omni Design Group

Both the building and surrounding landscape are intended to serve as teaching tools and will be used to demonstrate structural, mechanical, electrical, lighting, cladding, and other systems that combine materials to create a building—where possible recognizing the opportunity to respond to the dynamic nature of materials over the instructional lifespan of the building and associated spaces.

Sustainability was also considered during the design process, which impacted the selection of materials. In addition to a cool roofing system, future installation of half green roof coverage and half photovoltaics, fly ash as a substitute for cement in the concrete and natural ventilation for cooling, the architect used a combination of conventional materials and standard practices as well as sustainable materials and practices. As a result, students will be introduced to typical approaches used today as well as newer, more sustainable options.

"One of the goals, in using timber framing, was to incorporate environmentally-conscious materials," said Al Hauck, Chair of the Cal Poly Construction Management Department. "Wood is the only major building material that's renewable, sustainable and recyclable."

"The use of heavy timber allowed us to demonstrate the benefits wood offers in a non-residential setting," said Project Architect Tom Reay of Omni Design Group.

It was Reay's vision that brought HTBF forward as an architectural design element as well as the main seismic and wind vertical lateral force resisting system for the roof level. As an alumnus of the College of Architecture and Environmental Design, he saw the potential, not just for an interesting mesh between building envelope and structure, but for the deeper benefit of educating current and future students. "As a student I looked out my studio window onto the construction of the new Robert E. Kennedy Library. I like that today's students can watch a building being constructed on campus and learn from it." A motivating factor in the design was also the Cal Poly model of "Learn by Doing." In this spirit, the Lab will provide a robust understanding of the materials and systems that are at the heart of building design, planning and construction. Ultimately, said Reay, "thinking about the college's interdisciplinary and hands-on pedagogy led to our design."

Project History

The SSTMDL was originally slated to be constructed at the same time as the new approximately $17 million Construction Innovations Center (see **Figure 1**), which was completed in the summer of 2008. Due to budgetary concerns and other issues, the University decided to give the project its own attention and the redesign of the Lab was awarded to Omni Design Group. The original concept for the SSTMDL came about when the University, and in particular the Construction Management Department, secured major funding from the Simpson Strong-Tie Corporation in 2005.

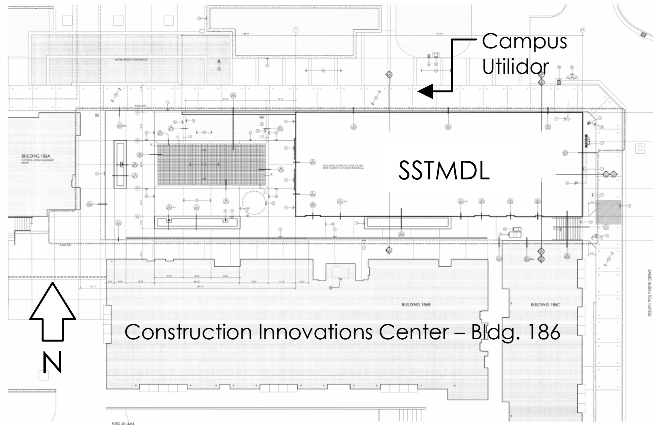


Figure 1: Project Site Plan
Courtesy Omni Design Group

The original concept took several early forms including a pre-fabricated steel building. However, due to the fact that Simpson Strong-Tie is a major manufacturer of structural connectors, prefabricated lateral systems, anchors, and fastening systems for wood and timber construction, it became evident that these ties to the wood and timber construction industry should be echoed in the building structural systems. This led to a revised concept focused around the use of heavy timber framing.

Selection of Structural Material

One of the first decisions most design professionals are faced with in a project are the big picture choices such as which materials to incorporate. The SSTMDL is a materials demonstration laboratory, and not just in its final occupancy; the building itself was designed to demonstrate the use of several different building materials within its own construction. Concrete cast-in-place walls were incorporated on the lower level to demonstrate soil retention and durability. The use of steel columns along with a composite concrete filled metal deck and steel girders to frame the mezzanine served to support the concrete walls' out-of-plane demands. For the roof framing and vertical lateral resisting system, the project architect chose heavy timber for several reasons, including the desire to have the building itself serve as a pedagogy, wood's aesthetic value and sustainable qualities, and to meet the fire protection requirements of the building code with a structural scheme that was code compliant and serviceable to the end user's needs.

Pedagogy

As mentioned, the building is intended to serve as a place of learning where students can experience a variety of different structural approaches, so it made sense to include three of the four major building materials: concrete, steel and wood. In this way, the facility becomes both a place to teach about building materials and a visual display of their use. With its concrete walls, steel mezzanine framing and timber roof structure and braced frames, the SSTMDL has a full spectrum of structural materials in one place, all exposed for the students to observe and enjoy.

Aesthetics

Many architects and building designers feel that exposed wood enhances aesthetics by providing an inviting and enriching environment. Wood also provides visual interest and softens interior spaces. As a result, it makes learning more comfortable for students than steel or concrete, both of which can have a cold, institutional feel.

Japanese researchers studied how the educational environment is shaped by the type of materials used for school buildings, surveying teachers and students to measure their impression of wood versus reinforced concrete. Both groups had similar, favorable impressions of wood schools over concrete. Results also showed that teachers and students in wood buildings felt less fatigue, and that students perceived schools with larger areas of wooden interiors to be brighter than reinforced concrete structures. Wood's natural beauty provides an organic expressiveness with its visual variety.

Bringing warmth to both the interior and exterior environments was one of the reasons the SSTMDL architect chose wood for the vertical lateral resisting system in addition to the exposed wood framed roof of heavy timber girders and decking. The exterior walls consist of translucent polycarbonate panels that allow the heavy timber braced frames to be viewed from the exterior of the building, allowing incorporation of the structural system as a major architectural design element.

Sustainability

One reason for choosing wood for the structure was due to its role as a sustainable material. Contrary to what most structural engineers believe, they have considerable influence over a building's environmental impact through their choice of building materials and structural systems. While operating energy tends to receive most of the attention in a green building context, the energy required to manufacture and transport building products and to erect the buildings is significant—and varies considerably based on the choice of wood, steel or concrete as the main structural element.

Each year, 40 percent of the world's raw materials are used in by building sector. The result is millions of tons of greenhouse gases, toxic emissions, water pollutants and solid waste, all of which can be reduced with appropriate material choices. In particular, structural engineers have an opportunity to influence several areas related to structural system design, all of which are highly dependent on the specified materials. These include: embodied energy/effects, service life, durability and adaptability. The embodied energy of a building—which includes the energy required to extract, process, manufacture, transport and maintain its materials (and associated emissions)—has typically represented a small portion of a building's overall energy consumption. However, as the operating efficiencies of buildings increase, the embodied energy contribution becomes proportionally more important.

For example, one study compared the energy consumption related to a typical Canadian home in 1970 versus a current R-2000 rated home. (R-2000 is a performance-based standard for energy efficiency.) While lifetime heating energy accounted for 92 percent of the total energy required by the 1970 home, it accounted for just 77 percent in the R-2000 home. As the overall energy usage of the building was reduced because the operating energy decreased, the embodied energy of the building remained the same, thus increasing the contribution of embodied energy from 8 percent to 23.

Life cycle assessment, or LCA, is a method for assessing the environmental impacts of a service, process, material, product, assembly or building, over its entire life cycle. LCA practitioners follow a strict ISO (International Organization for Standardization) standard to model the product system, collect data, and characterize the impact potentials so they can then be normalized and weighed (both voluntary parts of the standard).

The Athena Sustainable Materials Institute has undertaken and directed innovative research and development activities that now allow architects, engineers and others to factor environmental considerations into the design process from the conceptual stage onward. Athena currently offers the only tools in North America for the life cycle assessment of whole buildings and assemblies, including:

- The ATHENA® *Impact Estimator for Buildings* – allows users to analyze entire buildings and assemblies base on LCA methodology
- The ATHENA® *EcoCalculator for Assemblies* – provides instant LCA results for over 400 common building assemblies and is available free of charge from the Athena website (www.athenasmi.ca)

LCA considers the embodied effects of all the life cycle stages—including product manufacture and building construction, building maintenance and product replacement, and building demolition.

Figure 2 illustrates the life cycle carbon dioxide (CO_2) emissions of different building materials. The manufacturing processes associated with concrete and steel products are fossil fuel-intensive, which is reflected in higher CO_2 emissions. However, the CO_2 absorbed by trees during their growing cycle and subsequently stored in wood products offsets the energy required to harvest, transport, process and maintain these products over time, which is why their net emission are below zero. *(Source: Building Information Foundation, RTS; CEI-Bois.)*

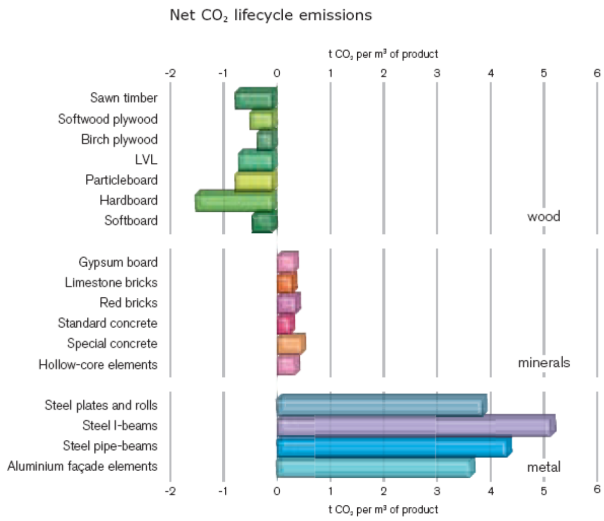


Figure 2: Product CO_2 Emissions [CEI-Bois]

In addition to the embodied energy effects, specifying wood as the structural system has some other environmental advantages:

- Wood is the only major building material that's renewable, sustainable and re-useable.
- Wood is unique in that more carbon is removed from the atmosphere during the tree's growing cycle than is emitted during that same tree's manufacture into products and its transportation to the point of use.
- Wood buildings can be easily adapted or deconstructed and re-used, which means they can continue to store carbon indefinitely while reducing the need for new materials.
- Wood biomass, which is a byproduct of both wood product manufacture and forest management, can be used to generate clean, renewable bioenergy, which can be used as a substitute for coal, natural gas, diesel and other fossil fuels.

Serviceability

Serviceability is defined in AISC 360-05 Chapter L as “a state in which the function of a building, its appearance, maintainability, durability, and comfort of its occupants are preserved under normal usage.” The SSTMDL is designed as a student learning laboratory; a place where students will observe and work with common building materials. Examples of serviceability related to students as the end users include the following:

- The lower walls of the building are cast-in-place concrete. The use of concrete helps withstand most all abuse the students will impart upon the walls over its lifespan.
- The building envelope of translucent polycarbonate panels provides access for students outside the laboratory to observe the happenings within the space from balconies of the adjacent buildings or sidewalks of the bordering plaza.
- If any bracing member becomes damaged for whatever reason, be it water intrusion, major seismic event or even students, the connections were oriented so that each member could be removed and replaced without having to deconstruct any connecting member above or below the damaged member.
- Vibrations due to human activity were considered for the design of the steel framed mezzanine, utilizing the procedures of AISC Steel Design Guide 11: “*Floor Vibrations due to Human Activity*”

Overall the intent of the project program was incorporated into the design of the building with serviceability in mind.

Fire Protection

When choosing the Construction Classification of a building for Business Group B Occupancy to adequately provide the allowable height and building areas, architects don’t always think of selecting wood or selecting Type IV Heavy Timber construction. Often times they default to Type I or II (steel or concrete) as a structural material. However, a close examination of Figure 3, CBC Table 503 Allowable Height and Building Areas reveals that Type IV Heavy Timber Construction provides the same height limitations and number of stories as Type IIA construction and provides nearly as much allowable square footage.

Figure 3: CBC TABLE 503 ALLOWABLE HEIGHT AND BUILDING AREAS

	TYPE OF CONSTRUCTION						
	TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A	B	HT	A	B
HT	65	55	65	55	65	50	40
S	5	4	5	4	5	3	2
A	37,500	23,000	28,500	19,000	36,000	18,000	9,000

In addition, for this particular project which is categorized as Type IIB, Type IV construction could have been used for the entire project. It exceeds the limitations for story height, number of stories and allowable square footage of Type IIB construction.

As mentioned previously, the building has an Occupancy Classification of B and a Construction Classification of Type IIB, fully sprinklered. CBC 602.2 defines Type II construction as “…those types of construction in which the building elements listed in Table 601 are of non-combustible materials, except as permitted in Section 603 and elsewhere in this code.” How was wood allowed for this project? Per CBC Table 601 Fire-resistance Rating Requirements for Building Elements (hours) for Type IIB, the required fire-resistance rating for the roof construction is 0 hours. Footnote d states the following: “In all occupancies, heavy timber shall be allowed where a 1-hour or less fire-resistance rating is required.” This footnote also applies to Type IB and Type IIA; in addition, per footnote c, fire retardant treated wood could have been used where the roof construction is 20 feet or more above any floor immediately below.

Heavy timber construction has been recognized by the model building codes for many years. Within the codes, limitations are placed on the minimum size, including depth and thickness, of all load-carrying wood members. Other requirements include the avoidance of concealed spaces and the use of approved construction details.

A technical paper, “Superior Fire Resistance,” by the American Institute of Timber Construction states, “The performance of heavy timber structures under fire conditions is markedly superior to most unprotected “non-combustible” construction.” This is evident in Figure 4 which is a picture from a test sponsored by the National Forest Products Association at the Southwest Research Institute.

Figure 4: This photo shows a sixteen-inch, 40 lb/ft steel beam (W16x40) and a 7”x 21” glulam beam following fire testing under full load. The steel beam collapsed after only 30 minutes of exposure while the glulam member remained straight and true, charring on ¾” of exposed surfaces.

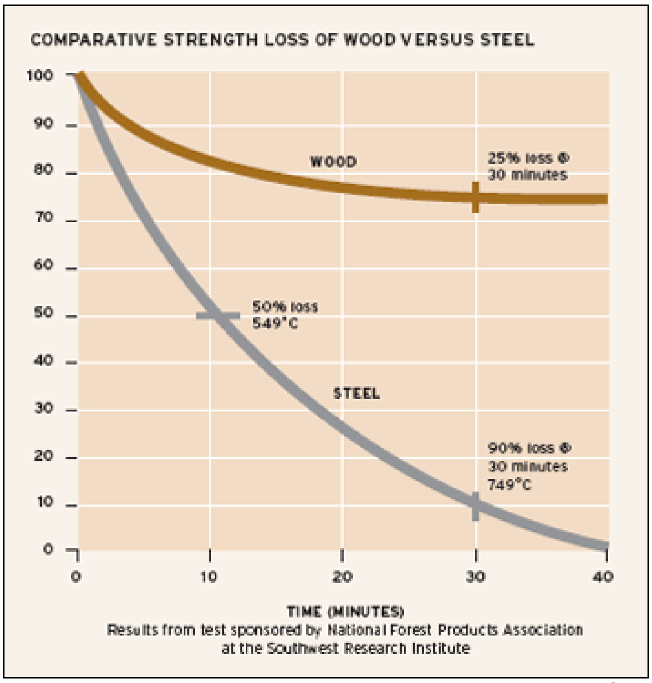


Figure 5: Material strength versus time during fire exposure

When exposed to fire, wood retains its strength for a longer period of time than steel. Unprotected metals quickly lose their strength and collapse suddenly, often with little warning. In contrast, wood loses strength slowly and only as material is lost through surface charring. When wood catches fire it typically develops char, which acts as a natural insulator and enables the wood to withstand higher temperatures. Thus, in a 30-minute fire, only ¾ of an inch of each exposed surface of the glulam was lost to charring, leaving most of the original cross section intact. As you can see from Figure 5, an unprotected steel beam (similar to Type IIB Construction) of comparable strength and exposed to the same fire lost 90% of its strength after 30 minutes.

Foundation

The project site is constrained by existing construction on all sides. The site is bordered on the south and west by the newly constructed Construction Innovations Center and the remaining north and east by the main University underground utilidor. A schematic site plan is provided in Figure 1. This leaves little room for extensive reworking of site material or over-excavation. The site is slightly sloping east to west with a total grade change of approximately 8 feet along the long axis of the building. The existing adjacent building was founded on concrete caissons varying in depth approximately 40 to 50 feet. The site soils varied drastically along the length of the proposed building location. The sloping topography allowed the eastern half of the foundation to rest in a layer of soft rock, while the western half floated up over the rock in a layer of stiff soil.

These varying soil conditions led the project geotechnical engineer, Earth Systems Pacific, to propose two possible foundation systems: a drilled concrete caisson foundation system or an extensive over-excavation and earthwork program in conjunction with a mat foundation system. The use of the earthwork program with a mat foundation system was ultimately chosen due to the relatively light dead load of the SSTMDL and the client’s preference. Because the mat was chosen and will allow more significant settlement than would a caisson foundation, the bridge connecting the second level of the SSTMDL to its neighbor the Construction Innovations Center was designed with this possible vertical movement in mind.

Effects of Earthquakes on the SSTMDL

“Earthquakes affect buildings differently depending on the type of ground motions and characteristics of the building structure. If the ground motion is strong enough, it will move the building’s foundation. However, inertia tends to keep the upper stories in their original position, causing the building to distort. Since inertial forces are greater when objects are heavier, earthquake forces are greater in heavier buildings. Higher ground accelerations also create more stress in a structure” (WoodWorks, 2008). The SSTMDL is located in a high seismic region, formerly classified as Zone 4 in the *Uniform Building Code*. The Site Specific Design Spectral Acceleration, Short Period, 5% Damped, is equal to S_{DS} = 0.85g. This is a relatively moderate Short Period Spectral Acceleration for an area of high seismic area assigned to

Seismic Design Category (SDC) D. Although the project is located in an area of high seismic area, it benefits from the fact that it is a relatively light structure above the concrete and steel mezzanine. The wall framing is almost non-existent as the wall cladding is light polycarbonate material and the roof is comprised entirely of timber framing. 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 a major seismic event.

Considerations when Designing with Heavy Timber Braced Frames (HTBF)

Braced frames are one of the straightforward and most economical structural lateral force resisting systems. In wood buildings, these systems can be used in heavy timber, post and beam, or conventional wood-framed structures, when the architectural design requires large open spaces and shear wall systems cannot be used. Generally, the triangulated brace systems have virtually no eccentricity in the joints and the lateral load is resisted by the brace in pure axial loading. Braced frames are usually stiffer than shear walls or moment-resisting frames because the axial stiffness of diagonals governs the system stiffness. In some regards, the stiff nature of the braced frames represents an advantage because serviceability requirements are easily met and less lateral drift causes less damage to nonstructural components and cladding systems. However, this stiff nature also results in higher lateral forces induced by earthquakes on the structure because it increases the natural frequency of the system. "The seismic response of a braced timber frame in general is a complex issue, involving many interacting factors that need to be understood and quantified. One of the most important considerations is to provide a system that can absorb large amounts of energy, and thus lower the earthquake induced forces, while maintaining adequate stiffness to avoid excessive deformations." (Karacabeyli and Popovski 2003) The seismic design needs to have a careful balance of strength, stiffness, and ductility of all components to provide a structurally efficient and sound system. Additionally, the brace connections are typically the "weakest link" in the system and will govern the inelastic behavior. Therefore, it is important that the connections are able to sustain nonlinear deformations to limit the force level in the braces.

HTBF Seismic Design Criteria

The CSU system utilizes a Seismic Peer Review Board that sets standards for buildings to be constructed on each of the 23 CSU campuses across the state. In turn, board members also provide seismic peer review for projects proposed on those same campuses. In order to pursue the use of HTBF as a seismic load resisting system, seismic design criteria was determined for the non-prescriptive system under the provisions of ASCE 7-05 §12.2.1 which states: Seismic force–resisting systems that are not contained in Table 12.2-1 are permitted if analytical and test data are submitted that establish the dynamic characteristics and demonstrate the lateral force resistance and energy dissipation capacity to be equivalent to the structural systems listed in Table 12.2-1 for equivalent response modification coefficient, R, system overstrength coefficient, Ω_0, and deflection amplification factor, C_d, values.

The approved seismic design criteria included all of the following major items:

The use of the HTBF as a seismic vertical lateral force resisting system shall be limited to a single story. The maximum height for the SSTMDL project is 28 feet. However, the maximum height of the HTBF elements is 21 feet. This is still well below even the most stringent height limitation on any structural system for Seismic Design Category D of 35 feet under prescriptive design in ASCE 7.

The load path of any braced frame system is very transparent. The SSTMDL, being no exception, is rectangular in plan with no horizontal or vertical irregularities. In fact, there are no plan or vertical offsets in the design. The avoidance of any vertical or horizontal irregularities from ASCE 7-05 Table 12.3-1 and 12.3-2 is a requirement of the approved Seismic Design Criteria. However, it is worth noting that it would be difficult to obtain a vertical irregularity in a system that has a one story height limitation.

The roof diaphragm is approximately 120 feet x 45 feet in dimension, resulting in a diaphragm ratio of 2.67:1. This ratio is below the limitation of 3:1 for unblocked diaphragms per CBC §2305.2.3. However, all edges of the plywood are supported by the 3x decking and the diaphragm is considered blocked when designing the nailing requirements based on calculated diaphragm unit shear. The roof diaphragm consists of 5/8" thick Structural I plywood over 3x tongue and groove decking, which admittedly is a fairly 'rigid' system. However, it is historically acceptable and common practice to consider untopped plywood diaphragms as flexible with respect to lateral load distribution. It should also be noted that the building is doubly symmetric in plan with no torsional or mass irregularities. The code allows a wood diaphragm to be idealized as flexible provided the following prescriptive requirements are met:

ASCE 7 12.3.1.1 Flexible Diaphragm Condition includes the following: Diaphragms constructed of untopped steel decking or wood structural panels are permitted to be idealized as flexible in structures in which the vertical elements are steel or composite steel and concrete braced frames, or concrete, masonry, steel, or composite shear walls.

CBC 1613.6.1 Assumption of Flexible Diaphragm adds the following text at the end of Section 12.3.1.1 of ASCE 7: Diaphragms constructed of wood structural panels or untopped steel decking shall also be permitted to be idealized as flexible, provided all of the following conditions are met:

1. Toppings of concrete or similar materials are not placed over wood structural panel diaphragms except for nonstructural toppings no greater than 1½ inches (38 mm) thick.
2. Each line of vertical elements of the lateral-force-resisting system complies with the allowable story drift of Table 12.12-1.
3. Vertical elements of the lateral-force-resisting system are light-framed walls sheathed with wood structural panels rated for shear resistance or steel sheets.
4. Portions of wood structural panel diaphragms that cantilever beyond the vertical elements of the lateral-force-resisting system are designed in accordance with Section 2305.2.5 of the *California Building Code.*

The SSTMDL does not qualify all four prescriptive assumptions of a flexible diaphragm due to the use of HTBFs rather than light-framed walls with wood structural panels. Therefore, comparison of the lateral drift of vertical (HTBFs) and horizontal elements (roof diaphragm) was required. ASCE 7-05 Section 12.3.1.3 provides criteria for flexible diaphragm by comparing the in-plane deflection of the diaphragm to the average story drift of the adjoining vertical elements for the seismic force resisting system. It states that in-plane deflection of the diaphragm needs to be greater than or equal to two times the average story drift vertical resisting system. Due to the stiffness, redundancy and configuration of the bracing elements supporting the roof diaphragm, the diaphragm drift was calculated on the order of twenty times that of the vertical bracing elements. Axial deformation of collector members and connection slip was considered during the review of vertical element drift calculations. Therefore, the assumption of a flexible diaphragm was used in distribution of lateral forces.

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 to verify the approximate period of the building in accordance with ASCE 7-05 §12.9. For a one-story building with such a direct load path, it makes 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 the use of a low value for the Response Modification Factor in seismic design of the Heavy Timber Braced Frame systems in the SSTMDL. See Table 1.

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

In addition, a historical comparison of seismic base shear was completed with previous model building codes applicable to the project site. A list of the historical seismic base shear values at service level is provided in Table 2. In reviewing relevant procedures dating back to the 1970 *Uniform Building Code*, prescribed forces were in line with the project's non-prescriptive Heavy Timber Braced Frames utilizing the current Equivalent Lateral Force Procedure of ASCE 7-05.

Table 2: HISTORICAL SERVICE LEVEL SEISMIC BASE SHEAR COMPARISON

Model Code	Base Shear
2007 CBC(1) (2006 IBC(2))	$0.247w_d$
2001 CBC(1) (1997 UBC(3))	$0.166w_d$
1995 CBC(1) (1994 UBC(3)) (4)	$0.275w_d$
1970 through 1985 UBC(3)	$0.186w_d$

(1) CBC: California Building Code
(2) IBC: International Building Code
(3) UBC: Uniform Building Code
(4) Equivalent in the 1988 & 1991 UBC

By using a low Response Modification Factor value, the assumption is a more elastic response during the 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 the connections, the system employed two separate overstrength factors, see Table 1. The overstrength factor for the system as a whole, including drags, drag connections, brace connections and columns, was equal to 2.0. The overstrength factor for the braces was 25% higher at 2.5. Using a Response Modification Factor of 3.0 in conjunction with an Overstrength Factor of 2.5 and the Importance Factor of 1.25 essentially means that the braces were designed for an $R_{equivalent} = (R/I)/\Omega_o = (3.0/1.25)/2.5 = 0.96 \sim 1.0$. An R = 1.0 assumes no ductility in the system, therefore designing the system for strictly elastic force levels.

This approach of applying the higher overstrength factor to the brace member itself and a lower value to the brace connection is the reverse of how a steel braced frame is designed. In a steel brace frame, the inelastic buckling of the brace is assumed to occur and the connection is designed for a higher force level, ensuring continuity of the lateral load path. In a HTBF, due to the low ductile properties of wood, it is 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 is not desirable for the connections of the HTBF to be designed for the expected capacity of the member, only the amplified seismic loads, as the ductility is designed to be introduced in the yielding of the connection itself.

A failure of a braced frame due to buckling, no matter the material, is a failure mode that would progressively result in collapse of the roof framing system. Since bracing members that are slender are governed almost entirely by stiffness (i.e., buckling) and timber is approximately twenty times less stiff than steel, preventing the heavy timber braces from buckling is extremely important. For this reason, the design of the HTBF incorporated several design intentions of AISC 341, Chapter 14, Design of Ordinary Concentric Braced Frames (OCBF). For example, all members' intersections are concentric and all minor eccentricities due to member thickness and interfaces were accounted for using the Uniform Force Method. Also, the slenderness of compression members was limited to kl/r approximately less than or equal to 100 [equivalent to an l/d approximately less than or equal to 30]. The bracing connections are to allow for a ductile failure mode in compression while protecting the brace from sudden buckling.

After consideration to the prevention of buckling of the brace members, the most important design attribute for a building frame system of heavy timber is the connections themselves. A 2003 report documents a series of shake table tests conducted on single-storey 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 riveted 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).

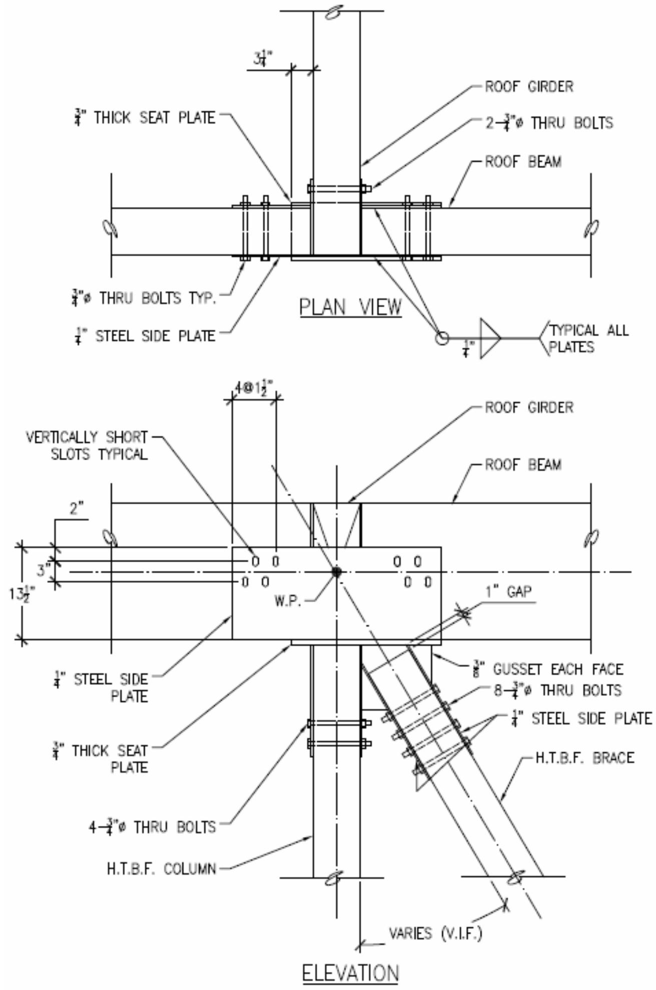


Figure 6: Typical HTBF Connection

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 shown in Figure 6 and Figure 7, the bolt slenderness ratio is 7" / 0.75" = 9.33 > 8. Slender bolts are only useful if the bolts have the ability to deflect under load and the end distances are significant.

Figure 7: Typical HTBF Connection – As-built Photo

Figure 8: SSTMDL Construction Photo

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 the results showed that fastener end distances "in current practice [are] adequate to conservative." (Rammer) Thus the required end distances for tension members as specified per the American Forest & Paper Association/ American Wood Council (AF&PA/AWC) National Design Specification® for Wood Construction (NDS®) is more than adequate. The addition of a 1" gap at the end of each brace allows the bolts to deflect or yield in both tension and compression. The 1" gap and the proper end distance per the NDS provided the detailing for the bolts to resist the loads as assumed.

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 less bolts. This added ductility and more redundancy to the connections.

The connection design also considered the effects of group tear-out. 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 the 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.

Conclusion

As one of the first HTBF buildings designed and approved under the 2007 *California Building Code* and ASCE 7-05 (if not the only one so far), the Simpson Strong-Tie Materials Demonstration Laboratory is unique in both architectural and structural appeal. The building incorporates three major structural materials to fulfill not only the architectural requirements of providing a built environment that meets spatial needs, is aesthetically pleasing, and is environmentally responsible, but also meets code requirement for fire protection. In addition, the SSTMDL is itself a pedagogy that will help to fulfill the educational needs of a University that is known for students who become highly respected design professionals. Future generations of students will be able to learn not only within the walls and roof of this building, but through the walls and roof as well. The building presented several design challenges from a structural perspective. The use of the non-prescriptive lateral system in a high seismic region on a University campus is a testament to the use of timber systems in non-residential applications. Should this type of system be investigated further under full-scale testing models with testing standards, it is possible that prescriptive design requirements could be produced for consideration in subsequent versions of the applicable standards or codes. The inclusion of prescriptive requirements will allow greater use of wood as a design element benefitting future building occupants for years to come.

Acknowledgements

The authors wish to express appreciation to those who contributed to the successful completion of the design for the Simpson Strong-Tie Materials Demonstration Laboratory and/or this technical paper. They are numerous and all of the individuals listed below had a helpful hand in the project. Any omissions are entirely unintentional.

- *Ricardo Arevelo, S.E.,* Simpson Strong-Tie Corporation
- *Kevin Dong, S.E.*, Professor, Architectural Engineering Department, Cal Poly, San Luis Obispo
- *Rob Down, P.E.*, Earth Systems Pacific
- *Lee S. Engelmeier, P.E.*, Lampman & Smith
- *John S. Fonturbel, P.E.*, Lampman & Smith
- *Alan Hanson*, Simpson Strong-Tie Corporation
- *Allan Hauck, PhD*, Construction Management Department Head, Cal Poly, San Luis Obispo
- *R. Thomas Jones, AIA*, Dean, College of Architecture and Environmental Design, Cal Poly, San Luis Obispo
- *Perry Judd*, Project Manager, Facilities Planning & Capitol Projects, Cal Poly, San Luis Obispo
- *Christopher I. Lampman, S.E.*, Structural Engineer of Record, Lampman & Smith
- *Philip Line, P.E.*, American Wood Council
- *Joel Neel*, Senior Associate Director, Facilities Planning & Capitol Projects, Cal Poly, San Luis Obispo
- *Kelsey Anne Parolini, S.E.*, Lampman & Smith
- *Fred Potthast, G.E.*, Project Geotechnical Engineer, Earth Systems Pacific
- *Thomas G. Reay*, Project Architect, Omni Design Group
- *Thomas A. Sabol, Ph.D., S.E.*, CSU Seismic Review Board / Engelkirk & Sabol, Consulting Structural Engineers, Inc.
- *Michael F. Smith, P.E.*, Lampman & Smith
- *Roxane Ward,* Editor, WoodWorks
- *Aaron Williams*, Project Manager, Omni Design Group

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