

Appendix A: Detailed Material Strategies

Strategy 1: Straw Insulation & Clay Wall Panel



-7,860
kg CO2 reduction

72,500
kg CO2 stored

Compared to
fiberglass batt & gyp board exterior
wall of same R-value

Assumptions

Straw insulation within hybrid straw bale exterior walls is used at the upper floors in lieu of more conventional fiberglass batt insulation. Bales on end act as insulation infill between 3x4 framing at 24" on center, as an alternative to fiberglass batts between 2x6 wood or light steel framing, with thermal break wrap of foam insulation.

Rather than 5/8" gypsum board panels, 3/4" clay plaster provides the interior finish surface for hybrid strawbale exterior walls. The panels could be built with interior framing and gyp. bd. as well.

A heavier wall system can incur an increase in concrete foundation, resulting in higher embodied carbon (negative savings), but is surpassed nearly 10x by the carbon storage of straw.

Benefits

Straw is a remarkably high-performance building material both from the specific lens of insulation and soundproofing and the wider lens of the circular economy. Straw bale wall assemblies offer high thermal performance, are durable in a wide range of climates, are fire-resistant in their final form, and can complement a variety of structural systems. Overall, straw accomplishes more performance and ecological objectives than any other insulation material.

While strawbale construction is included in appendices S of the International Residential Code (IRC), and is a fully adopted part of the California Residential Code (CRC), in this case study it is used as an insulation material only, with a flame spread index (10) and smoke developed index (350) shown through ASTM E84 test to be within the limits of the IBC/CBC.

Clay can absorb large amounts of water vapor without saturating or transmitting the moisture to the straw, which helps protect the strawbale (or other moisture-sensitive wall types) from humidity generated indoors.

See the Natural Building Material Assemblies section in Appendix C and article in Appendix H for more info.

Challenges

Thicker exterior walls (15" bale depth vs. 5.5" fiberglass batt) can reduce useful floor area if the exterior face of this building method is constrained to the property line in the same manner as conventional facade assemblies. Local policy allowances to allow lower R-value per inch, carbon-storing materials to extend into the right-of-way above the first floor would help to retain the same internal leasable space. Some jurisdictions allow one to count just the inner 6" of the wall for floor-to-site area ratio (FAR) and tax calculations. This could be instituted state-wide for carbons-storing materials to remove the primary inhibitor for using a lower R-value per inch.


Sustained moisture content of 19 percent or more can lead to dry rot, which can cause damage. Intermittent moisture is manageable however, as long as wall assemblies can transpire accumulated moisture. The East Bay and most places throughout the world are suitable.

Currently, any additional cost associated with straw-bale assemblies is due to time and labor. For most residential and some commercial construction, bale assemblies are typically site-built and fairly customized to the building frame, making the building process more time-intensive compared to installing batt or spray-applied insulation. However, new techniques have been proven in Europe and Canada for prefabrication off-site which reduces the time, and thus cost, significantly. This design incorporates prefabricated bale panels to avoid the time-intensive details that are common in site-built bale installs.

Because clay plaster is currently more common in small and medium scale residential applications, and because it is typically hand-applied, its finished cost is higher per square foot than gypsum board. Actual costs can vary depending on the degree of finish desired and total area, but rough costs for a two-coat plaster with a higher-quality medium-fine finish has been around \$10-14 psf for a large single-family home. However, clay is a readily available material both locally and regionally, and is relatively simple to process and refine, so modest industrialization of the process, cost-effective plaster details, and increased square footage of plaster will all reduce cost considerably. Prefabrication of the bale panels with plaster will further reduce time, labor, and cost.

See natural building material assemblies for more info on clay sourcing and supply chains

Examples of this strategy in use already:	Resources:	Other benefits
<p>Jules Ferry Residence, France https://www.thelaststraw.org/jules-ferry-residence-straw-bale-panels/</p> <p>Mahonia https://www.arkintilt.com/mahonia-mixed-use-building</p>	<p>https://www.buildinggreen.com/feature/straw-next-great-building-material https://ecococon.eu/us/ https://www.modcell.com/</p> <p>See Natural Building Material Assemblies section in Appendix C.</p>	<p>Straw: abundant sources in Northern California; provides useful life for a waste product; healthier alternative to foams;</p> <p>Clay: non-toxic and zero VOC, mold-resistant, supports bioregional economies</p>

Strategy 2: Cellulose insulation and Straw-based wallboard for interior partition walls between units (aka party walls)		
10,200 kg CO2 reduction	102,400 kg CO2 stored	Compared to Fiberglass batt and gypsum wallboard
<p>Assumptions</p> <p>The cellulose insulation used throughout the interior partition walls and between floor joists, plus the straw-based medium density fiberboard, store a significant amount of carbon. In comparison to fiberglass batt, which is common in residential construction, the embodied carbon reduction opportunity is not as high as found with other strategies. Note that there is also a very large range in embodied carbon for different insulation alternatives, so the hypothetical reduction could be much smaller or larger depending on the specific insulation products compared, even within the same insulation type and manufacturer.</p> <p>Strawbased MDF is now available to the Bay Area from CalPlant1 in the form of its Eureka MDF product which can come in 1/2" x 4' x8' sheets. While the cost of Eureka MDF is more than gypsum wallboard, it is about the same as standard MDF and can save costs in taping and mudding the seams because its edges are mitered and much less prone to crushing and crumbling than gypboard.</p> <p>This assembly remains under the 10 psf mass allowance for interior partitions typically used for the structural design, so there was no need to redesign other elements of the building.</p> <p>Similar ideas</p> <p>Many other carbon-storing insulation products are on the market and together span a wide range in carbon emissions used to manufacture them and stored in them. Luckily, the more exact “global warming potential,” which is the scientific term for embodied carbon, can be found in Environmental Product Declarations, and of all building product types, insulation offers a great many EPDs. The key is to obtain an EPD that is product-specific, meaning it reflects the specific product made by a particular manufacturer. For insulation it is also essential to compare values that are functionally equivalent, meaning they take into account the amount of material needed to provide the same acoustic, thermal, and/or other kinds of performance. The information in EPDs can better assist selection of lowest embodied carbon options.</p>		

Challenges

While cellulose insulation is a standard option for residential construction, builders often turn to fiberglass batt, mineral wool, or spray foam for wall and floor cavities in multi-family construction.

On the other hand, straw-based finish products remain a rarity in the marketplace. However, the establishment of CalPlant1 shows the viability of transforming California's waste straw problem into a useful, carbon-storing building material.

Examples of this strategy in use already:


Project - link


Resources:

<https://calplant1.com/>
<https://durrapanel.com/benefit/fire-resistant/>
<https://www.cmsgreen.com/insulation/ecocell-batts>

Other benefits

The CalPlant MDF does not use formaldehyde, which is a chemical linked to cancer that is often found in construction products made of wood and agricultural fibers

Strategy 3: Compressed straw board between rooms within residential units		
9,500 kg CO2 reduction	107,000 kg CO2 stored	Compared to Typical studs and gypsum wallboard
<p>Assumptions</p> <p>Compressed straw panels store a significant amount of carbon. If combined with strategy 2, the net carbon storage is near that of the entire podium CLT and glulam beam floor. In comparison to 2x4 studs and gypsum wallboard, which is common in residential construction, the embodied carbon reduction opportunity is not as high as found with other strategies. Also note that there are lightweight gypsum wallboards with much lower embodied carbon than standard wallboard. so the hypothetical reduction could be much smaller depending on the specific wallboard product used, even by the same manufacturer.</p> <p>Using compressed straw boards would not exceed the 10 psf mass allowance for interior partitions typically used for the structural design, so there was no need to redesign other elements of the building.</p>		
<p>Challenges</p> <p>Like straw-based insulation and MDF, straw-based finish products remain a rarity in the marketplace. The two main sources of compressed straw panels are a long way from California -- Durra Panel in Australia and Stramit in the UK. However, this is changing, signaled by the expansion of EcoCocon to North America, on top of the addition of Straw Bale Construction and Light Straw Clay to the International and California Residential Codes. The tested and proven fire-resistive qualities of these systems and related materials such as rice hulls, cork, hemp and other natural fibers signal new opportunities for products, provided consumers overcome perceptions to the contrary.</p>		
Examples of this strategy in use already: Project - link	Resources: https://durranel.com/benefit/fire-resistant/	Other benefits These products use heat and pressure to bind the straw and do not rely on formaldehyde-laden adhesives common to other products that use residual bio-based fibers.

Strategy 4: Clay Floor Finishes		
57,800 kg CO2e reduction	4,100 kg CO2 stored	Compared to Carpet and Luxury vinyl tile (LVT)
<p>Assumptions</p> <p>Outside of the restroom and janitorial areas that use ceramic tile, the upper floors use ¾" clay flooring poured directly over the plywood floors. (The podium deck level has a cork interlayer between the clay and cross-laminated timber deck to provide additional acoustic isolation between the residential units and the ground floor retail and parking functions.)</p> <p>The embodied carbon savings of these floor finishes comes from comparing them to conventional floor coverings like carpet and LVT. Unlike manufactured materials, clay has virtually no embodied carbon. There is also a small amount of carbon storage coming from the cork. The total weight of the clay and cork is within the range of carpet and LVT with padding, so no structural changes were necessary to the frame or foundation when running this comparison.</p> <p>Similar ideas</p> <p>Clay floors offer a durable, low carbon option for retail spaces. Wood, cork, or linoleum are also low-carbon options, but these are less durable for high traffic retail spaces.</p>		
<p>Challenges</p> <p>Clay floors should not be used in areas with persistently high moisture or heavy equipment use. Clay floors should be sealed in order to prevent dusting and improve durability. Boiled linseed oil is often formulated specifically as a surface sealant over clay, though other low-VOC sealants and waxes can be used in combination with oil.</p> <p>Because clay floors are sealed and hardened with multiple applications of a linseed oil-based formula, drying/curing time is relatively slow and needs to be factored into the construction schedule. As with clay plasters, the most common application currently for clay floors is small to medium-scale, and mix design is typically custom when using local or regional clays. Mix designs for scaled up application of clay floors could potentially be formulated with other low-carbon,</p>		

nontoxic hardeners to speed curing.

Cost

The cost of clay flooring is primarily in labor and sealants, and is currently comparable to hardwood or custom tile. As with clay plasters, the cost of clay flooring per square foot will decrease with greater installed square footage and modest industrialization of mixing and application. See *Natural Building Materials Assembly section*.

Examples of this strategy in use already:

Project - link
<http://www.claylin.com/photos/photo-gallery.php>


Resources:

<http://claylin.com/>

Earthen Floors –
S.R.Crimmel (2014)

Other benefits

Readily available material, can support local economy, healthier material

Strategy 5a: Cross-Laminated Timber (CLT) Deck with HT-BRB frames		
317,300 kg CO2e reduction	377,100 kg CO2 stored	Compared to Post-tensioned slab and reinforced concrete wall podium
<p>Assumptions</p> <p>The CSB has a CLT podium which is compared to a more conventional pre-stressed concrete podium. In order to appropriately represent a conventional PT podium assembly the ground floor lateral system of the concrete podium needed to change to 10" thick poured concrete shear walls, and increase the foundation to match, for this strategy.</p> <p>At the podium deck, 7-½" cross-laminated timber deck, including the glulam framing and heavy timber BRB lateral system, is compared against a conventional pre-stressed concrete podium with mildly reinforced concrete shear walls.</p> <p>As Type III-A or V-A construction, the fire code requires 3-ply or 4" CLT at a minimum, but many building departments may require an extra ply used as a sacrificial layer during fire where end-grain is exposed. Thus, the carbon-storing design uses a 4-ply 7-½" CLT deck between the ground floor parking level and housing above in place of the post-tensioned (PT) concrete slab commonly seen in mid-rise multi-family housing.</p> <p>In addition to replacing a carbon-intensive material like concrete with the carbon-storing engineered timber, post-tensioned concrete tends to have much higher embodied carbon than mildly reinforced concrete because of the high early strength needed at time of tensioning. Faster strength gain typically demands a larger amount of cement content and less flexibility to use supplementary cementitious materials (SCMs) as an alternative. The PT podium used for comparison is assumed to contain 600 lbs/cyd of cement and no SCMs. If the number of days to strand stressing can be lengthened, it could be possible to reduce the cement content of the concrete.</p> <p>The resulting reduction is nearly as much as the total carbon stored in the 15,000 sq-ft CLT and glulam beam floor system.</p> <p>Similar ideas</p> <p>Mass plywood panels are also an appropriate option for this application. Mass plywood uses smaller diameter trees than CLT, and offers the same structural performance as CLT with less</p>		

wood, but it also contains more adhesive.

The CLT podium deck assembly provides sufficient thermal insulation to meet code, but if more thermal insulation were needed or desired between the unconditioned parking area and conditioned occupied spaces above, cellulose spray insulation is a carbon-storing option that could be applied to the underside of slab regardless of whether the slab is CLT, concrete or metal deck.

Challenges

Code barriers are largely no longer an issue for CLT within Type III, IV, and V construction type allowances, but this form of construction is still not widespread, particularly not as a replacement to concrete podiums with wood framing above. The perception that CLT and wood construction generally offer inadequate fire resistance, while inaccurate, still persists.

Acoustical challenges can also arise due to wood's lighter weight compared to concrete, but can be resolved through comprehensive consideration by the design team. There are a variety of options for additional acoustic treatments when required. One of the most popular currently is to add a few inches of gypcrete, or a couple inches of concrete if structural stiffness is also needed, but these can significantly increase the embodied carbon of the floor assembly. For the design prototype, cork was chosen because it is a carbon-storing and rapidly renewable material already often used as an acoustic underlay.

Examples of this strategy in use already:	Resources:	Other benefits
Project - link		HT-BRB has a higher seismic R-factor (8) in the code compared to concrete shear walls (4). Low or no VOCs, renewable material Cork is harvested from tree bark, which does not require cutting down the trees

Strategy 5b: Heavy Timber Buckling-Resistant Braced Frames (HT-BRBs) with CLT deck



182,900

kg CO₂e reduction

377,100

kg CO₂ stored

Compared to

Steel BRBs and pan deck podium

Assumptions

The design prototype has hybrid heavy timber (HT) buckling-resistant braced frames (BRBs), which is compared to a more conventional grout-filled steel hollow structural section (HSS) BRBs. For this strategy comparison, in order to appropriately represent a grout-filled steel hollow structural section (HSS) BRBs assembly, the podium needed to change to composite metal deck above steel beams and columns, and the foundation needed to increase to match.

Using HT-BRBs) rather than conventional HSS BRBs reduces the amount of steel required, employing only a 5" x 1.25" steel plate between two 4" x 8" heavy timber glulam beams instead of 6x6x1/8 steel sections. In general, BRBs offer ease of constructibility and superior ductility compared to conventional bare steel sections for high seismic zones such as the Bay Area.

To accompany the HSS BRBs, the braced frames would be steel and the floor deck would be 5" concrete-filled composite metal deck above steel beams and columns instead of CLT deck and glulam frame. The foundation for the steel-framed podium was also resized for the increased loads.

The resulting reduction and storage in this comparison are on the same order of the comparison to a concrete PT podium. Thus, the strategy to use a wood-based podium results in the highest carbon savings compared to all the other assembly comparisons in this study.

Challenges

HT-BRB's are not as commonly used as conventional steel shapes, so construction teams are generally less familiar with them, particularly the connections.

Examples of this strategy in use already:


Project - link

Resources:

https://www.fpl.fs.fed.us/documnts/pdf2019/fpl_2019_murphy001.pdf

Other benefits

Renewable materials, may support local economy, makes efficient use of higher impact material (steel)

Strategy 6: Compacted gravel and clay at-grade floors vs. Concrete slab-on-grade		
46,200 kg CO2e reduction	0 kg CO2 stored	Compared to Concrete slab-on-grade in parking area
<p>Assumptions</p> <p>The compacted gravel in the parking area, alongside the clay floors in retail and lobby space, offer notable embodied carbon reduction compared to a conventional 4" reinforced concrete slab-on-grade throughout the ground floor. The gravel area assumes 6" of compacted crushed aggregate. The clay floors consist of ¾" of clay over a 2-¼" clay/pumice base layer. Recycled aggregates from building demolition offer an opportunity for further embodied carbon reduction while any aggregates that involve heat or high-energy manufacturing processes, such as some expanded clay aggregates, will lower the savings.</p>		
<p>Challenges</p> <p>Compacted gravel can involve more housekeeping to control unintentional dispersion of dust and rocks outside the parking area. However, cleaning and removing stains is easier with gravel that can be collected and replaced compared to lifting stains out of concrete.</p> <p>Cost</p> <p>Initial cost will be substantially lower than poured concrete slabs, on the order of one-third to one-fourth the cost, particularly in today's market. Standard Caltrans ¾" aggregate base can be compacted to a suitable density for parking of vehicles at relatively little cost, as it is a typical substrate for slab-on-grade.</p>		
<p>Examples of this strategy in use already:</p> <p>Project - link</p>	<p>Resources:</p> <p>https://allaboutparkinglots.com/gravel-parking-lots/ https://www.homeadvisor.com/cost/outdoor-living/pave-a-parking-lot/</p>	Other benefits

Strategy 7: Low-Cement Concrete



26,200

kg CO₂e reduction

0

kg CO₂ stored

Compared to

Industry average concrete

Assumptions

The footings and slab-on-grade for the carbon storing building are assumed to contain 70% supplementary cementitious materials (SCM) content. For comparison, concrete with an average SCM content of about 25% was used to calculate the reduction potential of this strategy.

The volume of concrete on this project is very small already, since less than 15% of the ground floor is finished in concrete. If the entire ground floor were concrete slab-on-grade, the CO₂ reduction in making this change in cement content would increase by about 50%.

The most common SCMs in the Bay Area are fly ash and slag. Cement replacement with these SCMs is frequently used and well-tested among the largest suppliers in the Bay Area. Such a strategy is ideal for foundation elements which ordinarily do not need high early strength. Specifying these concrete mixes to reach strength at 56 days or later helps concrete suppliers use less cement. Over the last decade in the Bay Area, lower carbon concrete has been generally available at cost parity with conventional concrete for applications that do not need fast strength gain.

Similar ideas

Concrete impact can also be reduced through other methods, including injecting captured carbon dioxide into ready mixed concrete (CarbonCure™) and use of recycled aggregate or (in the near future) aggregate produced through carbon capture.

Challenges

Success with this strategy is higher if coordinated between the contractor, concrete supplier, structural engineer, and architect well ahead of concrete approval and placement. Low cement content concrete may not be as feasible for elements that need to support early loads or release moisture earlier for finishing floors. Different kinds and sources of SCMs will also have different effects on final appearance. As with exposed concrete in general, the architect should request

samples and mock-ups to achieve the desired aesthetics.

As coal combustion declines and blast-furnace steelmaking becomes less common, fly ash and slag are becoming less readily available. This may lead to future challenges in acquiring supplementary cementitious materials for cement replacement. SCMs that are currently not as commonly used, such as ground glass pozzolan, may offer alternatives in the future.

Examples of this strategy in use already:	Resources:	Other benefits
Project David Brower Center “ Sustainability Through Strength ” https://www.tippingmar.com/projects/project_details/19	https://www.stopwaste.org/concrete https://centralconcrete.com/wp-content/uploads/2019/07/Specification-Guide_Capturing-Value_LowCarbon_Jul_10_2018_Final_r4.pdf	Local economy, resource efficiency and use of waste products

Strategy 8: Earthen Masonry Units



25,000

kg CO2e reduction

0

kg CO2 stored

Compared to

Concrete masonry units (CMU)....

Assumptions

Earthen block with clay-based geopolymers and lime, slag, and natural aluminosilicate binders offers a lower embodied carbon alternative wall material compared to traditional CMU for the podium wall. Watershed blocks™ use only 4% cement⁵ compared to typical CMU comprised of about 10%⁶ cementitious materials.

Similar ideas

CMU with a high level of cement replacement with supplementary cementitious materials is also a viable alternative. While cast-in-place and precast concrete walls can often be thinner, they tend to have higher cement content and thus higher embodied carbon per unit of wall area. Earthen block tends to be lower in embodied carbon than all of these.

Challenges

Earthen blocks are higher in cost than conventional CMU by about 10-20%, but due to their more attractive appearance, can be left unfinished, which can help recoup the additional cost or equate to enhanced aesthetic value of a space.

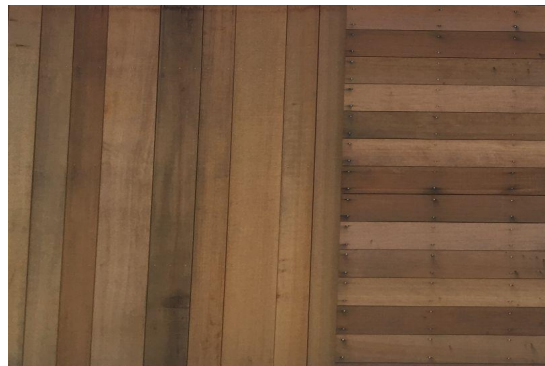
EMU's have a greater shrinkage percentage and larger quantity of fines than permitted in ASTM C 426 - Standard Test Method for Linear Drying Shrinkage of Concrete Masonry Units. For the lowest embodied carbon block, compression strengths, if suitable for the application, lower than those permitted for conventional CMU are recommended. It has been documented that these changes are inconsequential to the durability and reliability of the blocks, though they make it an alternative material which would require jurisdictional approval.

⁵ J. Dahmen and J. Kim, "Cradle to gate life cycle assessment of alternative masonry units," 2018.

⁶ https://www.concreteconstruction.net/_view-object?id=00000154-1cfb-db06-a1fe-7ffb900000

<p>Cost</p> <p>Watershed block or similar products cost approximately double the material cost of standard concrete block, but are on par with polished face or other finish-grade products. More importantly, labor represents the bigger portion of the cost of a block wall, which is equal to conventional.</p>		
<p>Examples of this strategy in use already:</p> <p>Project - link https://www.arkintilt.com/watershed-straw-bale-residence</p>	<p>Resources:</p> <p>https://watershedmaterials.com/</p> <p>https://buildwellsource.org/materials/materials-natural-ural/earth</p>	<p>Other benefits</p> <p>Resource efficiency Can match surrounding landscape</p>

Strategy 9: Exterior Wood Siding



16,400

kg CO₂e reduction

20,500

kg CO₂ stored

Compared to

Fiber-cement siding

Assumptions

Redwood siding is used in the CSB prototype because of its inherent resistance to fire and pests without the need for adding hazardous chemical preservatives. While there are several options for cladding, fiber-cement panels were chosen for the embodied carbon savings comparison due to their local popularity for the mid-rise multi-family aesthetic. The calculations show that not using fiber-cement siding reduces the embodied carbon almost as much as the amount of carbon stored in the 1" siding over 14,500 sq-ft of clad area.

Similar ideas

Sustainably harvested wood is also preferable to metal, brick, or plastic siding. Cork was also considered but decided against due to the additional weight which would require redesign of the structural brace and foundation systems.

Challenges

In the long-term, wood requires more maintenance and needs replacement sooner than many other products. It is currently often used in this type of construction in a limited capacity, for accents, so applying it on a broader scale is not a stretch. Wood in a nominal 1x thickness with a lapped joint does meet the WUI (wildland urban interface) fire standards, but it may not meet all local fire codes.

FSC certified quality wood is going to be more expensive than many fiber-cement, metal or stucco finishes. Given the broad range of options for both it is difficult to provide an order of significance of this increase. However, if the true cost of carbon were taken into account, the cost of redwood siding would invariably sink closer to parity with fiber-cement and metal, while if the human and environmental health cost of toxic chemicals (or their release in fire) were accounted for, natural wood would look favorable to plastic siding. Vinyl siding is already discouraged in multi-family construction in Albany because of the toxic fumes that would be released in fires.

<p>Examples of this strategy in use already:</p> <p>Project - link</p>	<p>Resources:</p> <p>Albany Multifamily Green Building Guidelines</p> <p>https://www.albanyca.org/home/showpublisheddocument?id=387</p>	<p>Other benefits</p> <p>Wood is a healthier material than some plastic siding options, and selection of redwood avoids chemical fire and preservative treatments for exterior use.</p>

Strategy 10: Wood verified from managed forests



n/a

kg CO₂ reduction

800,500

kg CO₂ stored

Compared to

Wood from unmanaged forests or of unknown source

Assumptions

Here the assumption is that, at a minimum, carbon taken from the forest (in the form of logs) is replenished (trees are replanted) in a way that maintains an overall carbon balance. In other words, within the timeframe that a given amount of carbon has been removed and is stored in various building products, it must be replaced by the same amount of carbon back into the forest. Without assurances of stable carbon stocks, the prototype presented flips from a net carbon sink to a net carbon emitter.

So how do we know if the trees are getting replanted? At a bi-national scale, forest cover in Canada and the US has been steady, even slowly increasing, over recent decades. However, single forests under individual ownership may deviate from this trend significantly, and the addition of trees in a plantation in one area does not make up for the removal of stands from a more biodiverse, less undisturbed forest in another area. So there needs to be a way to link individual wood products to the forest management practices from which the logs were sourced to ensure the practices were in concert with the overall national trend of forest carbon stock retention and growth.

Luckily the wood industry offers several certification programs which include both chain-of-custody and carbon management requirements. Chain-of-custody helps to link wood products to the management practices within their source forests while carbon management requirements mean the land owners must have a plan for replenishment of carbon stocks. While enforcement and uptake challenges mean there is always a chance a few participants are not in complete alignment and also that some forests are aligned but not certified, these programs are the best tool the building industry has at this time, to assess whether a given wood product comes from forests managed in a way that supports carbon-storing claims.

It is important to note that this is not the same as broader ecosystem management, which has the potential (but no guarantee) to increase carbon stores in forests, which is described further in the Climate-Friendly Sourcing section. Instead this strategy is focused on above ground carbon management, which is still critically important to claim the carbon storage in the wood mass of building products. If the carbon stored in the products is not replenished as new trees in the forests, there is no net benefit that can be claimed in upfront carbon savings. If this most basic type of management is not happening, then our Carbon-Storing Building cannot claim any of the carbon

storage numbers presented that are related to wood and wood-fiber products, including the CLT, glulam, plywood, lumber, and wood fiberboard.

Challenges

At times, certified wood can become difficult to locate, or require advanced lead times. Much like the early days of organic produce, there is a lingering perception that certified timber is of a lesser quality, or significantly more expensive, or tied to a political agenda; none of these is true, but these perceptions persist.

In particular, FSC wood is often more expensive, by varying degrees. Outlets such as Home Depot have committed to selling only FSC lumber and it does not come at a significant premium—and at times is less expensive—than comparable wood from other retailers.

Examples of this strategy in use already:

Project - link

<https://living-future.org/lbc/case-studies/>

Resources:

<https://carbonleadershipforum.org/blog/2020/10/10/wood-carbon-seminars/>

Other benefits

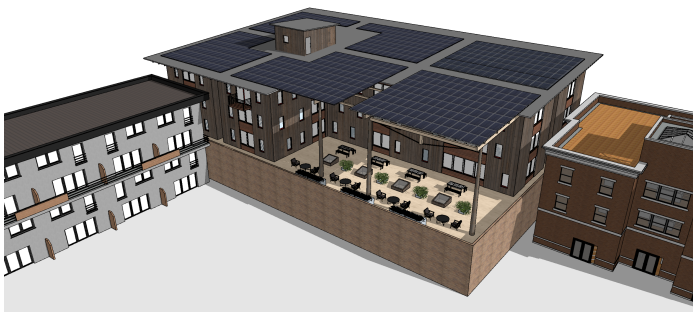
May also contribute to local sustainability mandates for green building ratings or other measures that might require certified wood

Appendix B: Detailed Architectural Description of Carbon-Smart Building Prototype

To make our example generic, the East Bay Carbon Storing Building is assumed to be built on a flat site, on an urban corner lot measuring 150 feet by 100 feet. The building consists of retail and parking on the ground floor, with apartment units above, and an outdoor space on the podium deck over the parking garage.



The roof is assumed to be unoccupied other than for maintenance, and supports a PV array that extends over the podium deck outdoor space and is supported by full redwood trunk columns.



The ground floor has wood braced and stud-framed walls, with a 15' floor-to-floor height. The upper level floors are 10' from floor to floor, with taller ceilings at the top (4th) floor units, on the fourth floor along the north side of the building, given the sloping roof. The fourth floor roof is 15' above the fourth floor at the north, and 10' at the south, a 0.6:12 slope. The roof has an EPDM membrane.

On the upper floors, plywood shear walls resist lateral forces, while straw bale provides infill. Upper level floor and roof structure consists of 12" engineered wood I-joists with a 3/4" plywood subfloor and dense pack cellulose insulation. The upper level floors are finished with 3/4" poured clay, with tile in bathrooms and other high-use zones.



Perimeter shear walls are a hybrid wood-strawbale assembly, with 3x4 wood framing at 24" on center, bales on end infill, and clay plaster interior finish. Exterior cladding at this wall type has 1" (nominal) horizontal redwood siding, with a 10% window to wall ratio.

Between the perimeter shear walls, stacked glazed exterior walls provide additional access to daylight. This wall type consists of 2x wood framing, with cork or Gutex™ rigid thermal breaks, and a 65% window to wall ratio. Between glazing, exterior cladding at this wall type is 1" (nominal) horizontal redwood siding. Interior wood framed shear walls and acoustic partition walls are insulated with dense pack cellulose insulation. Within apartment units, partition walls consist of a double-layer of 2" compressed straw panels between rooms.

Ground floor storefront walls are LamBoo™, 10' tall. Above the storefront system, exterior cladding consists of 5' of horizontal redwood siding. A 18.5' high partially grouted Watershed Block™

surrounds the parking area and offers fire separation. The ground floor interior has wood-framed partition walls with gypsum board finish and cellulose batt acoustic insulation.



The ground floor podium level is a Cross-Laminated Timber (CLT) podium deck supported by glulam framing, including glulam beams to minimize CLT thickness, and a heavy timber buckling-restrained braced frame (HT-BRBs) lateral system. The HT-BRBs below the podium consist of a single diagonal set in a 10' wide glulam beam frame. All HT-BRBs feature a 5" x 1.25" steel plate between two 4x8 wood members.

Fire code requires 4" heavy timber, and a minimum of 3 plies for CLT, for a 1hr rating between the parking area and residential above. A sacrificial CLT layer has been provided, as many building departments require, and thus increases the CLT to 7-½ inches. To account for areas where greater acoustic isolation or hiding MEP runs is desired, 50% of the underside of CLT in the retail/lobby areas are given a gyp board drop ceiling supported with 1x4 strapping and filled with cellulose insulation.

The foundation consists of reinforced concrete spread footings and grade beams. Slab on grade is concrete in high use areas, such as the garbage and recycling room and elevator pits. The parking garage floor is a compacted aggregate base. In retail and lobby spaces, the floor consists of adobe clay slabs over 2-¼" pumice base rock. The first level is 15' from ground floor to podium deck.

Appendix C: Natural Building Material Assemblies

Design and spec guidance for these assemblies

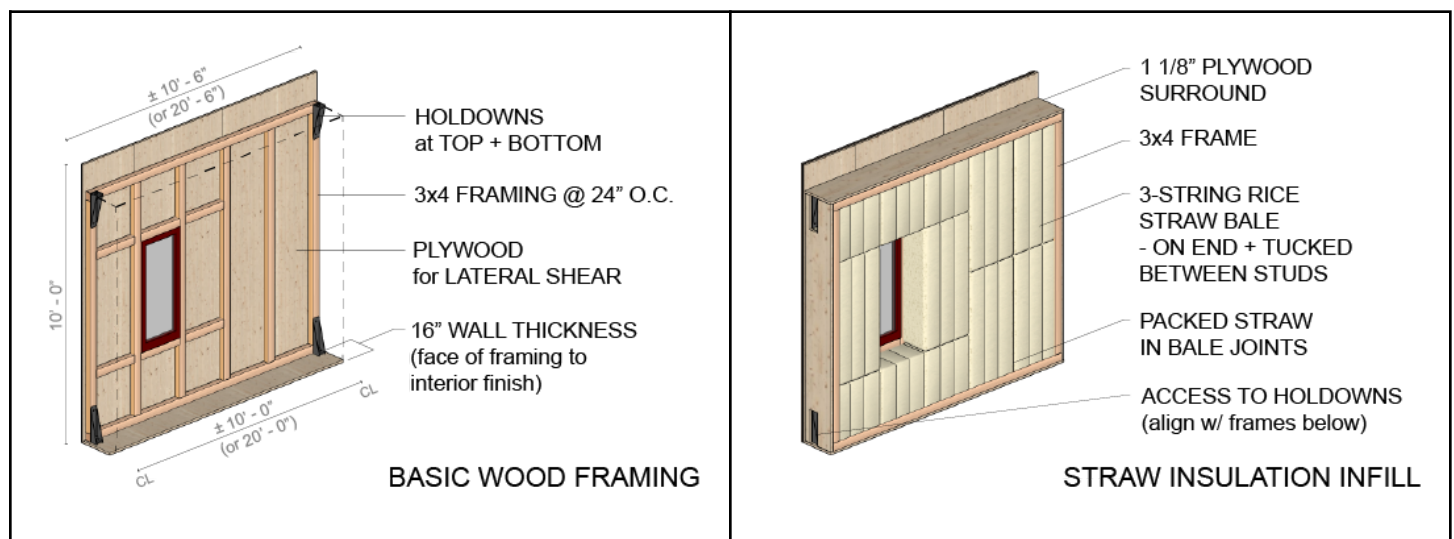
Strawbale walls

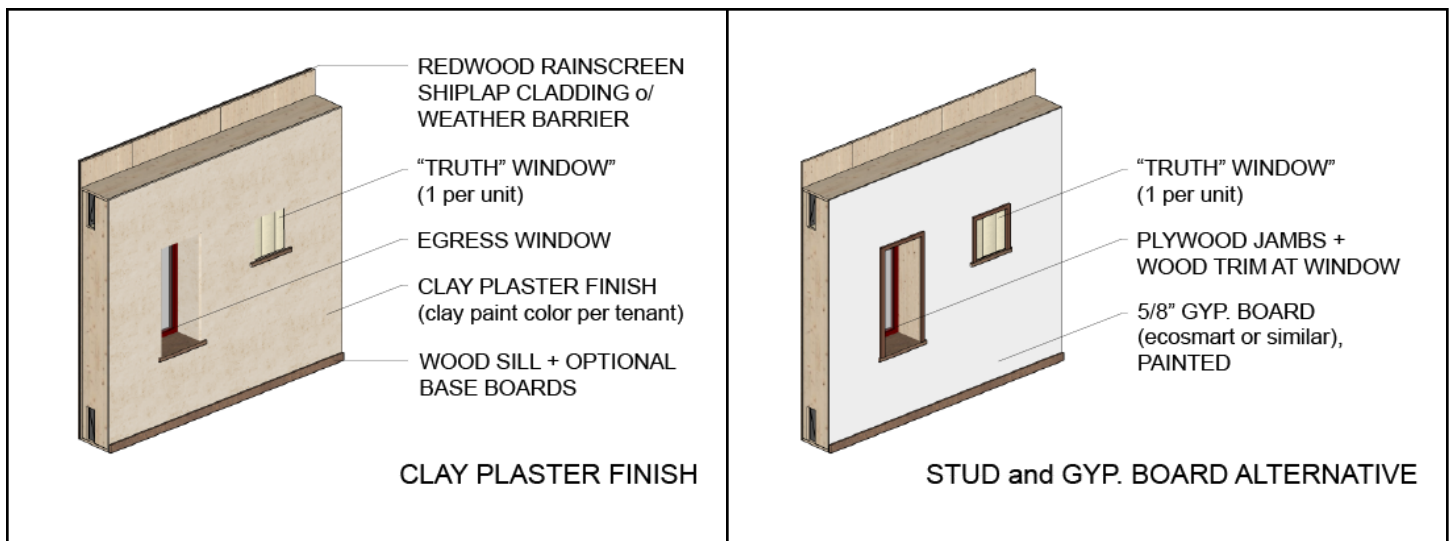
Straw-based building products have been in development in California ever since the state banned straw burning in 1995, driving a need to remove straw from agricultural lands. When not collected for other uses, straw is left to slowly decompose in place, adding more silica content to the soil, slowly degrading its quality to support vegetation. Farmers will also often try to accelerate the decomposition by flooding the land, which uses more water in an already water-intensive agricultural process. In addition, the flooding cycles associated with rice growing are one of the drivers of high methane emissions that can result from growing rice.

When a product of conventional agricultural practices, straw is a waste material generated annually as a byproduct of grain production. Globally, farmers frequently deal with this waste by burning it or selling as low-value material. In California, burning straw was banned, but by utilizing straw as a building construction material, a waste is turned into a high value resource. At end-of-life, straw is also compostable and non-toxic, as compared to more conventional building materials that straw can replace.

Furthermore, when produced in combination with regenerative agriculture (multispecies and perennial crops, reduced tillage, cover cropping, organic pest management, integrated managed grazing, etc.) the carbon storage benefits can as much as double with sequestration in the soil, as well as increased soil health for the long term. This is further explained under the Climate-Friendly Sourcing section.

The method of assembly for the exterior straw-based wall of our carbon-storing prototype is shown below:





As noted in Strategy #1, the use of strawbale construction as load-bearing walls is codified in Appendix S of the International Residential Code (IRC), and was included in the 2019 California Residential Code, adopted by the Department of Housing and Community Development for statewide use, starting January 1, 2020. Appendix R Light Straw Clay Construction, from the 2018 IRC, was included in the 2019 California Residential code, for voluntary use by local jurisdictions. This code includes prescriptive guidelines for simple buildings, as well as reference guidance for larger and nonresidential projects. Structural properties and detailing are also covered in the code, and discussed in greater depth in the Appendix S Code with Commentary, available for free download from the California Straw Building Association (CASBA) website [here](#).

While the CSB prototype does not rely on straw bales for structural support, this code addresses concerns that building designers and officials may still have when using it as the primary exterior insulation and in other forms throughout the building. Such issues include moisture content and concerns, bale suitability and density, use of partial bales, plaster finishes and their permeability needs, and other important aspects.

Pre-fabrication

As noted previously, building the wall could be made more efficient, consistent, and economical if prefabricated. Moving the construction off-site could further industrialize the process.

The prefab process requires a covered, relatively enclosed area with the capacity for good airflow. Panels will be assembled flat and then tilted up for drying and finishing the plaster. Clay plaster dries relatively slowly, so the process can be accelerated with fans and/or industrial dehumidifiers. To maximise efficiency use of space during the prefab process, a row of panels should be laid out as a group. These are completed to the point where they are tipped vertically and left to dry, and then another row should be laid out behind them. Clay plasters are typically finished in at least two coats, which is how these panels are designed, but developing plaster mix designs that can create a finished surface with one coat would help reduce the cost of the panels, and would be a worthwhile detail to prototype.

Earthen floors

Modern earthen flooring is a descendant of traditional earthen flooring methods from Mexico, Japan, and other parts of the world. Wet clay is combined with various aggregates and reinforcing fibers, poured and compressed in place, and sealed and hardened with thinned boiled linseed oil which will prevent dusting. The floors can be additionally finished with a variety of natural waxes for additional resistance to wear. Earthen floors are cleaned normally, though harsh cleansers should be avoided, and can be repaired by sanding and refinishing or patching. They are softer than concrete or hardwood but harder than fir or other relatively soft floors. There is the option of a premixed earthen floor, Claylin, or of creating custom floor mix designs with locally available clays and aggregates. A finish layer of clay floor is typically $\frac{3}{4}$ " thick and can be installed over multiple substrates, including compacted gravel and a clay subfloor, concrete slab, wood, or gypcrete.

Clay floors as they are currently constructed are adequate for this context; however, for buildings of this type it may be useful to continue developing the typical clay floor mix design to yield floors that dry more rapidly than a conventional residential clay floor, are easily pumped, and can achieve a greater range of colors. These objectives could be accomplished by adding a small amount of non-cementitious pozzolan (such as slag) to the mix, working with light-colored aggregates, and prototyping a wider range of sealants for finishing the floor surface.

In current practice, clay floor mix designs are typically developed from subsoils excavated from the site or nearby. Because subsoils vary from site to site, and because clay floors can express a range of colors and textures, mix designs are usually custom. This is particularly true of the greater Bay Area and California coast ranges because of the geological history of the coast. While this current form of practice may need to be adapted for scaling up even in a localized way, the ability to use hyper-local materials in construction is worth highlighting from a land management perspective.

Clay construction is a form of masonry, and materials used in masonry typically require large-scale, high-impact excavation and processing. Clay floors and plasters are low carbon primarily because they require very little processing and transport. In addition, they offer the advantage of sourcing from many small excavations in a landscape, rather than one big mine. While this may sound prohibitive to scaling up in the way that materials typically scale in the built environment, relatively decentralized clay sourcing allows for landscape disturbances that are relatively small and easy to heal. Creating a more formal mix design lab would considerably streamline the process of using varying site clays. In addition, there are two relatively local mines that provide good, consistent clays for clay floors and plasters: Gladding-McBean in Lincoln, CA, and Nunn's Canyon quarry in Napa. Scaling up bio-regionally would likely be a combination of both approaches, as well as identifying other appropriate local quarries

Other bio-based materials

For more detail about the panelized system proposed here, and other emerging methods for building with straw, please see Appendix H - 'Time to Give Straw Another Look', an article featured in Green Building Advisor. The article also contains a broader discussion of straw and other bio-based resources that store carbon

Of important note is BamCore, a product of Global Bamboo Industries Inc., which is a panelized wall system of considerable strength that can be used in construction Type 3A applications. It is used on the lower storefront of the CSB prototype. While BamCore does not offer the waste-utilization benefit

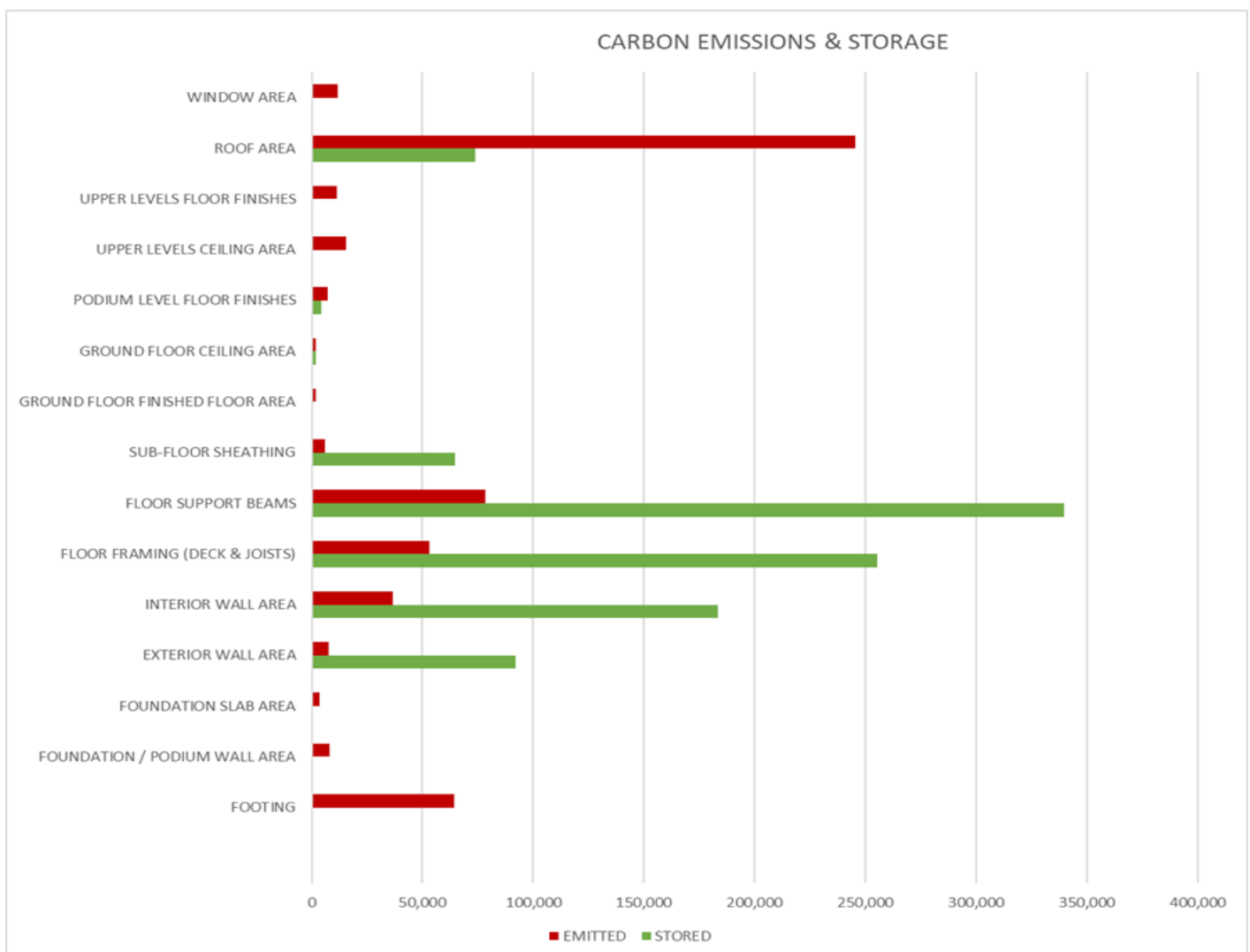
of straw, it may be a more attractive product for taller buildings due to its prefabricated, panelized nature. Learn more about Bam Core [here](#) and its carbon storing potential [here](#).

Another system option discussed in Appendix C is straw bale walls that are lime plastered on both sides. These have been tested to achieve a minimum 2 hour fire rating, and offer yet another possible carbon-storing Type 3A exterior wall panel. While bale and lime-plaster walls would have eliminated the need for additional structural frame and exterior cladding, they were deemed less suitable for the height of the CSB prototype and the authors' desire to show an assembly with potential for scalability through prefab panelization.

Appendix D: BEAM Calculator Results

The Carbon-Smart Building design described in Appendices B and C approximately results in the following amounts of carbon emissions and storage in the various parts of the building, as categorized by the BCA BEAM calculator results. As noted earlier, the amount stored is over twice the amount emitted. After the end of life of the building materials that store carbon, it is likely that the carbon will be released back into the atmosphere, in the form of CO₂ due to burning for energy, decomposition, or in the form of methane (CH₄) if landfilled.

The temporary nature of CO₂ sequestration in bio-based products is why the CO₂ stored is tracked separately from the permanent CO₂ emitted in manufacturing of the products. Delaying the release of CO₂ from these products, through reusing our buildings, reusing building components when we build new buildings, and even recycling to some extent, help prolong the storage of CO₂, essentially “buying us time” in our need to reduce emissions over the next few decades we have left to curb climate change.



Appendix E: Climate-Friendly Sourcing

Wood

The terms “sustainable forest management” -- and in particular “sustainable forestry” -- are often used in a way that unfortunately conflates replenishment of above ground biomass, i.e. the trees, with broader management practices that do more than business-as-usual, which is simply maintaining carbon stores in forests at a broad national scale over time. Whereas certified wood (or wood verified by other means to be sourced from managed forests) help provide some confidence in replenishment of trees removed, climate-friendly wood sourcing refers to practices that prioritize carbon sequestration, climate change mitigation, and resilience to global warming impacts. For example, climate-friendly sourcing aims to optimize growth cycles for carbon sequestration, which means letting the trees age and store more carbon before cutting them down, and to manage forests for resilience against future climate hazards, such as through selective thinning and restoring biodiverse ecosystems which have shown to be more resistance to wildfires.

Recent research from EcoTrust⁷ shows that, on average, forests managed to these higher sustainability standards (in this case, those certified by the Forest Stewardship Council, FSC) sequester more carbon per board foot than forests managed in a business-as-usual (BAU) scenario. Based on EcoTrust’s study of the Pacific Northwest region forests, Arup has approximated that the amount of carbon that can be sequestered in forests with climate-friendly management practices is on the same order of magnitude as the amount of biogenic carbon stored in the wood products, i.e. Strategy #10.⁸ While the basis for these studies is currently limited to the coastal douglas fir regions of the Pacific Northwest, this is the primary source for lumber for the whole western US. Meanwhile, Ecotrust and their Climate-Smart Wood partners are seeking support to expand the study to other US forest regions. For more information or to get more involved with this group, visit <https://us.fsc.org/en-us/newsroom/newsletter/id/1073>

Challenges

Owners are often reluctant to pay a premium for FSC or other verification of practices that correlate with increasing carbon stocks of managed forests. Sometimes finding FSC certification for the entirety of large volume orders or some specific wood products at the right time can also be challenging. While slightly more expensive than conventional wood, incentivizing climate-friendly wood is a more effective means to reduce greenhouse gas emissions. Otherwise, owners can consider purchasing high quality carbon offsets specifically from forest projects to support the climate-friendly practices desired across our wood industry.

⁷ Diaz et al, 2018: “Tradeoffs in Timber, Carbon, and Cash Flow under Alternative Management Systems for Douglas-Fir in the Pacific Northwest”, *Forests* 2018, 9, 447; doi:10.3390/f9080447

⁸ Sperry, R, “Proposed Methodology for Assigning Sequestered CO₂ from “Climate-Friendly” Forest Management to Timber used in Long-Lived Building Products,” Arup, 2021
<https://www.arup.com/perspectives/publications/research/section/forestry-embodied-carbon-methodology>

Straw

For straw and other annually produced agricultural fibers (like hemp), climate-friendly sourcing is primarily referring to a group of land management principles and practices known collectively as “regenerative agriculture.” Regenerative agriculture includes multispecies and perennial crops, reduced tillage, cover cropping, organic pest management, integrated managed grazing, and other alternative methods of cropland management. These practices increase resilience, soil health, water retention, and nutrient uptake, and as a result, significant amounts of carbon are removed from the atmosphere and stored in the soil. Some of this carbon will return to the atmosphere relatively quickly in both conventional and regenerative systems, but in a regenerative system, stable soil carbon—which remains in the soil for decades or centuries—increases over time. This is the reverse of agriculture that depends upon industrial fertilizer and other chemical inputs, which tend to strip carbon from soils and convert it to atmospheric carbon. As well as helping to reverse climate change directly, rebuilding soil carbon is essential for creating agricultural systems that are resilient enough to handle the increased climate instability that we are already experiencing, with presumably more to come.

Agricultural and grassland soils offer an important opportunity on a global scale for responding effectively to climate change. Restoring and protecting soils globally could remove 5.5 billion tons of carbon dioxide per year from the atmosphere, and 60% of that amount is the potential result of restoring degraded agricultural soils. Even more importantly, soil restoration is a relatively inexpensive carbon drawdown strategy, with many important co-benefits as described above. The amount of carbon that can be stored per acre of cropland varies depending upon the type of soil and what is being grown in it, but a commonly accepted range is from 0.2 tons to 3+ tons of carbon sequestered per acre per year, and some figures are even higher.

Challenges

Climate-friendly straw does not yet have a fully developed tracing system comparable to the chain-of-custody system for FSC wood. However, certifications such as the Savory Institute’s ecological outcome verification (EOV) for the products of regenerative agriculture, and the Nori methodology for establishing carbon credits for climate-friendly agriculture offer a framework that comes close to capturing the same information. The question of allocation is also tricky, since straw is usually one of several products that come from a given regeneratively managed field in a given year. Because the main purpose is to reward and support farmers who are practicing climate-friendly farming, the EOV methodology is currently moving toward certifying ecosystem services, including carbon drawdown, as products that are separate from the physical products produced by the land and the farmer. The result is much simpler for farmers and investors, but for the purposes of this report it is difficult to assess exactly how much more carbon storage is associated with growing straw regeneratively. CASBA and the Savory Institute are collaborating on a paper that examines this question in more detail.

Climate-friendly agricultural practices are a rapidly developing field, including verification and chain-of-custody systems. These may come at a cost premium compared to conventional straw. This is actually desirable because then the market can reward and support a transition to regenerative agriculture. It is a tangible example of how the built environment can become a driver for regenerative and resilient land management practices.

Other bio-based materials

The concepts presented above for wood and straw can be extended to nearly all other biobased materials. The idea that the building industry can generate more attention and awareness of the wider impacts of where construction materials come from applies to all building products made from raw materials grown from the earth. In this way, the built environment can create the investment necessary to store more carbon in our forests and crop lands and strengthen stewardship of our natural environment.

Appendix F: Engineering Approach

Carbon Storing Building Engineering Approach by Verdant Structural Engineers

The engineering of a concept project can be more complex than a structure with strictly defined parameters and also can be simplified through focusing only on aspects relevant to the pursuit and defining favorable parameters where inconsequential. Below is an explanation of the balancing of these issues in the engineering of the Carbon Storing Building.

1) Location

This structure is intended to be applicable to most, reasonable locations in the East Bay. Areas similar to downtown Oakland, Berkeley, Albany, and Walnut Creek. This is primarily relevant to structure as it relates to seismic forces and soil capacity.

a) Seismic

The values shown on the table below are very similar to those obtained from the USGS for a building located in the City of Berkeley downtown region.

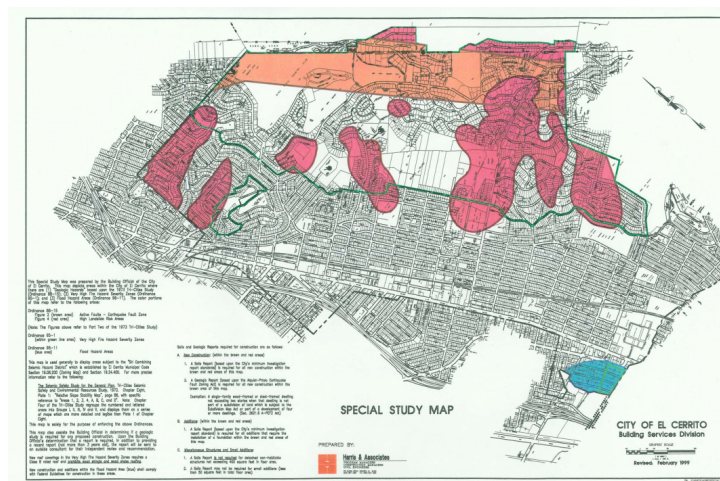
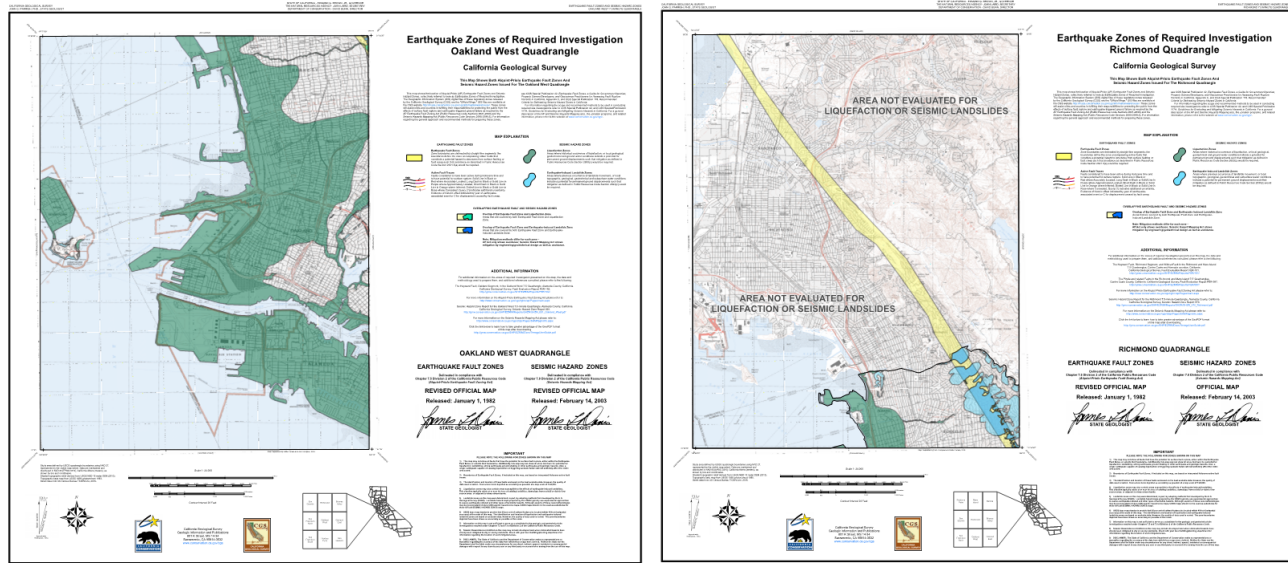
Though Seismic design category E is prevalent in the East Bay, it is not common in areas zoned for this type of structure. Therefore, it was decided to limit this design to a highly loaded case in SDC D.

From USGS:

Site Class:	D
Ss :	2.400 g
Sms :	2.400 g
Sds :	1.600 g
S1 :	1.000 g
Sm1 :	1.500 g
Sd1 :	1.000 g
Risk Cat :	II
I :	1
SD :	D
p :	1.3

b) Soil

The primary characteristics of the soils of the East Bay are defined on the maps below:



For practicality, it was decided that the design would be conducted considering a 4000 psf total load soil bearing strength.

If the project is located in an area of weak soil warranting soil bearing strengths of less than 4000psi or a foundation system other than a spread solution, such as pier and grade beams, it is assumed that soil augmentation techniques will be employed to strengthen the soil in close proximity to the structure if applicable. Soil augmentation such as geopiers can utilize rammed earth type technologies in the pier design, significantly limiting additional cement use. Though this technique still requires some embodied carbon.

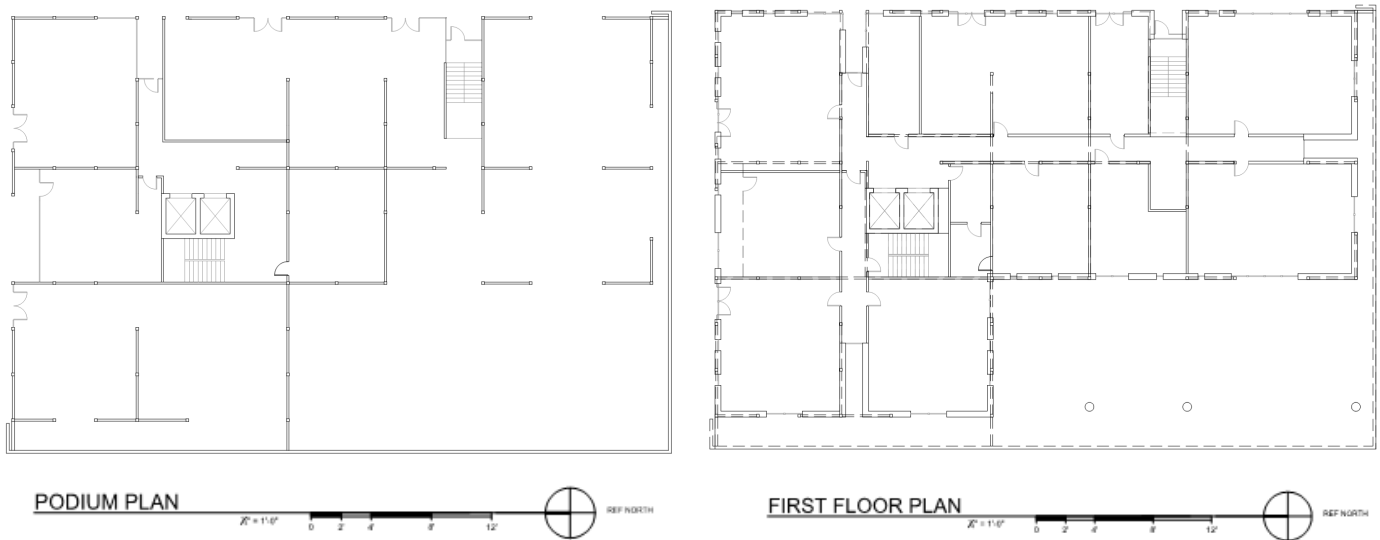
A required depth of 2'-0" was used for the foundations in this document. Other depth requirements in this region are reasonable, though with close attention and collaboration with a geotechnical engineer limiting foundation depth to 2'-0" is possible.

2) Architecture

- Podium height: 15ft
- Floor height: 10ft
- Number of stories: 4
- Podium area: 14545 sf
- Floor area: 10560 sf

a) Floor plan

The floor plan provided by Arkin and Tilt Architects that was used on the modeling of this project is below.



b) Loads

The loads considered on the analysis of each system are shown below:

- Balance was determined considering appropriate CLT span vs dead load vs required beams.
- Balance was determined considering appropriate clay thicknesses vs weight.

Loads

Strawbale		Fiberglass	
EXTERIOR WALLS	PSF	EXTERIOR WALLS	PSF
Wood Siding	2.5	Wood Siding	2.5
1/2" Sheathing (2 side)	4.5	1/2" Sheathing (2 side)	4.5
3x4s @24"	1.1	3x4s @24"	1.1
1" Clay	9.6 (115 pcf)	5/8 gypboard	2.8
Insulation Bale 15"	10.0 (8 pcf)	Insulation fiberglass 6"	0.4 (1.5 pcf)
Misc	2.0	Misc	2.0
DL= 30.0		DL= 13.5	
INT. STUD WALLS	PSF	PODIUM PANDECK	PSF
SHEAR WALLS	10.0	5" Slab	50.0
DL= 10.0		Misc	2.0
		MEP	2.0
ROOF	PSF	DL= 54.0	
PV	5.0	LL= 40.0	
12" TJI Framing	3.0	PODIUM CEILING 50%	PSF
Insul. D.P. Celullose	3.5 (3.5) pcf	5/8 gypboard	2.8
Misc	2.0	2x4s @24"	0.4
Slope Adj 2:12	0.2	Misc	1.0
DL= 18.0		DL= 4.5	
LL= 20.0			
UPPER FLOOR	PSF	PODIUM PT SLAB	PSF
3/4" Sheathing	2.5	8" Slab	100.0 150 pcf
12" TJI Framing	3.0	Misc	2.0
Insul. D.P. Celullose	3.5 (3.5) pcf	MEP	2.0
Misc	2.0	DL= 104.0	
3/4" Clay	7.2 (115 pcf)	LL= 40.0	
DL= 18.0			
LL= 20.0			
PODIUM CLT	PSF		
3/4" Clay topping	7.2 (115 pcf)		
CLT (191V) t=7.5"	16.3 Max span 14 ft		
MEP	1.5		
Cork	0.3 (7 pcf)		
Misc	2.0		
DL= 27.5			
LL= 40.0			

MATERIALS DENSITY WEIGHT	
Clay	115.0 pcf
Bale	8.0 pcf
Fiber glass	1.5 pcf
Insul. D.P. Celullose	3.5 pcf
Cork	7.0 pcf

3) Structural System

a) Force-Resisting Systems

Different lateral systems were considered, in search of the most efficient and environmentally friendly system to suit the purpose of this project. The analysis of systems are not included in this report.

Table of System Options:

System	Description
--------	-------------

System 1	3 Plywood Shear Wall Stories & CMU Shear Walls below separated by CLT podium (Spread ftg) (1) (2)
System 2	3 Plywood Shear Wall Stories & HT-BRB below separated by CLT podium (Isolated ftg w/thickened edge) (2)(3)
System 3	4 Stories of HT-BRB (Isolated ftg w/thickened edge) (3)

(1) Fully grout vs partial grout vs Block PSI of Watershed block option still needs to be explored.

(2) 3x4 studs for all plywood options

(3) **Heavy Timber - Buckling Resisted Brace (HT-BRB)**

All plywood shear walls and brace frames are assumed to have an aspect ratio of at least 1:1.

Coefficients and factors for the Force-Resisting Systems

A. Bearing Wall		A. Bearing Wall		D. Dual System	
15. Light Framed w/WSP		7. Special Reinf. CMU wall		12. Heavy Timber Encased - Steel BRB	
R =	6.5	R =	5	R =	8
Ω_o =	3	Ω_o =	2.5	Ω_o =	2.5
Cd =	4	Cd =	3.5	Cd =	5

b) Force-Resisting System Selection

System 2 was chosen as the lateral system for the project, this system is consistent with similar buildings in the bay area with an upper wood shear wall system over a podium.

Possible variations of System 2: The shape and length of the HT-BRB system can have significant effects on the structural outcome. Following a preliminary review, diagonal bracing was chosen due to being more flexible architecturally though less efficient structurally than a full X brace and more efficient structurally, though less flexible architecturally than a sparser brace system.

4) Models

To calculate and compare the embodied carbon of a typical building vs a carbon storage building, the following models were designed based on the architectural requirements.

Model 1 (Primary CSB Base Case, All Strategies, Except Strategy 2): HT-BRB first floor with CLT podium and wood shear walls with straw bale insulation over podium

Model 2 (Strategy 1): HT-BRB first floor with CLT podium and wood shear walls with fiberglass interior insulation over podium

Model 3 (Strategy 5b): Steel BRB first floor with pan deck podium and wood shear walls with straw bale insulation over podium

Model 4 (Strategy 5a): Concrete shear walls below a post tensioned slab and wood shear walls with straw bale insulation over podium

Componet	Area (sf)	Thickness (in)			
		SB - Building	FG - Building	PD - Building	PT - Building
Ext Wall ⁽¹⁾	10485	15	4	15	15
Int Wall	8545	4	4	4	4
Podium floor	14545	7.5	7.5	5	12
Upper floor x2	21120	12	12	12	12
Roof	10560	12	12	12	12

(1) Total wall area with no openings

5) Analysis

a) Two stage analysis.

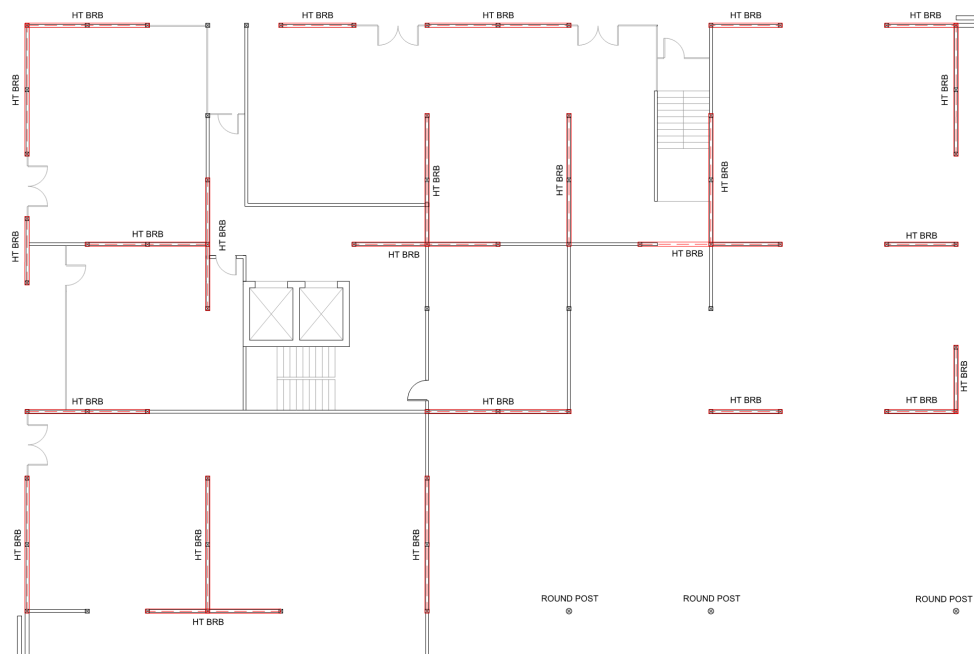
This method allows the design of the upper portion independent of the lower part using different seismic parameters that depend on the specific characteristic of the lateral resisting system.

b) Shear Wall Lines at upper stories

To perform the 2 stage analysis, the upper portion of the building was divided into plywood shear wall lines, as shown in the figure below.

c) HT- BRB location

Four shear lines of HT-BRB were considered in each direction, as shown in the image below.



d) Lateral analysis:

Upper floors

For all the models the design of the upper portion is identical. The use of conventional plywood shear walls with straw bale as insulation are capable of withstanding the lateral loads using just one side of sheathing. Some of the interior, non-bale walls must have sheathing on both sides of the wall due to greater tributary areas.

Lower floor

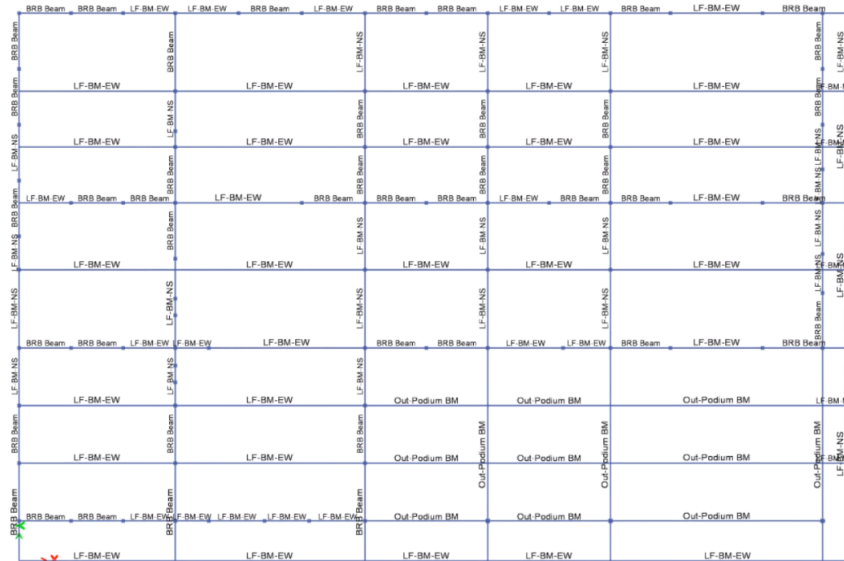
- **Model 1 and 2:** First Story HT-BRB lateral resisting system is located on the same shear lines as the walls above. The design for model 1 and 2 is identical
- **Model 3:** The steel brace frame was located at the same location as in model 1 and 2, design procedure was according to industry standards.
- **Model 4:** 10 ft concrete shear walls were designed to take the laterals loads. On each shear line between 2 to 3 of the concrete walls were located to transfer the loads from the upper portion to the foundations.

6) Elements Sizing

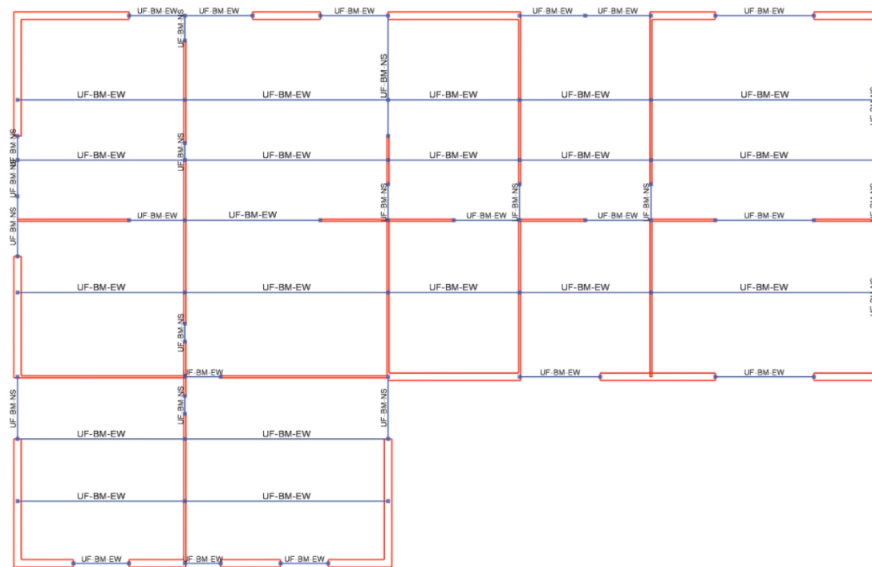
a) Framing system.

Beams were located to optimize the CLT maximum span. The beams shown on the plan below were selected to represent beam distribution for the different systems.

- Podium beams



- Upper floor beams



I) Model 1 & 2

Elemets	Total L (ft)	SB & FG Buildings Sections ⁽¹⁾
BRB Brace	783	2-4X8
Podium Floor Beams	2179	
BRB Beam	504	8.75 X 24
LF-BM-E/W	959	14.25 X 30
LF-BM-N/S	356	8.75 X 24
Open Podium	360	14.25 X 42
Upper Floor Beams	2644	
UF-BM-E/W	2301	12.25 X 24
UF-BM-N/S	343	8.75 X 22
Podium Floor Posts	1245	
BRB Post	975	9X9
LF-POST	225	10.5X10.5
Round Post	45	7X7
Upper Floor Posts	2280	
Story2	760	8X8
Story3	760	6X8
Story4	760	6X6

(1) All wood beams and post are Gluelam 24F-V4

II) Model 3

Elemets	Total L (ft)	PD Building
		Sections ⁽¹⁾⁽²⁾
BRB Brace	783	HSS 6X6X1/8 + grout
Podium Floor Beams	2179	
BRB Beam & LF-BM-N/S	18	W10X112
BRB Beam & LF-BM-N/S	226	W10X15
BRB Beam & LF-BM-N/S	14	W10X17
BRB Beam & LF-BM-N/S	38	W10X22
BRB Beam & LF-BM-N/S	54	W10X30
BRB Beam & LF-BM-N/S	10	W10X39
BRB Beam & LF-BM-N/S	391	W12X26
BRB Beam & LF-BM-N/S	14	W12X40
BRB Beam & LF-BM-N/S	14	W12X58
BRB Beam & LF-BM-N/S	45	W12X79
BRB Beam & LF-BM-N/S	18	W12X87
BRB Beam & LF-BM-N/S	18	W12X96
LF-BM-E/W	575	W18X50
LF-BM-E/W	384	W18X76
Open Podium	360	W18X86
Upper Floor Beams	2644	
UF-BM-E/W	2301	12.25 X 24
UF-BM-N/S	343	8.75 X 22
Podium Floor Posts	1245	
LF-POST	225	W10X33
BRB Post	975	W8X48
Round Post	45	7X7
Upper Floor Posts	2280	
Story2	760	8X8
Story3	760	6X8
Story4	760	6X6

(1) All wood beams and post are Gluelam 24F-V4

(2) All steel beams and post are ASTM A992 (fy = 50 kips)

III) Model 4

Elemets	Total L (ft)	PT - Building Sections ⁽¹⁾
Conc. Wall L = 10 ft	220	10" thick
Podium Floor Beams ⁽²⁾	2179	
BRB Beam & LF-BM	482	10x12
BRB Beam & LF-BM	204	10x14
BRB Beam & LF-BM	333	10x16
BRB Beam & LF-BM	136	10x18
BRB Beam & LF-BM	142	10x20
BRB Beam & LF-BM	522	10x24
Open Podium	360	12x24
Upper Floor Beams	2644	
UF-BM-E/W	2301	12.25 X 24
UF-BM-N/S	343	8.75 X 22
Podium Floor Posts ⁽³⁾	1245	
LF-POST & BRB Posts	1200	10x10
Round Post	45	7X7
Upper Floor Posts	2280	
Story2	760	8X8
Story3	760	6X8
Story4	760	6X6

(1) All concrete beams and post are 3000 psi

(2) All concrete beams have an average of 1.7% of reinforcement steel

(3) All concrete column have an average of 1.8% of reinforcement steel

b) Ht-BRB system

The heavy timber –buckling restrained braced frame was designed for each of the models. To simplify the models all the BRB sections in each system are the same. See the design result on the table below. Also, see the typical section and connection of a HT-BRB system in images in the report above.

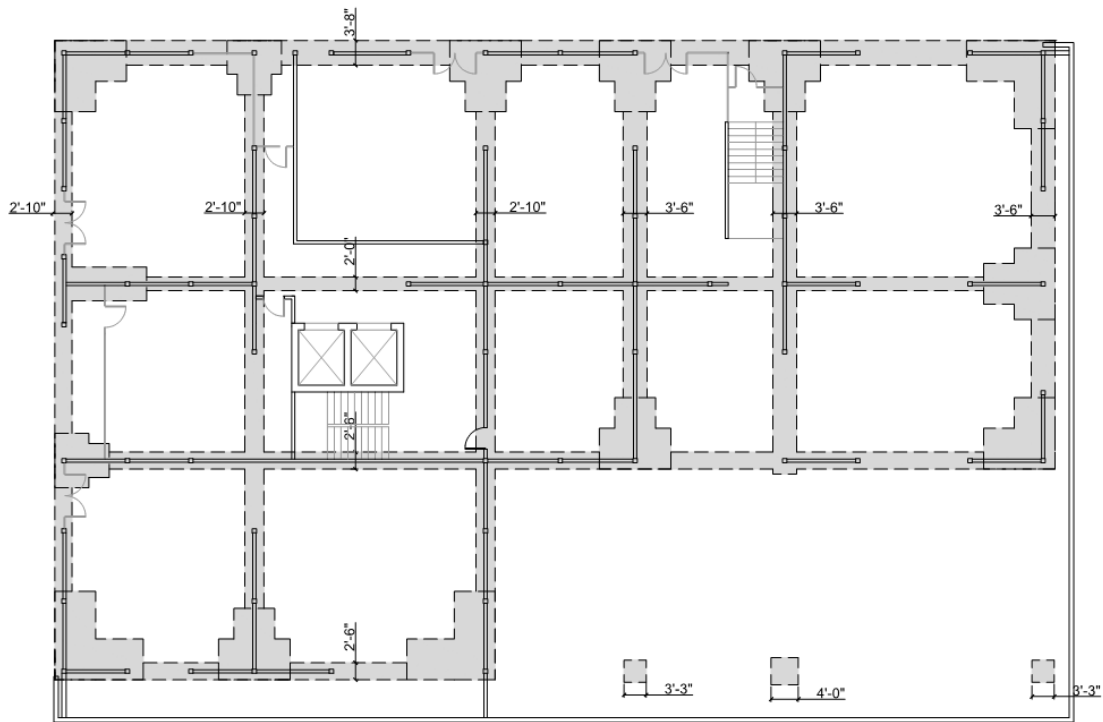
c) Foundation

The analysis of how the span direction of the CLT affects the gravity loads distribution on the foundation size was performed. For this particular floor plan, the beams are generally symmetrically distributed between the shear lines in the building that are used as bearing lines as well. All point loads from the superstructure were considered in the design of the foundations.

For the analysis of the model, the upper walls were considered stacked. All lateral and gravity loads are transferred down on the same shear line. Beams only transfer gravity loads to the lower floors.

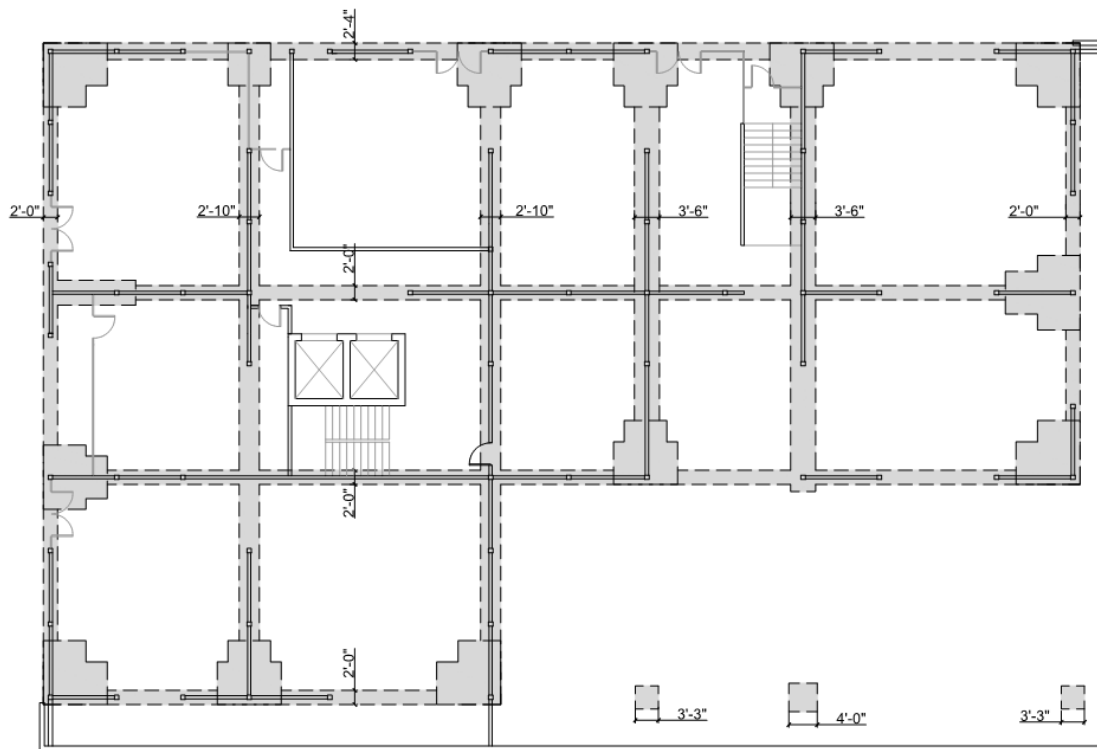
I. Foundation design, Model 1

3160.6 SF
STRAW BALE WALLS



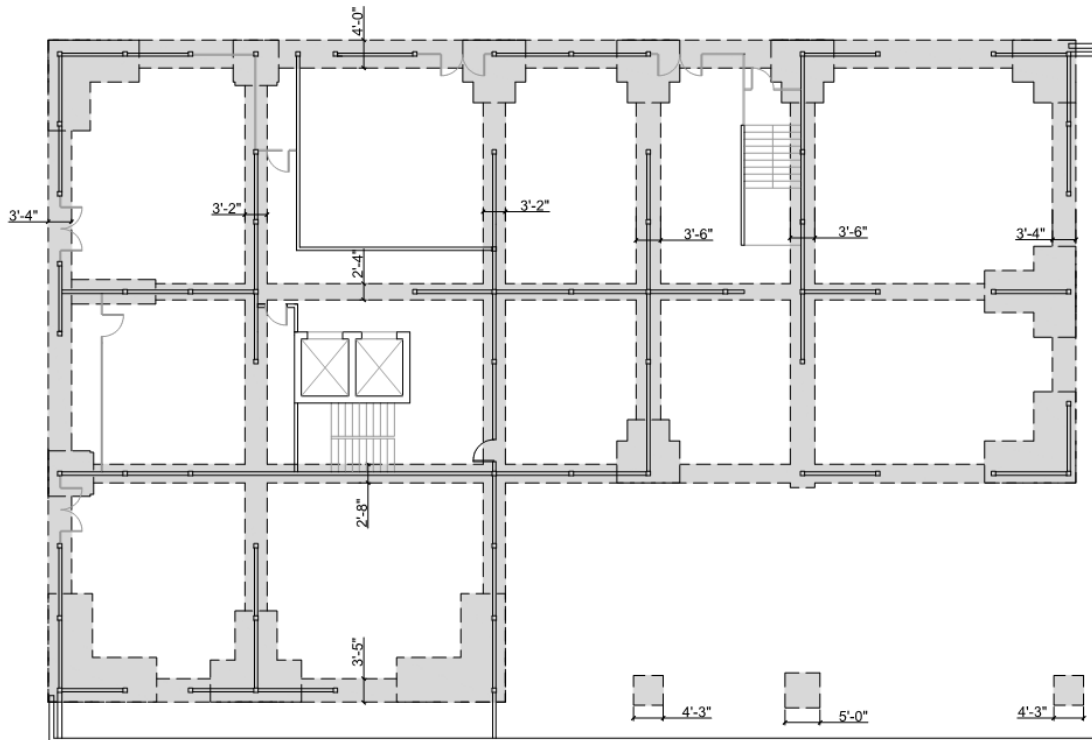
II. Foundation design, Model 2

2707.7 SF
FIBERGLASS WALLS



III. Foundation design, Model 3

3415.7 SF
PANDECK PODIUM



d) Concrete and reinforcement

Based on the design of the different models, the reinforcement of each element was estimated to be a percentage of the area of the concrete sections. These values were calculated as the average of the reinforcement, including longitudinal bars and stirrups of each element.

The results of each model were very similar, so it was possible to estimate an average percentage of reinforcement per element and generalize this result for all the models.

2500 psi concrete was used in the design of this project and supplies sufficient strength for the member sizing required. CBC and IBC Table 1808.8.1 prohibit concrete strengths of less than 3000 psi for this type of structure in SDC D. Coordination with the concrete batch plant to certify the durability of the 2500 psi mix meets the intent of the code and jurisdictional approval of this alternate would be required.

See result below:

Concrete Elements	Concrete type	Average % of reinf.
FND at GL inters.	2500 psi	1.3%
Grade Beams	2500 psi	1.0%
PT slab	3000 psi	1.0%
Conc. Beams	3000 psi	1.7%
Conc. Posts	3000 psi	1.8%
Conc. Wall	3000 psi	1.7%

(1) Reinforcement ratios applies to all building types

Appendix G: Time to Give Straw Another Look

Reprint of David's article in Fine Home Building's Green Building Advisor

BY TED CUSHMAN



The crew sets straw panels on site (1) in Leyden, Mass. In the shop, panels are assembled in a steel frame and packed with straw bales (2), then moved onto another work table (3) for installation of Gutex insulation and Intello vapor barrier.

Fighting Climate Change With Straw Panels

Buildings are a major source of carbon dioxide pollution on planet Earth. Recognizing that fact, some builders are working to lower the energy use, and thus the carbon output, of the homes they build. But there's a wrinkle: The CO₂ and other greenhouse gases emitted in the construction of a high-performance building can exceed the carbon footprint of the home's operation (especially in the near term).

However, that depends on the materials and methods used to construct the house. By using materials that capture and store carbon, builders can actually remove CO₂ from the atmosphere and sequester it in the home for the lifetime of the building. That's the approach Vermont-based New Frameworks Natural Design Build took for a recent project in Leyden, Mass. The company made the home's walls with an innovative structural insulated panel composed mostly of straw. The straw absorbs carbon dioxide from the atmosphere as it grows; when it's harvested and buried in a building, that carbon is locked up.

Every project uses energy to build, whatever the materials, and each project has to be evaluated individually, says New Frameworks founder Ace McArleton. But he says, "The calculations that have been done on a general basis about straw being used in the walls of a building is that it sinks so much carbon and stores so much carbon that the net offset gives us a huge leg up—more than any other material that we have out there."

New Frameworks is experienced in building straw-bale homes on site. But now the company is pioneering a different approach: integrating straw bales into a panelized system that the crew can fabricate in the shop, then set in a day or two on site. The method is inspired by European firms EcoCocon and ModCell. McArleton says, "As usual, the Europeans are ahead of the curve from us on these things: They're doing beautiful commercial buildings and giant office parks with straw-bale panels."

New Frameworks also learned from the work of Chris Magwood and his Ontario, Canada-based organization, the Endeavour Centre. Magwood, author of *Essential Pre-Fab Straw Bale Construction, The Complete Step-by-Step Guide*, brought New Frameworks some essential methods gleaned from a Canadian straw-bale-panel company started by one of his Endeavour Centre students. Armed with that knowledge, New Frameworks invested in basic equipment and started to build panels.

Jackson Mills, project lead for the Leyden house, explains the process. "It started with individual cut sheets for each panel from the design office," he says, "so every panel had its own design page. And we precut all the lumber and sheathing, and we had



Panel assembly takes place on tables at a convenient working height (4). This panel has Gutex fiberboard insulation, rainscreen strapping, and corner protection applied. Above, a closeup of the panel in cross section (5).

two assembly tables. One of those tables had a machined template, a kind of little cage that we built the frame inside of, to make sure that there was as little variation as possible. When we built the frame inside of that, it made sure that the frame was exact. After we built the frame, we installed the bales. Then we pulled out that panel [and moved it] onto the second assembly table. We trimmed the straw to make sure that it was exactly flush with the framing, and then installed the sheathing; and on the same table on top of the sheathing, we installed the Gutex fiberboard (we used Gutex Multitherm 60). And then it was strapping for the rainscreen on top of that, corner protection, and then we flipped it, shaved the bales down again flush with the framing, and then attached the Intello, which we used as the air barrier. And then corner protection on top of that.”

Including the Gutex fiberboard, each panel weighed about 500 pounds, says Mills. In the shop, the crew was able to roll the panels around on the assembly tables, and move and stack them using a rented forklift. On site, the crew set the panels using a telehandler.

Panels have a clear-wall R-value of about R-40, says Mills. To create a continuous air and vapor control layer, the crew taped

the Intello smart vapor retarder on the inside face of each panel to the adjacent panel on site when they set it. On the outboard face of the panels, the Gutex fiberboard forms the building’s drainage plane, and strapping outboard of that creates the air space for a rainscreen siding application.

Although New Frameworks is a design-build general contractor in Vermont, handling jobs from concept to completion, for this Massachusetts job its only function was to deliver and set the wall panels. The builder then set trusses for the roof and installed windows and doors to dry in the building. “They were able to roll up onto the site and say, ‘Whoa, there wasn’t a house here two days ago, and now there is,’” says McArleton, “and I just put the roof on, and now all I have to do is side on the outside and put the windows and doors in, and then do the inside finishes.” Intello on the underside of the trusses was taped to the Intello coming up the walls to create a continuous air control layer. The attic was insulated with blown cellulose.

Wiring on the inside of the house runs in a service cavity built with 2x2s, says Mills. Penetrations, where needed, are cut with a hole saw. “We entertained the idea of pre-installing conduit for all penetrations, but that would really require knowing down to the



Panels are set on site using telehandler forklifts. Above, a corner has been assembled from two panels on site (6). The completed walls of the house sit ready for roof trusses (7).

inch where the plumber or electrician or whoever was going to put the penetrations, so we decided against doing it ahead of time,” says Mills. “But when they do have the penetrations mapped out, they’ll hole-saw it and install the conduit, and gasket and tape to the Intello on the interior, and prime and flash tape to the Gutex on the exterior.”

Although this project is not a certified Passive House, the air-tightness goal is the Passive House standard of 0.6 ACH50.

The house is unusual, but McArleton says there was no difficulty with the local building department. “We have a fair amount of experience working with building inspectors in different municipalities because of the straw bales that we build with anyway on site,” he says. “And what we’ve found is that because straw is in the International Building Code and has fire testing—there’s an ASTM fire rating for it—we’ve moved out of the time where it’s this super wacky thing. It’s more acceptable to building inspectors overall. Really, it is cellulose insulation in a different form. So it’s not actually much of a big deal, we find, to most inspectors. And we are able to provide the ASTM testing if needed and also the IBC if needed, but we haven’t had an issue with that.”

One challenge on site, says Mills, is the need for a dead-level

sill plate. “We built the panels to such exacting standards that the transitions and connections between them are really tight,” he says, “so if your sill plate is out of level, then the connections won’t be tight. They would be off kilter to each other. It’s a double sill plate, meaning one to the interior and one to the exterior, because of the thickness of the wall. And they have to be level in both directions. We had to do some work to level the sills.”

With one house under its belt, New Frameworks is ready for more. “We’re a full design-build company,” says McArleton, “so as we’re working with owners and clients looking at potential projects, we now have this as an option to offer. Our goal as a company is to try to do at least one to two a year if we can for the next few years, just to get ourselves feeling like we’ve worked out the kinks. And then it’s a question for us of how much volume we would be interested in doing, and what that would mean for us to scale up to a larger production facility. That is still an open question for us. But we feel so dedicated to this idea taking off in the marketplace that we are excited to do it for our own projects, and then beyond that, help others to take this idea and run with it.”

Ted Cushman is a senior editor at JLC.

Appendix H: Fire Test of Strawbale Wall Assembly

ASTM E84 test report

ASTM E84-98

**SURFACE BURNING
CHARACTERISTICS**

001, Straw Bale

Report No. 16237 - 106770

May 12, 2000

Prepared For:

Katrina Hayes
818 E. Madison
Pulaski, TN 38478, U.S.A.



ABSTRACT

Test Material: **001, Straw Bale**

Test Standard: **ASTM E84-98 Standard Test Method for SURFACE BURNING CHARACTERISTICS OF BUILDING MATERIALS (ANSI 2.5, NFPA 255, UBC 8-1, UL 723)**

Test Date: **May 11, 2000**

Test Sponsor: **Katrina Hayes**

Test Results: **FLAME SPREAD INDEX = 10**
SMOKE DEVELOPED INDEX = 350

The description of the test procedure and specimen evaluated, as well as the observations and results obtained, contained herein are true and accurate within the limits of sound engineering practice. These results are valid only for the specimen(s) tested and may not represent the performance of other specimens from the same or other production lots.


Omega Point Laboratories, Inc. authorizes the client named herein to reproduce this report only if reproduced in its entirety.

The test specimen identification is as provided by the client and Omega Point Laboratories accepts no responsibility for any inaccuracies therein.



Guy A. Haby
Fire Test Technologist

Date: May 12, 2000



William E. Fitch, P.E. No. 55296
Executive Vice President

Date: May 12, 2000



I. INTRODUCTION

This report describes the results of the ASTM E84-98 Standard Test Method for SURFACE BURNING CHARACTERISTICS OF BUILDING MATERIALS (1) , a method for determining the comparative surface burning behavior of building materials. This test is applicable to exposed surfaces, such as ceilings or walls, provided that the material or assembly of materials, by its own structural quality or the manner in which it is tested and intended for use, is capable of supporting itself in position or being supported during the test period.

The purpose of the method is to determine the relative burning behavior of the material by observing the flame spread along the specimen. Flame spread and smoke density developed are reported, however, there is not necessarily a relationship between these two measurements.

“The use of supporting materials on the underside of the test specimen may lower the flame spread index from that which might be obtained if the specimen could be tested without such support... This method may not be appropriate for obtaining comparative surface burning behavior of some cellular plastic materials... Testing of materials that melt, drip, or delaminate to such a degree that the continuity of the flame front is destroyed, results in low flame spread indices that do not relate directly to indices obtained by testing materials that remain in place.”

This test method is also published under the following designations:

ANSI 2.5
NFPA 255
UBC 8-1 (42-1)
UL 723

This standard should be used to measure and describe the properties of materials, products, or assemblies in response to heat and flame under controlled laboratory conditions and should not be used to describe or appraise the fire hazard or fire risk of materials, products, or assemblies under actual fire conditions. However, results of this test may be used as elements of a fire risk assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard of a particular end use.

(1) American Society for Testing and Materials (ASTM), Committee E-5 on Fire Standards



II. PURPOSE

The ASTM E84-98 (25 foot tunnel) test method is intended to compare the surface flame spread and smoke developed measurements to those obtained from tests of mineral fiber cement board and select grade red oak flooring. The test specimen surface (18 inches wide and 24 feet long) is exposed to a flaming fire exposure during the 10 minute test duration, while flame spread over its surface and density of the resulting smoke are measured and recorded. Test results are presented as the computed comparisons to the standard calibration materials.

The furnace is considered under calibration when a 10 minute test of red oak decking will pass flame out the end of the tunnel in five minutes, 30 seconds, plus or minus 15 seconds. Mineral fiber cement board forms the zero point for both flame spread and smoke developed indexes, while the red oak flooring smoke developed index is set as 100.

III. DESCRIPTION OF TEST SPECIMENS

Specimen Identification: 001, Straw Bale

Date Received: 5/5/2000

Date Prepared: May 5, 2000

Conditioning (73°F & 50% R.H.): 6 days

Specimen Width (in): 24

Specimen Length (ft): 24

Specimen Thickness: 14-in.

Material Weight: N/A oz./sq. yd.

Total Specimen Weight: 262-lbs.

Adhesive or coating application rate: N/A

Mounting Method:

The specimen was tested on 1/4" steel rods and 2" galvanized hexagonal wire mesh.

Specimen Description:

The specimen was described by the client as "001, Straw Bale". The specimen consisted of (8) 18" wide x 38" long x 14" thick straw bales.



IV. TEST RESULTS

The test results, computed on the basis of observed flame front advance and electronic smoke density measurements are presented in the following table. In recognition of possible variations and limitations of the test method, the results are computed to the nearest number divisible by five, as outlined in the test method.

While no longer a part of this standard test method, the Fuel Contributed Value has been computed, and may be found on the computer printout sheet in the Appendix.

Test Specimen	Flame Spread Index	Smoke Developed Index
Mineral Fiber Cement Board	0	0
Red Oak Flooring	n/a	100
001, Straw Bale	10	350

The data sheets are included in the Appendix. These sheets are actual print-outs of the computerized data system which monitors the ASTM E84 apparatus, and contain all calibration and specimen data needed to calculate the test results.

V. OBSERVATIONS

During the test the specimen was observed to behave in the following manner: Steady ignition began at 1:17 (min:sec). The specimen began to char at 1:00. The test continued for the 10:00 duration. Upon completion of the test, the methane test burners were turned off and an afterflame continued to burn for 0:60+.

After the test, the specimen was observed to be damaged in the following manner: The bales were charred on the surface and smoldering inside from 0-ft. - 24-ft.



APPENDIX

DATA SHEETS



ASTM E84 DATASHEETS

Client: KATRINA HAYES

Date: 5/11/00

Time: 1:48 PM

Test Number: 3

Project Number: 16237-106770

Operator: CH/ME

Specimen ID: "001, STRAW BALE". THE SPECIMEN WAS TESTED ON RODS AND WIRE.

TEST RESULTS

FLAMESPREAD INDEX: 10

SMOKE DEVELOPED INDEX: 350

SPECIMEN DATA . . .

Time to Ignition (sec): 3

Time to Max FS (sec): 42

Maximum FS (feet): 2.2

Time to 980 °F (sec): Never Reached

Max Temperature (°F): 428

Time to Max Temperature (sec): 597

Total Fuel Burned (cubic feet): 45.49

FS*Time Area (ft*min): 21.3

Smoke Area (%A*min): 345.7

Fuel Area (°F*min): 3508.8

Fuel Contributed Value: 0

Unrounded FSI: 11.0

CALIBRATION DATA . . .

Time to Ignition of Last Red Oak (sec): 56

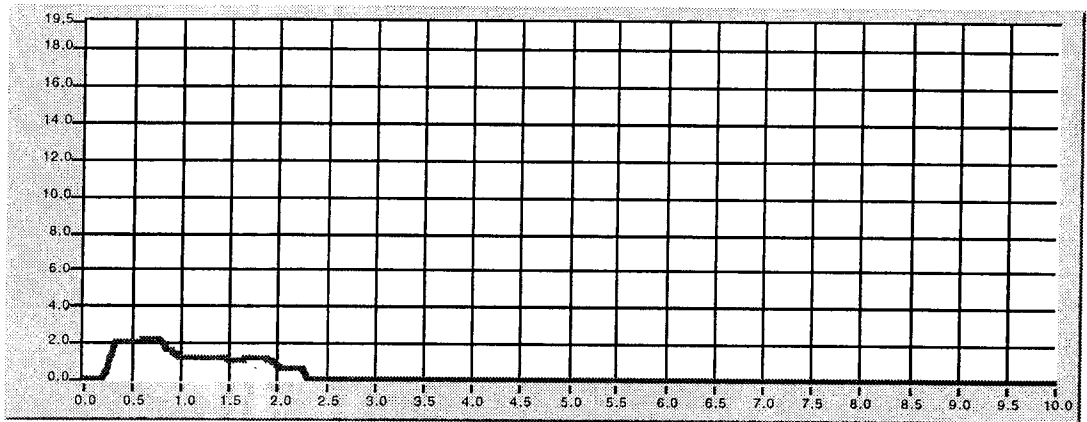
Red Oak Smoke Area (%A*min): 101.90

Red Oak Fuel Area (°F*min): 9191

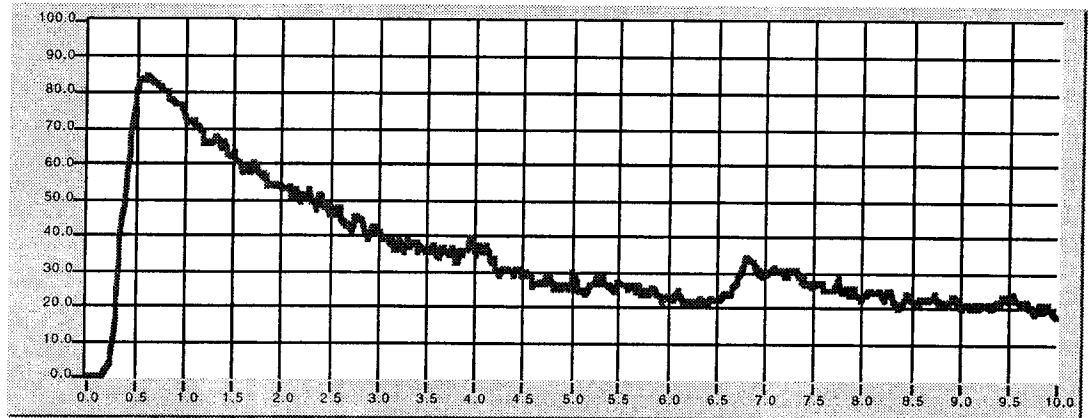
Glass Fiber Board Fuel Area (°F*min): 5185



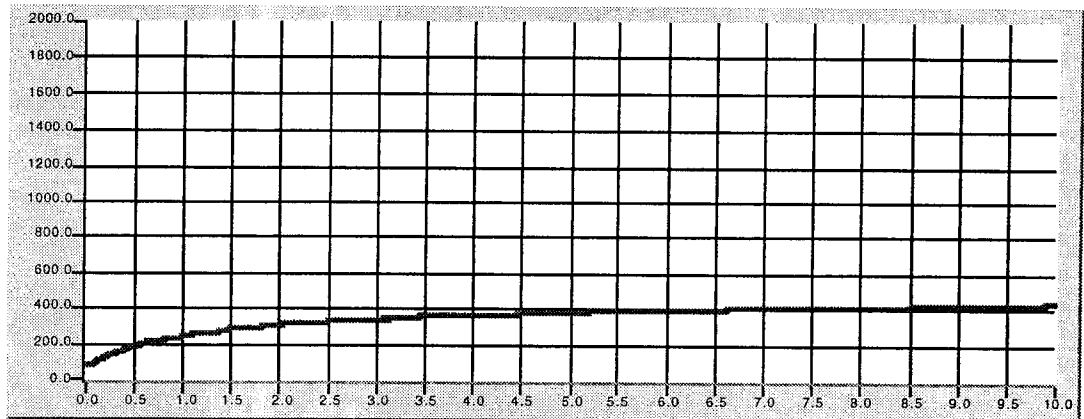
FLAME SPREAD (ft)



Smoke (%A)



Temperature (°F)



Time (min)



Appendix I: Moisture Risk of Strawbale Wall Assembly

Beyond Efficiency WUFI analysis results

MEMO

TO: David Arkin, AIA
FROM: Dan Johnson, Beyond Efficiency
DATE: 3/5/18
RE: WUFI Analysis of Strawbale Walls

Objective

To assess the natural drying ability of a conventional wood frame wall insulated with full size strawbales in several climate zones. This assessment will help determine the risk of moisture damage in each climate zone and help inform the selection of exterior sheathing and Water Resistant Barrier (WRB) materials.

Background

The basic wall assembly, described by David Arkin 10/24/17. From the outside - in:

- Cladding (a rain screen of some sort, allowing for moisture to escape while shedding direct water)
- High vapor permeable building wrap - FortiFiber [WeatherSmart Commercial ESR-3515, 15 perm] or similar: <https://www.fortifiber.com>
- 1/2" CDX plywood sheathing
- 2x6 studs at 24" on center
- 3-string straw bales stacked on-end, tucked between studs, $\pm 15"$ (5 1/2" between studs plus ± 9 1/2" all straw)
- $\pm 1"$ clay plaster (clay, sand and straw fiber)

BE set up simulations in WUFI 5.1 using the parameters outlined in the Appendix.

Conclusions

- This wall appears to do fine in cold locations, when interior humidity is kept within the "normal" 30-60%RH range. This is achieved when occupants use mechanical ventilation for cooking and showering. In the simulation, the moisture-laden indoor air that encounters the cold sheathing is insufficient to cause a moisture buildup. In very cold locations, interior humidity will be naturally lower in winter.
- This wall appears to get risky in wet locations (Eugene, Seattle), especially with high interior humidity, due to the limited drying potential for sheathing wetted by rain leaks.
- Conclusions are valid only for the specific parameters of the simulations, and should not be relied upon as the sole design criteria for these assemblies.
- This model setup remains available to test other climate zones and variations on this wall assembly.

2x6 Frame Wall with Strawbale Insulation

Martinez, California Climate Zone 12

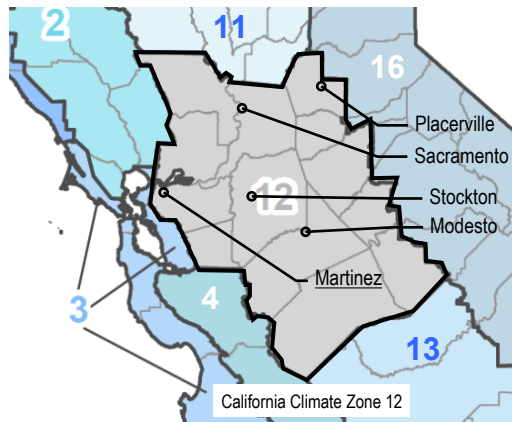
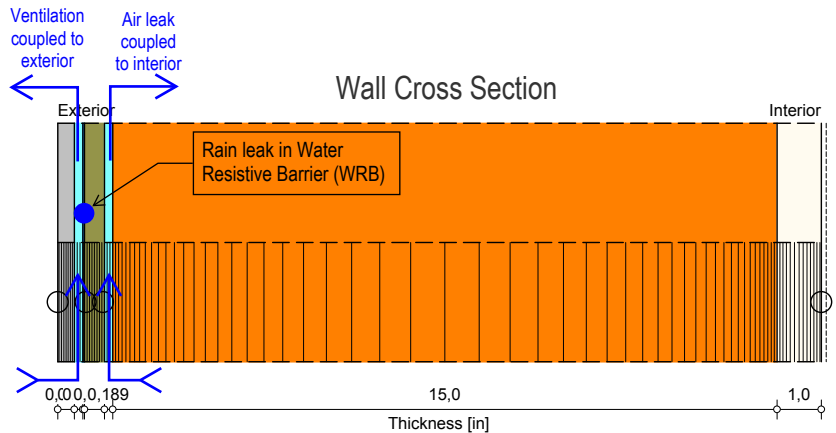
IECC Climate Zone 3B | 19" Annual Rainfall | 2600 HDD

Low Risk

Moisture risks simulated using WUFI 5.1

- 1. Built-in moisture** from natural water content of cellulose based materials and rain exposure during construction
- 2. Seasonal rain leakage** due to construction imperfections
- 3. Condensation** on the inner side of sheathing, derived from interior humidity that is driven by exfiltration and vapor diffusion into the wall

Simulation is started in October so that materials go through a cold winter before they have a chance to fully dry from construction moisture



Assembly from outside to inside:

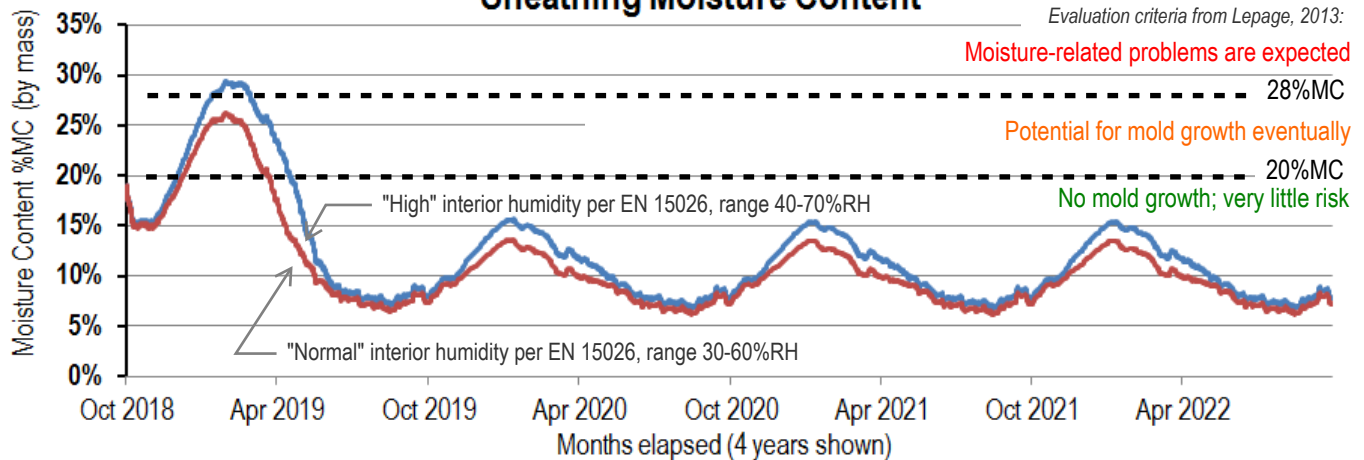
- Cement Board (generic exterior cladding)
- Air gap 3/16" with ventilation 20ACH coupled to exterior
- Water Resistive Barrier (WRB)
(e.g. Fortifiber WeatherWrap Commercial, 14 perm)
 > Rain leak equal to 2% of rain that adheres to cladding
- CDX Plywood sheathing, 1/2", 19% initial moisture content*[1]
- Air gap, 3/16" (unintentional)
 > Air leak 10 ACH coupled to interior, to simulate exfiltration
- Strawbale, 15", 20% initial moisture content*[2]
- Clay Plaster interior finish, 1"

*Moisture content (MC) as percent of dry mass

[1] Ref. CALGreen 4.505.3

[2] Ref. Cal. Residential Code AS103.4

Sheathing Moisture Content



Simulation conditions

- Exterior surface coating: [no coating]
- Short-wave radiation absorptivity: 0.8
- Long-wave radiation emissivity: 0.9
- Interior surface coating: 10 perm, latex paint

About this Report

These findings are for informational purposes only and are not intended as a comprehensive hygrothermal analysis. Design considerations should not rely on this report as the sole means for predicting assembly performance.

www.BeyondEfficiency.us | 415-236-1333



2x6 Frame Wall with Strawbale Insulation

Truckee, California Climate Zone 16

IECC Climate Zone 4B | 29" Annual Rainfall | 194" Annual Snowfall | 7500 HDD

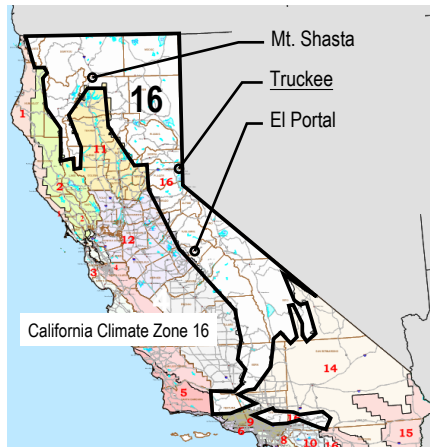
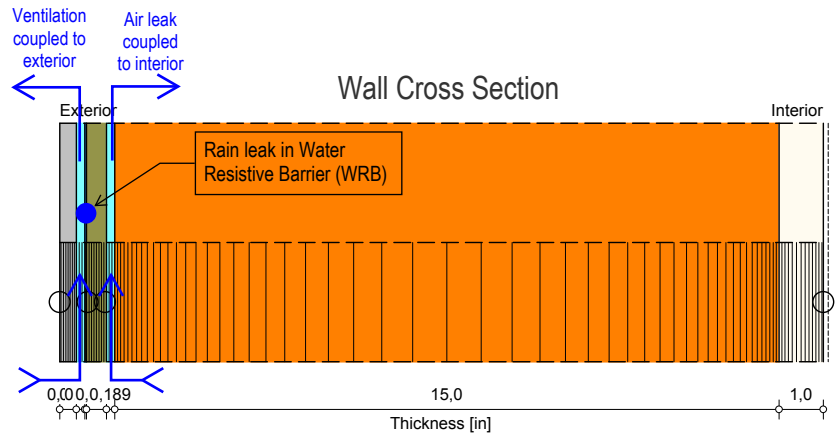
Low Risk

Elevated risk with high interior humidity

Moisture risks simulated using WUFI 5.1

- 1. Built-in moisture** from natural water content of cellulose based materials and rain exposure during construction
- 2. Seasonal rain leakage** due to construction imperfections
- 3. Condensation** on the inner side of sheathing, derived from interior humidity that is driven by exfiltration and vapor diffusion into the wall

Simulation is started in October so that materials go through a cold winter before they have a chance to fully dry from construction moisture



Assembly from outside to inside:

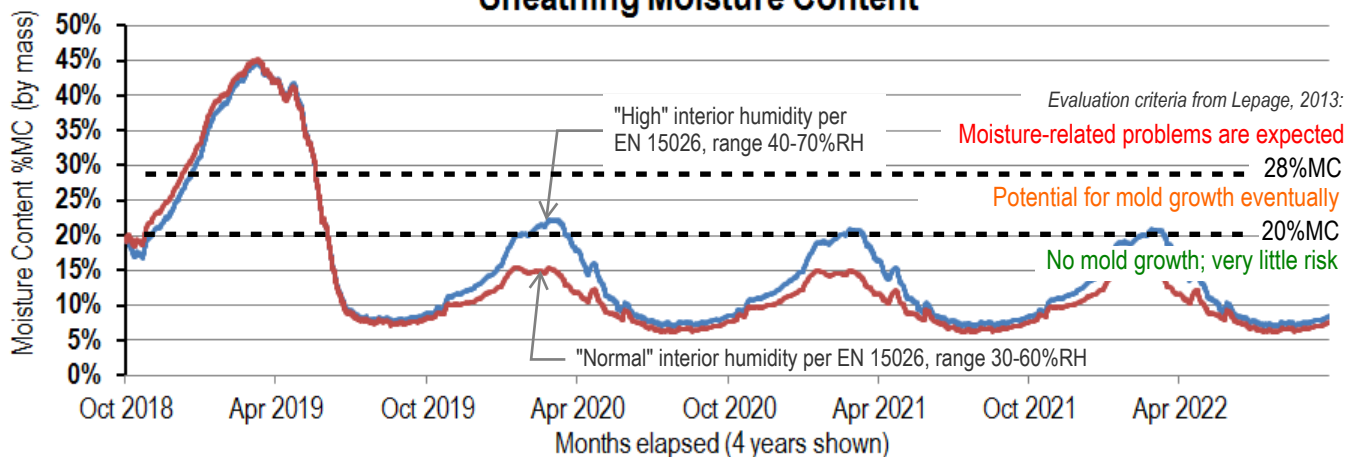
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[1] Ref. CALGreen 4.505.3

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Simulation conditions

- Exterior surface coating: [no coating]
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- Interior surface coating: 10 perm, latex paint

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2x6 Frame Wall with Strawbale Insulation

Eugene, Oregon

IECC Climate Zone 4C | 50" Annual Rainfall | 4" Annual Snowfall | 4700 HDD

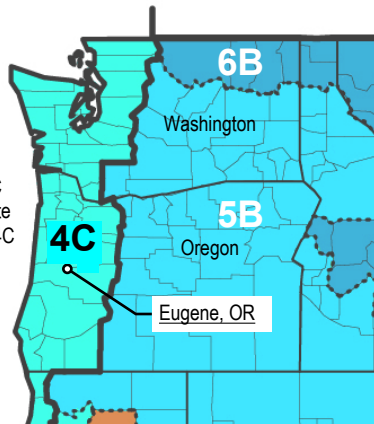
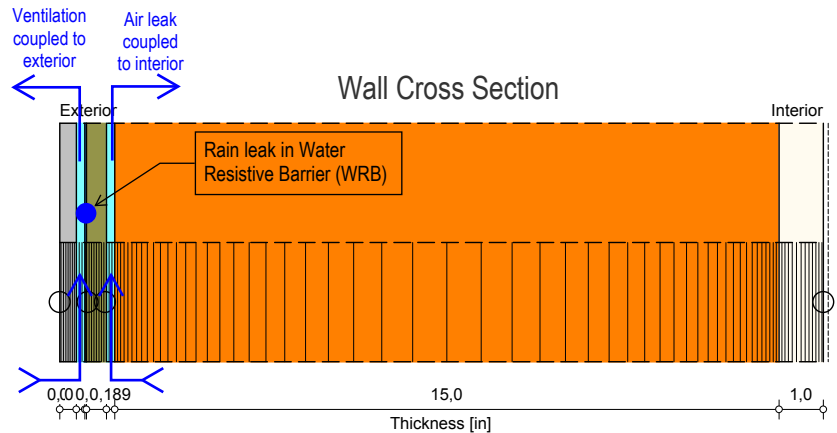
Low Risk

High risk with high interior humidity

Moisture risks simulated using WUFI 5.1

- 1. Built-in moisture** from natural water content of cellulose based materials and rain exposure during construction
- 2. Seasonal rain leakage** due to construction imperfections
- 3. Condensation** on the inner side of sheathing, derived from interior humidity that is driven by exfiltration and vapor diffusion into the wall

Simulation is started in October so that materials go through a cold winter before they have a chance to fully dry from construction moisture



Assembly from outside to inside:

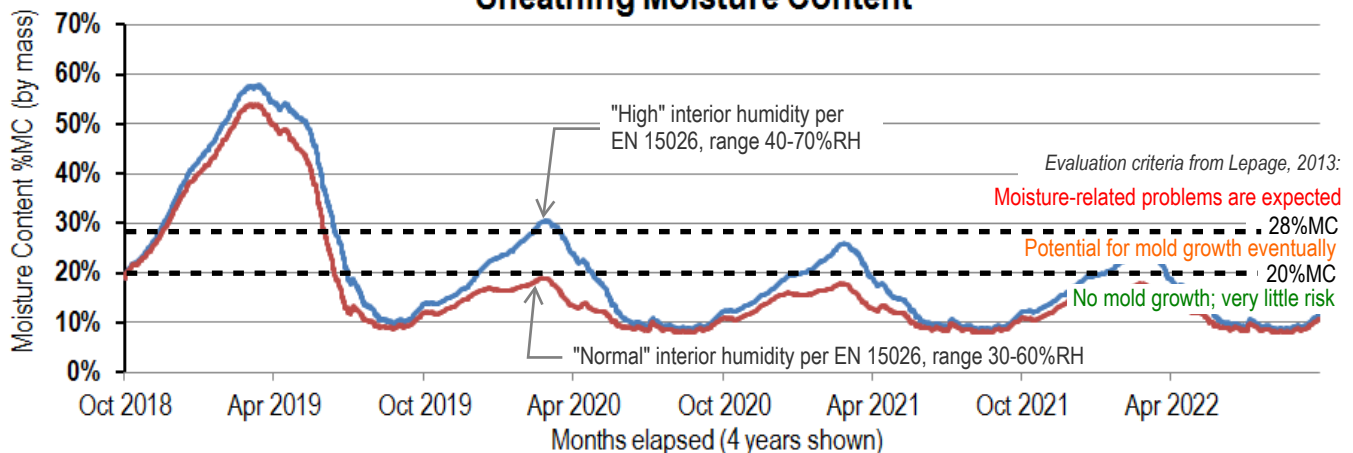
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*Moisture content (MC) as percent of dry mass

[1] Ref. CALGreen 4.505.3

[2] Ref. Cal. Residential Code AS103.4

Sheathing Moisture Content



Simulation conditions

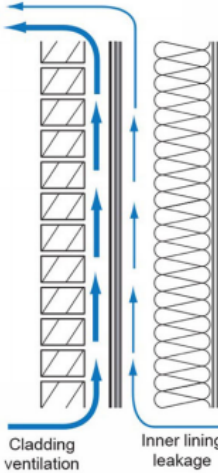
- Exterior surface coating: [no coating]
- Short-wave radiation absorptivity: 0.8
- Long-wave radiation emissivity: 0.9
- Interior surface coating: 10 perm, latex paint

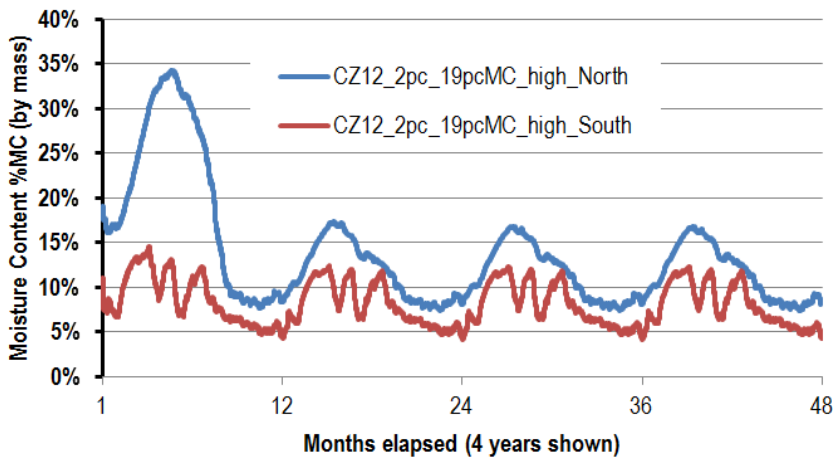
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These findings are for informational purposes only and are not intended as a comprehensive hygrothermal analysis. Design considerations should not rely on this report as the sole means for predicting assembly performance.

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Moisture risks we are simulating	<p>Moisture risks we are simulating</p> <ol style="list-style-type: none">1. Built-in moisture from exposure during construction, which must dry after the walls are assembled2. Rain leakage from the exterior. The wall must tolerate small rain leaks and still keep the moisture-sensitive (cellulose) materials dry3. Condensation on the interior faces of cold materials, derived from interior humidity that is driven by exfiltration and vapor diffusion into the wall assembly. <p>The wall must handle all three risks by drying more rapidly than wetting occurs.</p> <p>Simulation is started in October so that building materials go through a cold winter before they have a chance to fully dry from construction moisture, which is the most conservative assessment.</p>																																
Setting up air flow paths in WUFI	<p>How to set up WUFI, from <i>BSC Insight 089. Barking up the Wrong Tree</i></p> <table><tr><th colspan="4">Cladding Ventilation/Sheathing Ventilation</th></tr><tr><th></th><th>Flow Rate</th><th>Gap</th><th>ACH</th></tr><tr><td>Wood Siding</td><td>0.1 cfm/sf</td><td>3/16"</td><td>20</td></tr><tr><td>Vinyl Siding</td><td>0.5 cfm/sf</td><td>3/16"</td><td>200</td></tr><tr><td>Brick Veneer</td><td>0.15 cfm/sf</td><td>1"</td><td>10</td></tr><tr><td>Stucco (vented)</td><td>0.1 cfm/sf</td><td>3/8"</td><td>10</td></tr><tr><td>Stucco (direct applied)</td><td>none</td><td>none</td><td>0</td></tr><tr><td>Sheathing flanking flow</td><td>0.05 cfm/sf</td><td>3/16"</td><td>10</td></tr></table> <p>Table 2: Cladding Ventilation/Sheathing Ventilation—Flow rates, gap sizes and air changes per hour be for listed elements are given. The information in Table 2 comes from a combination of published work (ASHRAE 1091-RP, work done at Oak Ridge, work done at the University of Waterloo) and unpublished work.</p> <p>And leakage paths:</p> <div><p>Figure 11: Further Simplification of Airflow Pathways—The operative phrase is "further simplification of airflow pathways".</p></div> <p>Air leakage: (From <i>BSC Insight 089</i>), Assume a 3/16" gap on both sides of sheathing. With 20 ACH on the left side per table above ("Wood Siding"), coupled to the outdoors, simulating wind washing. Then 10 ACH on the right side ("Sheathing flanking flow"), coupled to the interior, simulating exfiltration. This handles the air leakage risk.</p> <p>Water leakage: (From <i>BSC Insight 089</i>), Assume 70% of driving rain adheres to cladding. Assume 1% of this penetrates WRB, therefore 0.007 fraction of driving rain penetrates WRB, deposited on exterior portion of wood sheathing layer. <i>Lepage 2013</i> increased this to 2% rain penetrating the WRB, to simulate a window leak (0.014 fraction of driving rain). BE found that results are nearly the same as 1% leakage, and used 2% leakage to be more conservative.</p>	Cladding Ventilation/Sheathing Ventilation					Flow Rate	Gap	ACH	Wood Siding	0.1 cfm/sf	3/16"	20	Vinyl Siding	0.5 cfm/sf	3/16"	200	Brick Veneer	0.15 cfm/sf	1"	10	Stucco (vented)	0.1 cfm/sf	3/8"	10	Stucco (direct applied)	none	none	0	Sheathing flanking flow	0.05 cfm/sf	3/16"	10
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<p>Initial moisture content of cellulose products</p>	<p>Initial moisture content of cellulose products:</p> <ul style="list-style-type: none"> • Bales. <i>Strawbale Code AS103.4</i> gives maximum allowable moisture content as 20% by mass. If minimum dry bale density is 6.5 lb/ft³ (<i>AS103.5</i>), and water weight is expressed as a percentage of the dry bale weight, then the max allowed water density comes out to 1.3 lb/ft³. BE used this figure for “Typical Built-in Moisture” at time of construction (initial conditions). • Plywood. CALGreen code 4.505.3 limits the allowable moisture content of wood framing members to 19% (percent of dry weight). Because no value is given for wood structural panels, BE used 19%. WUFI plywood has a dry density of 29.3 lb/ft³. Nineteen percent moisture content is 29.3 x 0.19 = 5.6 lb/ft³ maximum allowed moisture density. WUFI default initial moisture is 4.37 lb/ft³. BE increased this to 5.6 lb/ft³.
<p>Simulation conditions</p>	<p>Simulation conditions</p> <ul style="list-style-type: none"> • Outdoor climate: Per WUFI .WAC-format weather file for location specified • Indoor conditions: Per Standard EN 15026. Indoor conditions are derived from outdoor weather, using option for “high” moisture load and “normal” moisture load, as specified in reported simulation results • Orientation: Walls face north unless otherwise indicated. This is a more conservative simulation, because north-facing walls tend to stay wetter. An example chart indicating this simulation result is shown below. <p style="text-align: center;">Sheathing Moisture Content: South Exposure Stays Drier</p>  <p style="text-align: center;">Months elapsed (4 years shown)</p> <ul style="list-style-type: none"> • Exterior surface heat-resistance coefficient (air film R-value): wind-dependent, 0.3339 [h.ft².F/BTU] • Exterior surface coating: [no coating] • Short-wave radiation absorptivity: 0.8 (= 0.2 reflectivity, a dark surface) • Long-wave radiation emissivity: 0.9 • Adhering fraction of rain: 0.7 • Interior surface heat-resistance coefficient (air film R-value): 0.7099 [h.ft².F/BTU] • Interior surface coating: 10 perm, latex paint
<p>Evaluation Criteria</p>	<p>Evaluation Criteria From <i>Lepage 2013</i>:</p> <p>The peak daily OSB sheathing moisture content (MC) was determined and the risk was assessed based on the following criteria:</p> <ul style="list-style-type: none"> • Peak OSB sheathing MC < 20%, no mold growth; very little risk • Peak OSB sheathing MC 20%–28%; potential for mold growth eventually, depending on frequency and length of wetting, and temperatures during wetting. This design can be successful, but conservative durability assessments usually require corrective action • Peak OSB sheathing MC > 28%; moisture-related problems are expected and this design is not recommended.

References	<p>References:</p> <ol style="list-style-type: none"> 1. Lepage, Robert, Chris Schumacher and Alex Lukachko, November 2013, "Moisture Management for High R-Value Walls" Building America Report 1316 2. <i>BSC Insight 089. WUFI: Barking up the Wrong Tree</i> 3. WUFI official strawbale material data, with warning that much diversity exists in actual materials in any location: https://www.wufi-forum.com/viewtopic.php?t=514. Dry density of this WUFI bale is 5.3 lb/ft3. BE increased this to 6.5 lb/ft3 to meet the minimum density requirement of section AS103.5 (Appendix S, Strawbale Construction Code). 4. BSC Basic Material Properties Table (Latex Paint 10 perm) 5. 2016 CALGreen 4.505.3, Allowable moisture content 6. 2016 Cal. Res. Code Appendix AS103.4, Strawbale Construction, allowable moisture content
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