East Bay Carbon Storing Building

A Prototype Building Case Study for Alameda County

Intro/Purpose

[Why care about embodied carbon, why we created this case study, why we chose this building type]

Production of building materials accounts for over 22% of worldwide GHG emissions. Unlike carbon emission from operations, this "embodied" carbon is already emitted by day one of the building's operational life, meaning they have greater climate impact than a building’s operational GHGs over the near term. Yet building materials don't have to be only a carbon source -- some materials have the potential to be a carbon sink, locking up carbon for decades and buying time to slow climate change.

Bio-based materials, especially those made with agricultural wastes like straw, are a promising way to store carbon in buildings as agricultural materials pull carbon out of the air on an annual basis. Some bio-based materials have gained a following, mostly led by the natural building materials community, but so far they are generally confined to single-family or low-rise, specialty projects. If we are to reach a net zero carbon built environment by 2050, including embodied carbon, we must find a way to scale up the use of these materials. The first step is to show how this can be possible.

With this case study, StopWaste, CASBA, and Arup want to offer the East Bay Area and wider community a prototype that demonstrates how carbon-storing (i.e. bio-based) materials can be scaled to larger residential buildings, California's most desperately needed building type. Many bio-based materials have been confined to single-family homes to date but there are examples in several other developed countries where they have scaled to larger, taller construction. While most mid-rise multi-family housing in California is already framed using wood construction (which can also be carbon storing), there are many other fossil-fuel based materials still commonly used in multifamily housing that can be replaced with carbon-storing materials instead.

In the following pages we present a complete concept-level design and description of a carbon-storing building, followed by a closer look at 10 strategies within the project. Each strategy targets specific assemblies within the building, and both carbon reduction and carbon storage is estimated, using the *Builders for Climate Action’s ‘Upfront’ Materials Emissions Calculator*[1] (with some modifications), as compared to a more conventional choice of materials within the same type of assembly. Each strategy notes current challenges and local government actions that can help to overcome them. Additional explanation on how some of the less familiar materials can be used in multi-family construction is included in the Natural Building Material Assemblies section, as well as several references to the wealth of resources from CASBA and similar organizations.

We hope this prototype will inspire and catalyze the use of carbon-storing building materials throughout our built environment, starting with multi-family, transit-oriented housing in the East Bay Area!

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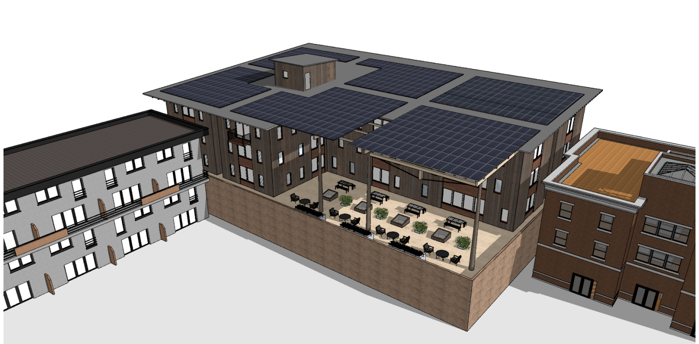
[1] Magwood, Chris. “Builders for Climate Action.” https://www.buildersforclimateaction.org/. Accessed October 2020.

Description of the Carbon-SmartBuilding 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 ¾” poured clay, with tile in bathrooms and other high-use zones.

2 UPPER FLOOR
SCALE: 1/16" = 1'-0"

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.

1 GROUND FLOOR
SCALE: 1/16" = 1'-0"

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 plys 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.

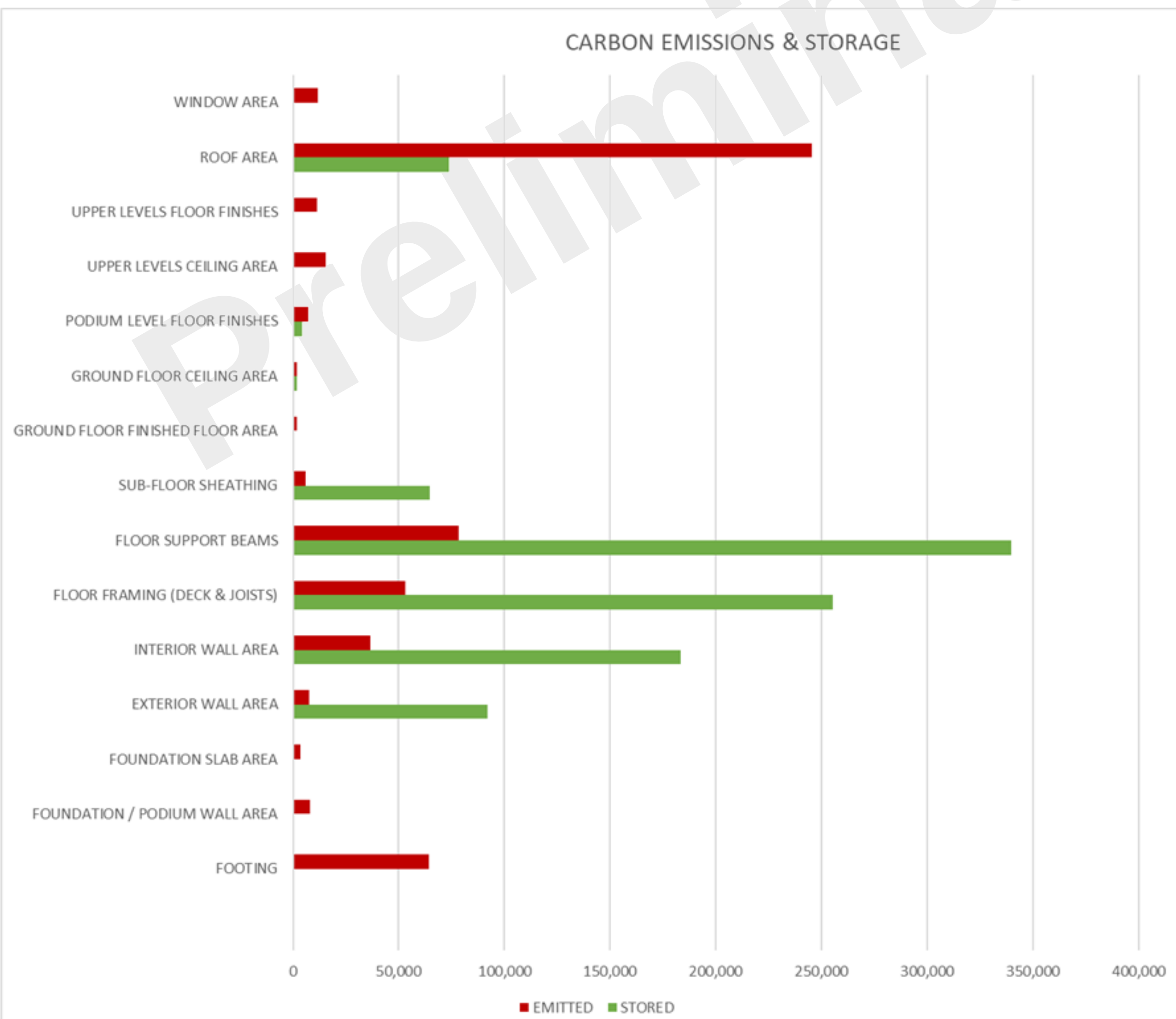
The foundation consists of reinforced concrete spread footings and grade beams. Slab on grade is concrete in high use areas, such as the garbage and recycling room and elevator pits. The parking garage floor is a compacted aggregate base. In retail and lobby spaces, the floor consists of adobe clay slabs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

Carbon-Smart Strategies

CO2 reductions, CO2 stored, challenges (market availability, possible/likely soft/hard cost increases), co-benefits, precedents, resources - See each strategy section

Based on this design, the embodied carbon emissions associated with producing, transporting, and installing the building materials amount to about 550 metric tons CO2e, but these materials store double this, or 1,100 metric tons CO2, which is equivalent to ***nearly 3 million miles driven by a typical American car.*** On a Gross Floor Area basis, this amounts to a net carbon sink of almost 100 kg CO2/m2, or 10 kg CO2/sf which is about the amount of carbon dioxide emitted in the energy use of a typical condominium for 5 years.

The distribution of this carbon emission and storage is shown in the chart below. While the structural floor and interior walls contain the greatest amounts of carbon storage, as noted earlier, these assemblies are already conventionally built with wood, a bio-based material. The strategies that are further detailed focus on other areas of the building where carbon-storage options are not the norm.



Each strategy presented below is also compared to more conventional construction for the assembly. For each comparison, an estimate was made of the difference in embodied carbon between the prototype and the more conventional assembly identified, and the additional carbon storage opportunity that comes from using materials from carbon-sequestering sources.

Some options have knock-on effects on other parts of the building design, such as when a difference in superstructure weight affects the size of foundation elements. The team included these differences in the comparison when considered significant. Note that some changes were deemed inconsequential when compared to the lack of precision expected in a concept-level design. A summary of the redesign consideration is shown in Appendix A.

Table 1: Summary of carbon savings

#	Strategy	Compared to	Embodied Carbon Reduction (kg CO2e)	Carbon Storage Potential in Product (kg CO2e)	Net Upfront Carbon Savings (kg CO2e)
#1	Straw insulation & Clay walls	6” (R-19) fiberglass batt + ⅝” gypboard [max assumes spray foam instead]	-7,860 [max = 14,200]	72,500 [no change]	64,640 [max = 86,700]
#2	Cellulose interior insulation & straw-based MDF	Gypboard & fiberglass batt insulation in party walls and floors [min uses lowest EC gypboard and fiberglass]	15,400 [min = 700]	157,800 [no change]	173,200 [min = 158,500]
#3	Compressed straw board partitions	Studs & gypboard for in-unit room partitions [min uses lowest EC gypboard]	9,500 [min = 4,600]	107,000	116,500 [min = 111,600]
#4	Clay floor finishes w/cork underlayment	LVT and carpet [min uses lowest EC carpet]	58,000 [min = -300]	4,100 [no change]	62,000 [min = 3800]
#5a	CLT podium, wood framing and HT BRB	Concrete PT podium and 10” concrete shear walls	317,300	377,100	694,400
#5b	CLT podium, wood framing and HT BRB	Pan deck podium with steel frame and HSS BRB	183,000	377,000	560,000

#6	Compacted gravel	Concrete slab-on-grade	46,200	n/a	46,200
#7	Low-cement concrete	Industry average concrete	26,200	n/a	26,200
#8	Partially grouted Earthen Block	Fully grouted CMU	25,000	n/a	25,000
#9	Exterior wood siding	Fiber-cement board	16,500	20,500	37,000
#10	Wood sourcing from verified replenishment of harvests	Wood sourcing not verified for replenishment of harvests	n/a	800,500 (wood floor framing only additional)	800,500
Note that these savings can not be summed because there is considerable overlap between them in the repercussions on other building components.					

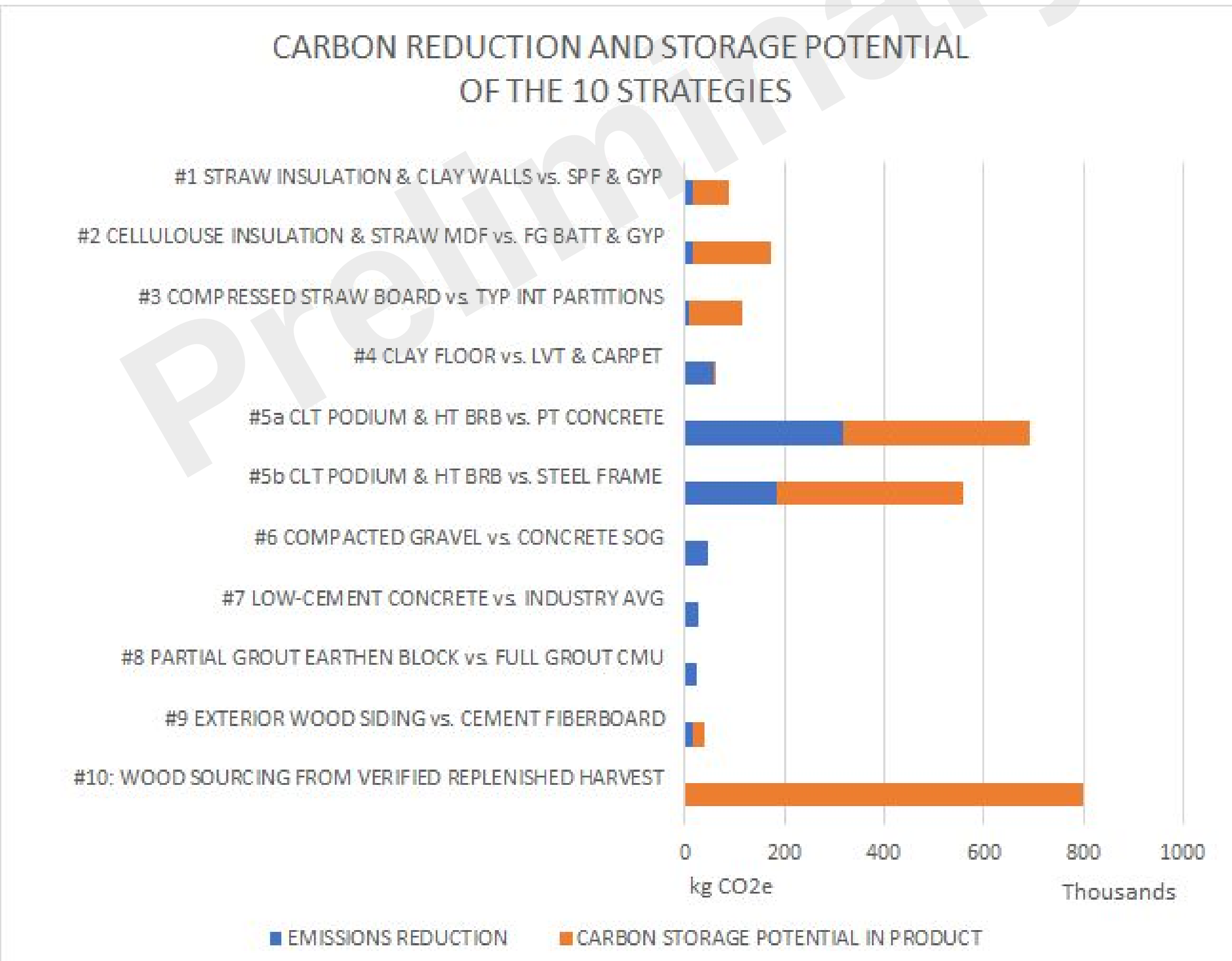


Table 2: Strategy implementation summary

Availability:
o Low – in prototype or one-off project precedent
o Med – readily available but in small quantities
o High – readily available and scalable

#	Strategy	Availability	Cost	Local government policies that could help to remove barriers	Local government initiatives that could support markets/ supply chains
#1	Straw insulation & Clay walls	Med - ample availability but needs specialist builders; potential for scaling via offsite prefab	Lower material cost, higher labor cost	Allow thicker walls without penalty to setbacks, floor area calculations, or other restrictions (e.g. use 6” equivalent for all) Allow overhang for lower R-value bio-based exterior walls to offset intrusion on interior lettable floor area. Codified in IRC, not IBC, but there are precedents using approved alternate means and methods, e.g. Mahonia	Support prototyping of locally produced prefab straw bale panels Carbon market that would give credit for use of carbon-storing materials. Local governments can consider expedited plan check, reduced fees, or other incentives.
#2	Cellulose interior insulation & straw-based MDF	HIgh (cellulose insulation) to Med (straw MDF	Low (insul) to Med (straw MDF)	Purchasing policies or incentives focused more on what goes into building products, rather than just the category of building product (like Buy Clean CA). State incentives to use straw waste such as IRC, erosion control, banning of straw burning.	More government emphasis on “green” ventures via debt financing for capital costs. (CalPlant1 benefitted from 100% CA state green bonds to build their plant.) Opportunities related to renewable materials, and carbon-storing materials that can promote sales, as currently there are none.
#3	Compressed straw board	Low (compressed straw board)	Med (compressed straw panel)	ditto	Incubate local production of compressed straw panels
#4	Clay floor	Med -	Lower		Convene potential

	finishes	depends on what is near the site, needs specialist builder	material cost, higher labor cost		supporters to create a natural building materials lab (Built It Green also recognizes this need)
#5	CLT podium, wood framing and HT BRB	High (CLT) to Med (HT BRB)	HIgher material cost, lower labor cost	Immediate adoption of IBC 2021 code changes for wood construction.	Carbon market that would give credit for use of carbon-storing materials. Expedited plan check, reduced fees, or other incentives.
#6	Compacted gravel	High	Low, higher maintenance	Incentives	Studies to show this is not as high maintenance as perceived?
#7	Low-cement concrete	HIgh	Med, little to no added cost, esp for foundations	Adoption of LCC code throughout Alameda Co and Bay Area	
#8	Partially grouted Earthen Masonry Unit	Medium	Med, comparable to visual grade block; EMU more expensive than CMU but visually higher grade and less grout offsets cost.	Acceptance of code alternates to ASTM C 426 for lower shrinkage rate and a greater quantity of fines contained in the EMU. For greater carbon savings, acceptance of lower compression strength than permitted by the standard is also recommended.	Low-to- no cement alts incentivized by LCC codes
#9	Exterior wood siding	High	Med, large range in alternative siding products; higher than fiber-cement	Disincentives for vinyl siding, e.g. Albany, justified by toxins in fire (also in manufacturing)	
#10	Wood sourcing from verified replenishment of harvests	High			

Strategy 1: Straw Insulation & Clay Wall Panel

photo/sketch

-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 ⅝” gypsum board panels, ¾” 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 and Appendix C 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
Jules Ferry Residence, France https://www.thelaststraw.org/jules-ferry-residence-straw-bale-panels/ Mahonia https://www.arkintilt.com/mahonia-mixed-use-building	https://www.buildinggreen.com/feature/straw-next-great-building-material https://ecococon.eu/us/ https://www.modcell.com/ See Natural Building Material Assemblies section.	Straw: abundant sources in Northern California; provides useful life for a waste product; healthier alternative to foams; Clay: non-toxic and zero VOC, mold-resistant, suppports bioregional economies

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**
photo/sketch	**Compared to** Fiberglass batt and gypsum wallboard

Assumptions

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.

Strawbased MDF is now available to the Bay Area from CalPlant1 in the form of its Eureka MDF product which can come in ½” 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.

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.

Similar ideas

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.

<table>
<tr><td colspan="3">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.</td></tr>
<tr><td>Examples of this strategy in use already:

Project - link</td><td>Resources:

https://calplant1.com/
https://durrapanel.com/benefit/fire-resistant/

https://www.cmsgreen.com/insulation/ecocell-batts</td><td>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</td></tr>
</table>

<table>
<tr><td rowspan="3" colspan="2">Strategy 3: Compressed straw board between rooms within residential units

photo/sketch</td><td>9,500
kg CO_2 reduction</td></tr>
<tr><td>107,000
kg CO_2 stored</td></tr>
<tr><td>Compared to

Typical studs and gypsum wallboard</td></tr>
<tr><td colspan="3">Assumptions

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.

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.</td></tr>
<tr><td colspan="3">Challenges

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.</td></tr>
<tr><td>Examples of this strategy in use already:

Project - link</td><td>Resources:

https://durrapanel.com/benefit/fire-resistant/</td><td>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.</td></tr>
</table>

Strategy 4: Clay Floor Finishes

photo/sketch

57,800

kg CO2e reduction

4,100

kg CO2 stored

Compared to

Carpet and Luxury vinyl tile (LVT)

Assumptions

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.)

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.

Similar ideas

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.

Challenges

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.

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, nontoxic hardeners to speed curing.

Cost

<table>
<tr><td colspan="3">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.</td></tr>
<tr><td>Examples of this strategy in use already:

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

http://claylin.com/

Earthen Floors – S.R.Crimmel (2014)</td><td>Other benefits

Readily available material, can support local economy, healthier material</td></tr>
</table>

Strategy 5a: Cross-Laminated Timber (CLT) Deck with HT-BRB frames *photo/sketch*	**317,300** **kg CO2e reduction** **377,100** **kg CO2 stored** **Compared to** Post-tensioned slab and reinforced concrete wall podium

Assumptions

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.

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.

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.

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.

The resulting reduction is nearly as much as the total carbon stored in the 15,000 sq-ft CLT and glulam beam floor system.

Similar ideas

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 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.

Cost

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

photo/sketch

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.

Cost

Examples of this strategy in use already:	Resources:	Other benefits
Project - link	https://www.fpl.fs.fed.us/documnts/pdf2019/fpl_2019_	Renewable materials, may support local economy, makes efficient use of higher

	murphy001.pdf	impact material (steel)

<table>
<tr><td rowspan="3" colspan="2">Strategy 6: Compacted gravel and clay at-grade floors vs. Concrete slab-on-grade

photo/sketch</td><td>46,200

kg CO2e reduction</td></tr>
<tr><td>0
kg CO2 stored</td></tr>
<tr><td>Compared to

Concrete slab-on-grade in parking area</td></tr>
<tr><td colspan="3">Assumptions

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.</td></tr>
<tr><td colspan="3">Challenges

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.

Cost

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.</td></tr>
<tr><td>Examples of this strategy in use already:

Project - link</td><td>Resources:

https://allaboutparkinglots.com/gravel-parking-lots/
https://www.homeadvisor.com/cost/outdoor-living/pave-a-parking-lot/</td><td>Other benefits</td></tr>
</table>

Strategy 7: Low-Cement Concrete

photo/sketch

26,200

kg CO_2e reduction

0

kg CO_2 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 CO_2 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: Project David Brower Center "Sustainability Through Strength" https://www.tippingmar.com/projects/project_details/19	Resources: https://www.stopwaste.org/concrete https://centralconcrete.com/wp-content/uploads/2019/07/Specification-Guide_Capturing-Value_LowCarbon_Jul_10_2018_Final_r4.pdf	Other benefits Local economy, resource efficiency and use of waste products

Strategy 8: Earthen Masonry Units *photo/sketch*	**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% cement[2] compared to typical CMU comprised of about 10%[3] 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.

Cost

Watershed block or similar products cost approximately double the material cost of standard

[2] J. Dahmen and J. Kim, "Cradle to gate life cycle assessment of alternative masonry units," 2018.
[3] https://www.concreteconstruction.net/_view-object?id=00000154-1cfb-db06-a1fe-7ffbfd900000

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.		
Examples of this strategy in use already: Project - link https://www.arkintilt.com/watershed-straw-bale-residence	Resources:	Other benefits Resource efficiency

Strategy 9: Exterior Wood Siding

photo/sketch

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.

Examples of this strategy in use already:	Resources: Albany Multifamily Green	Other benefits

Project - link	Building Guidelines https://www.albanyca.org/home/showpublisheddocument?id=387	Wood is a healthier material than some plastic siding options, and selection of redwood avoids chemical fire and preservative treatments for exterior use.

Strategy 10: Wood verified from managed forests

photo/sketch

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 Carbon-Smart 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.

<table>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">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.</td></tr>
<tr><td>Examples of this strategy in use already:

Project - link

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

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

May also contribute to local sustainability mandates for green building ratings or other measures that might require certified wood</td></tr>
</table>

Natural Building Material Assemblies

Design and spec guidance for these assemblies

Strawbale walls

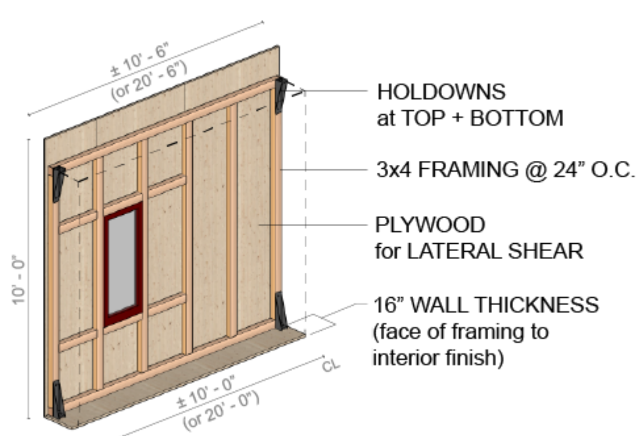
[More detailed description of the straw-based wall system, code and moisture considerations, sourcing options for Bay Area projects, regenerative agriculture, etc. Anything that didn't fit in the Strategy 4.1 summary above but should be said. Still, keep this brief - think of it as a teaser and quickly send them to existing guidance!]

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.

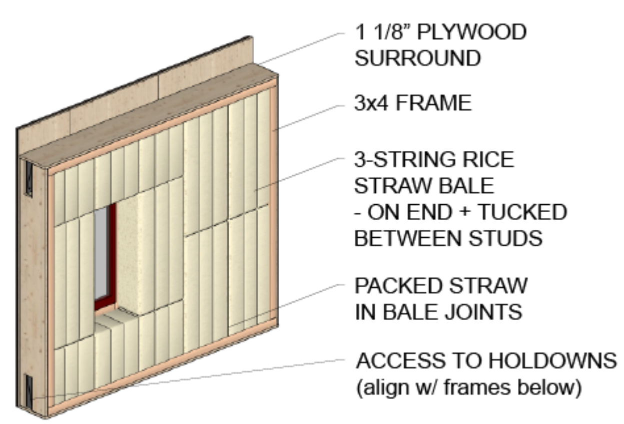
When a product of conventional agricultural practices, straw is a waste material generated annually as a byproduct of grain production. Globally, farmers frequently deal with this waste by burning it or selling as low-value material. In California, burning straw was banned, but by utilizing straw as 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 Carbon-Smart Sourcing section. (Massey please review and confirm)

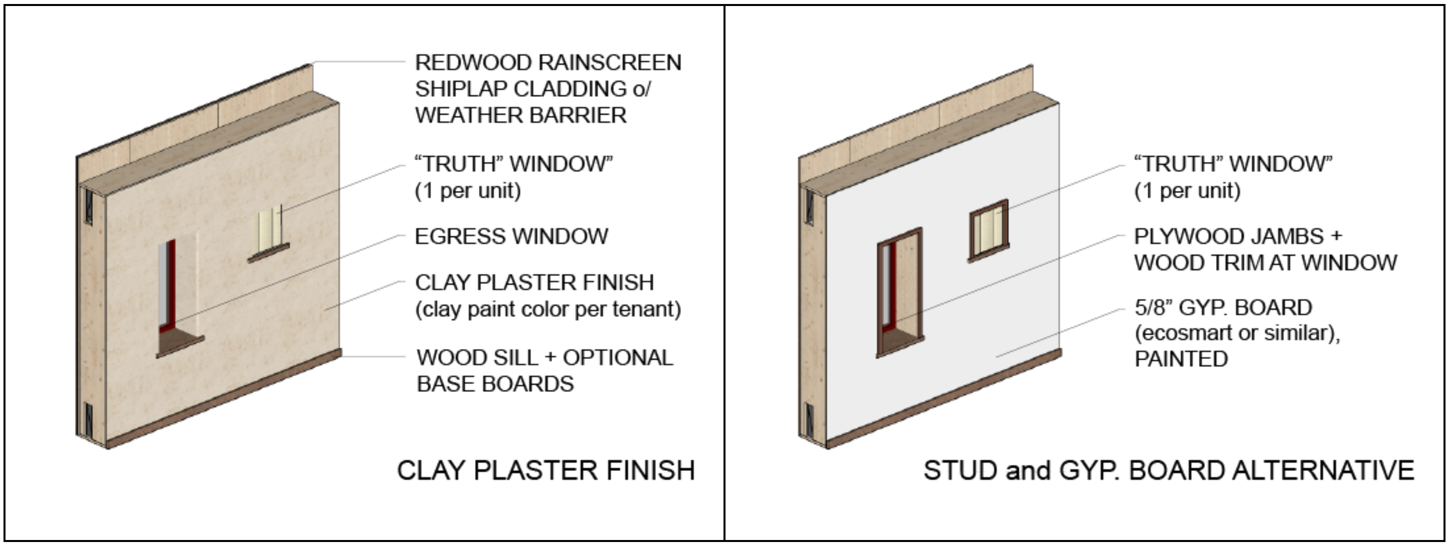
The method of assembly for the exterior straw-based wall of our carbon-storing prototype is shown below:



BASIC WOOD FRAMING



STRAW INSULATION INFILL



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

[More detailed description of the clay floor system, durability considerations, top coat options, compatible substrates, etc. Anything that didn't fit in the Strategy 4.2 summary above but should be said. Still, keep this brief - think of it as a teaser and quickly send them to existing guidance!!]

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 ¾" 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 C - '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.

Climate-Smart 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-smart wood sourcing refers to practices that prioritize carbon sequestration, climate change mitigation, and resilience to global warming impacts. For example, carbon-smart 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 EcoTrust[4] 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-smart management practices is on the same order of magnitude as the amount of biogenic carbon stored in the wood products, i.e. Strategy #10.[5] 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-smart 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-smart practices desired across our wood industry.

Straw

For straw and other annually produced agricultural fibers (like hemp), carbon smart 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,

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[4] 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

[5] Sperry, R, “Proposed Methodology for Assigning Sequestered CO2 from “Climate-Friendly” Forest Management to Timber used in Long-Lived Building Products,” Arup, 2021 [URL].

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

Carbon-smart 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 carbon-smart 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 carbon-smart 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.

Carbon-smart 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.

White paper co-authored by Massey coming soon!

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.

Conclusion

[Summary, discussion, call to action]

Resources

General, no need to repeat the ones already listed under specific Strategies or under the Natural Building Material Assemblies section

General

- CarbonSmart Materials Palette
- International Living Futures Institute "Zero Carbon Certification"
- BuildWell Library
- New Carbon Architecture

Organizations

- CASBA
- Carbon Leadership Forum
- Architecture 2030

Strawbale

https://www.strawbuilding.org/Straw-Bale-Building-Details/
https://www.strawbuilding.org/recommended-reading

Compressed Straw Board (or Panels)

- https://www.ortech.com.au/
- https://durrapanel.com/benefit/fire-resistant/
-

Clay

- The Natural Building Companion (p 315-328) – J.D.Racusin & A.McArleton (2012)
- Earth Construction (p 272-273, attached) – H.Houben & H.Guillaud (1994)
- A Handbook for Building Homes of Earth (Ch13, p91-92, Handbook attached) – Peace Corps, USAID, HUD (1981)
- Refined Earth Construction & Design with Rammed Earth – (p51, 56-63, will send in next email) – Martin Rausch (2015)
- In progres: ASTM Earthen Floor (guide) https://sn.astm.org/?q=features/earthen-floor-standard-aims-promote-sustainability-improve-health-ma19.html

Lamboo

https://www.lamboo.us/rainscreen

https://www.lamboo.us/exteriorresources
https://b7393589-5223-4ace-b042-1ef6ade91e63.filesusr.com/ugd/da42be_a748964566d749b893227fd26720976a.pdf

LCA and Embodied Carbon Tools

- Builders for Climate Action Building Emissions Accounting for Materials (BEAM) calculator https://www.buildersforclimateaction.org/beam-calculator.html
- Athena Impact Estimator
- Tally
- EC3
- Inventory of Carbon and Energy Database v3

Appendix A

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.

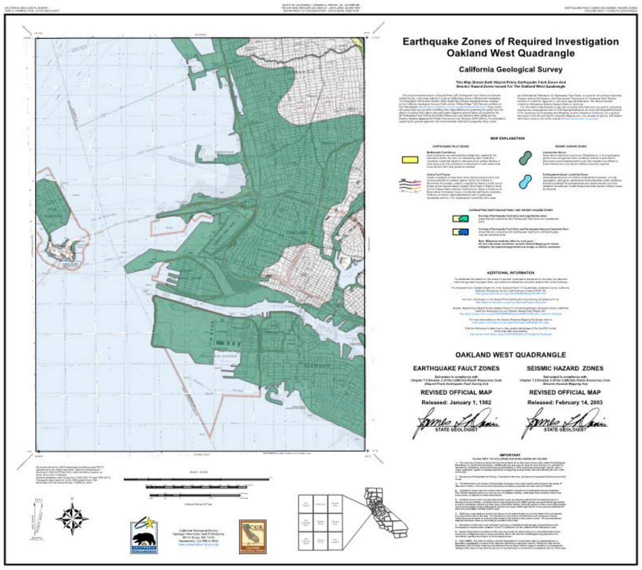
Though Seismic design category E is prevalent in the East Bay, it is not common in areas zoned for this type of structure. Therefore, it was decided to limit this design to a highly loaded case in SDC D.

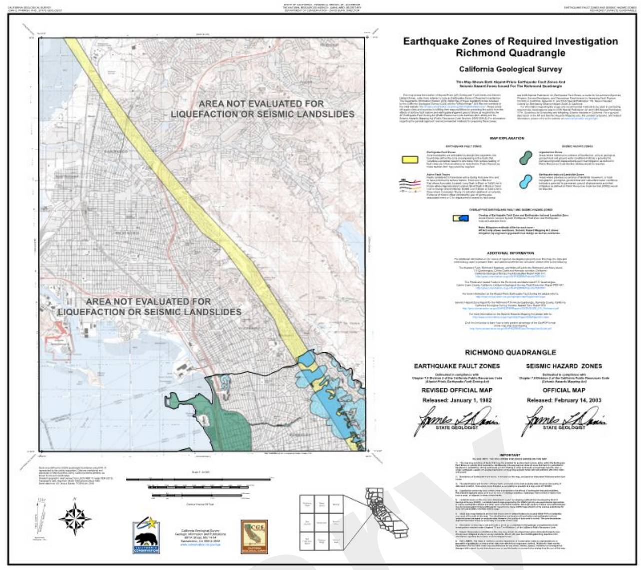
From USGS:

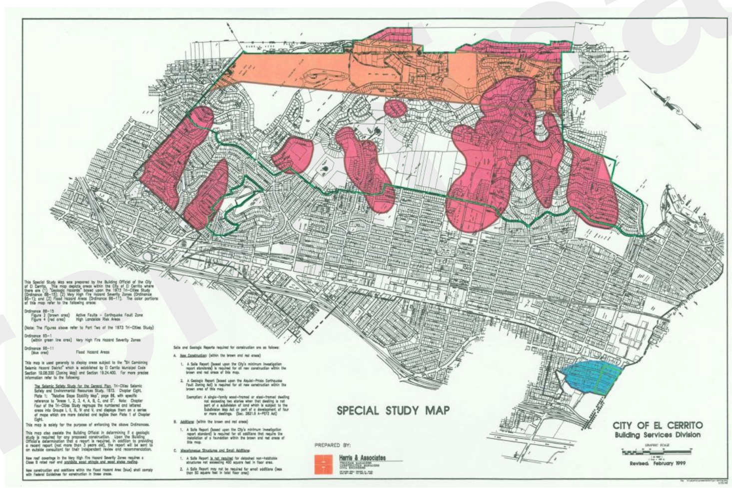
Site Class:	D
Ss :	2.400 g
Sms :	2.400 g
Sds :	1.600 g
S1 :	1.000 g
Sm1 :	1.500 g
Sd1 :	1.000 g
Risk Cat :	II
I :	1
SD :	D
ρ :	1.3

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.

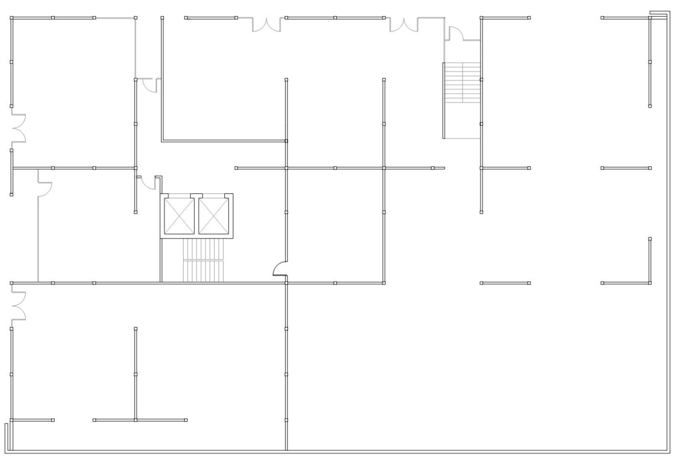
2) Architecture

- Podium height: 15ft
- Floor height: 10ft

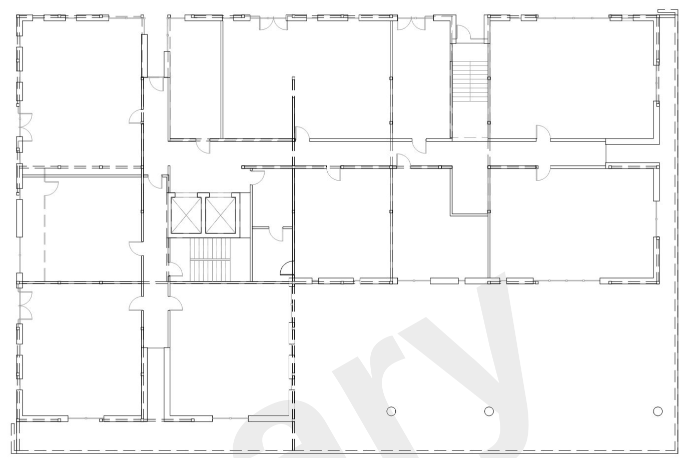
- Number of stories: 4
- Podium area: 14545 sf
- Floor area: 10560 sf

a) Floor plan

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



PODIUM PLAN



FIRST FLOOR PLAN

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

EXTERIOR WALLS		PSF	
Wood Siding		2.5	
1/2" Sheathing (2 side)		4.5	
3x4s @24"		1.1	
1" Clay		9.6	(115 pcf)
Insulation Bale 15"		10.0	(8 pcf)
Misc		2.0	
	DL=	30.0	

INT. STUD WALLS		PSF
SHEAR WALLS		10.0
	DL=	10.0

ROOF		PSF	
PV		5.0	
12" TJI Framing		3.0	
Insul. D.P. Celullose		3.5	(3.5) pcf
Misc		2.0	
Slope Adj	2:12	0.2	
	DL=	18.0	
	LL=	**20.0**	

UPPER FLOOR		PSF	
3/4" Sheathing		2.5	
12" TJI Framing		3.0	
Insul. D.P. Celullose		3.5	(3.5) pcf
Misc		2.0	
3/4" Clay		7.2	(115 pcf)
	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**	

Fiberglass

EXTERIOR WALLS		PSF	
Wood Siding		2.5	
1/2" Sheathing (2 side)		4.5	
3x4s @24"		1.1	
5/8 gypboard		2.8	
Insulation fiberglass 6"		0.4	(1.5 pcf)
Misc		2.0	
	DL=	13.5	

PODIUM PANDECK		PSF
5" Slab		50.0
Misc		2.0
MEP		2.0
	DL=	54.0
	LL=	**40.0**

PODIUM CEILING 50%		PSF
5/8 gypboard		2.8
2x4s @24"		0.4
Misc		1.0
	DL=	4.5

PODIUM PT SLAB		PSF	
8" Slab		100.0	150 pcf
Misc		2.0	
MEP		2.0	
	DL=	104.0	
	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 MPP podium (Spread ftg) (1) (2)
System 2	3 Plywood Shear Wall Stories & HT-BRB below separated by MPP 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	
15. Light Framed w/WSP	
R =	6.5
Ω o =	3
Cd =	4

A. Bearing Wall	
7. Special Reinf. CMU wall	
R =	5
Ω o =	2.5
Cd =	3.5

D. Dual System	
12. Heavy Timber Encased - Steel BRB	
R =	8
Ω o =	2.5
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 5): Steel BRB first floor with pan deck podium and wood shear walls with straw bale insulation over podium

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

		Thickness (in)			
Componet	Area (sf)	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.

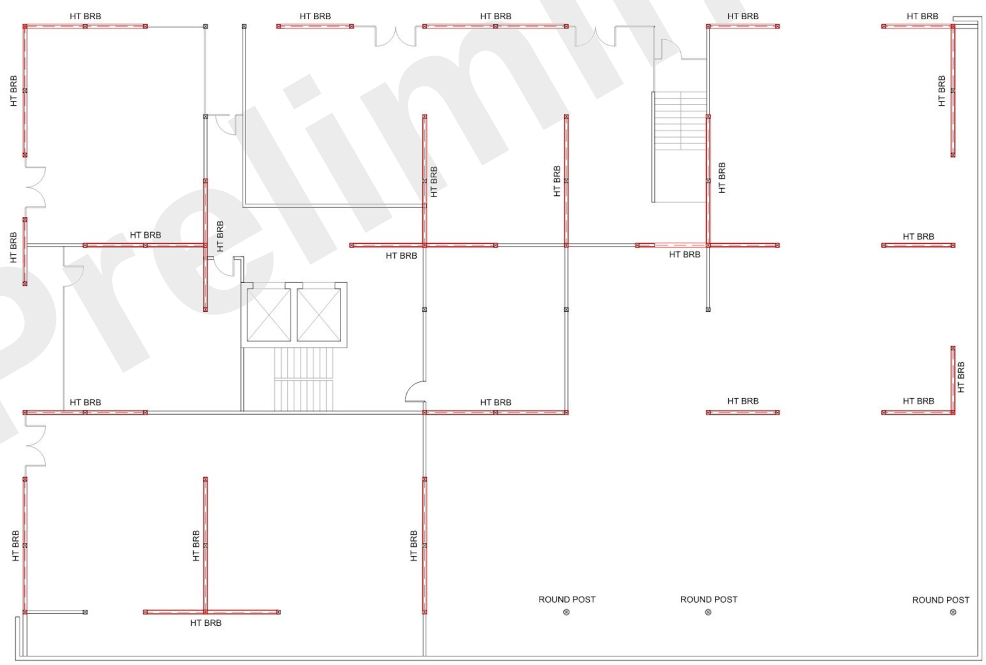
This method allows the design of the upper portion independent of the lower part using different seismic parameters that depend on the specific characteristic of the lateral resisting system.

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 l 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

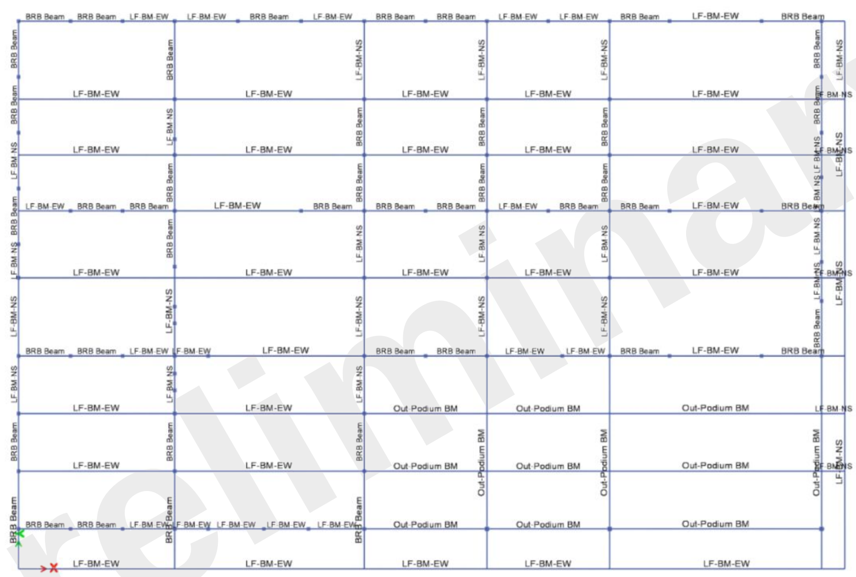
- **Model 1 and 2:** First Story HT-BRB lateral resisting system is located on the same shear lines as the walls above. The design for model 1 and 2 is identical
- **Model 3:** The steel brace frame was located at the same location as in model 1 and 2, design procedure was according to industry standards.
- **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

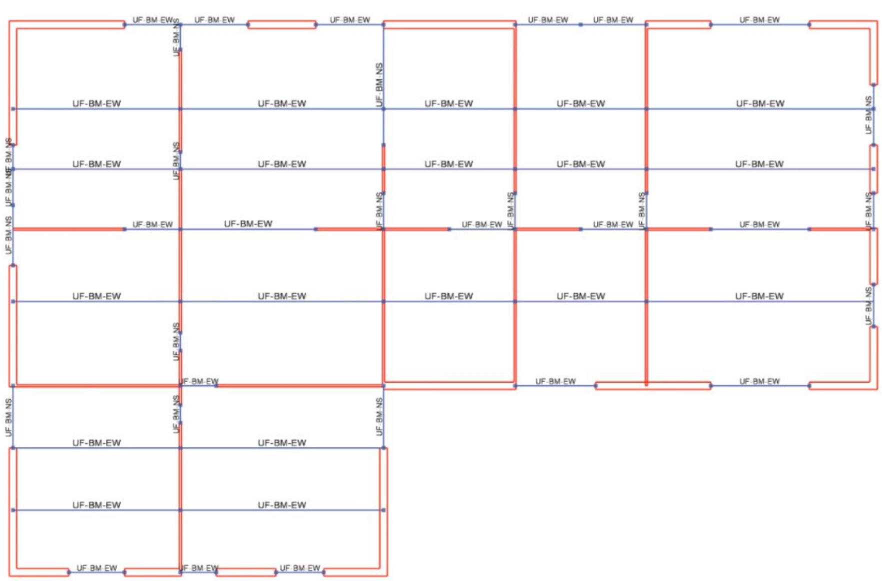
a) Framing system.

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

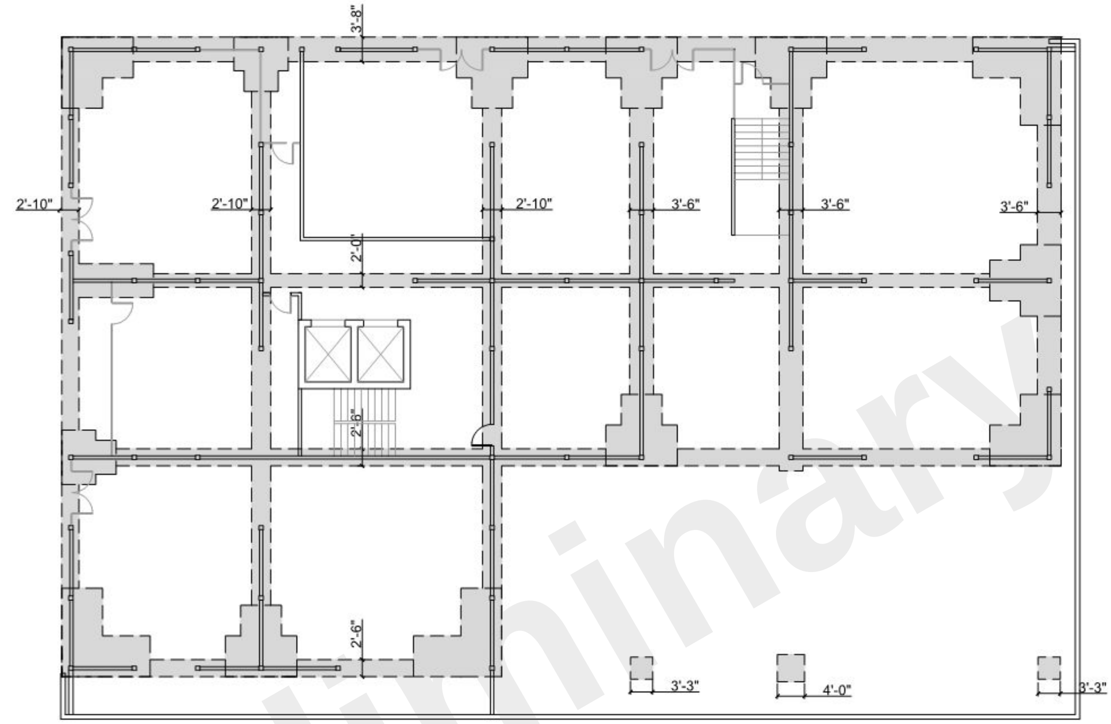
The analysis of how the span direction of the CLT affects the gravity loads distribution on the foundation size was performed. For this particular floor plan, the beams are generally symmetrically distributed between the shear lines in the building that are used as bearing lines as well. All point loads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

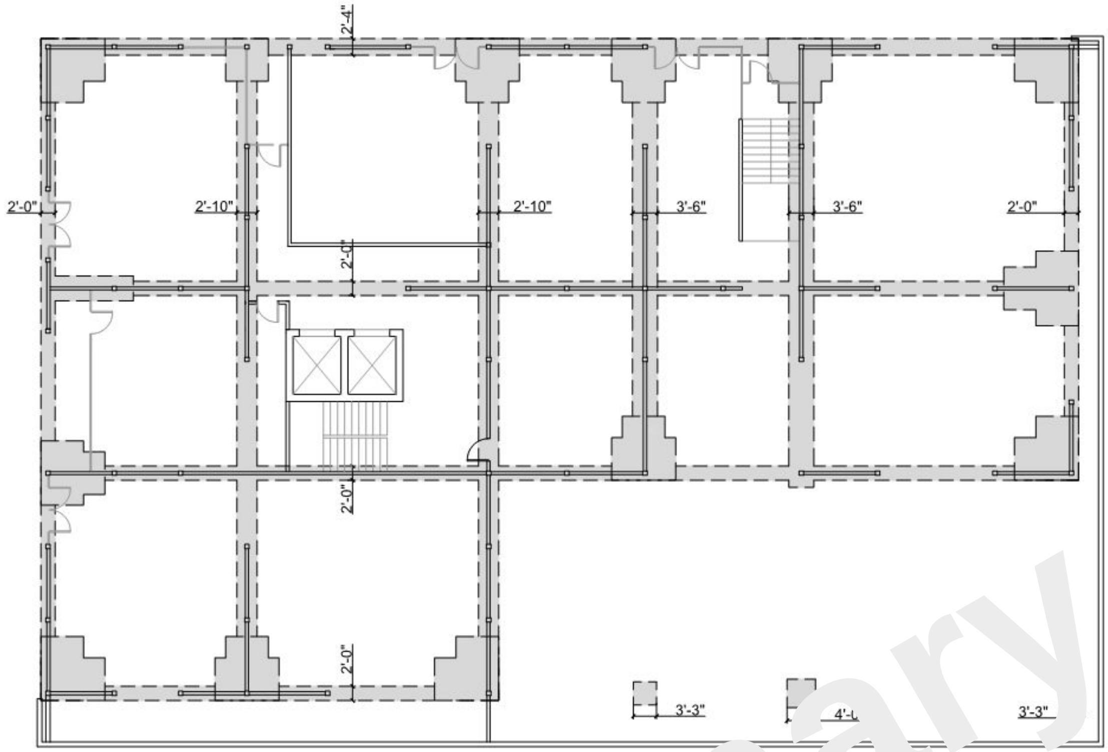
STRAW BALE WALLS



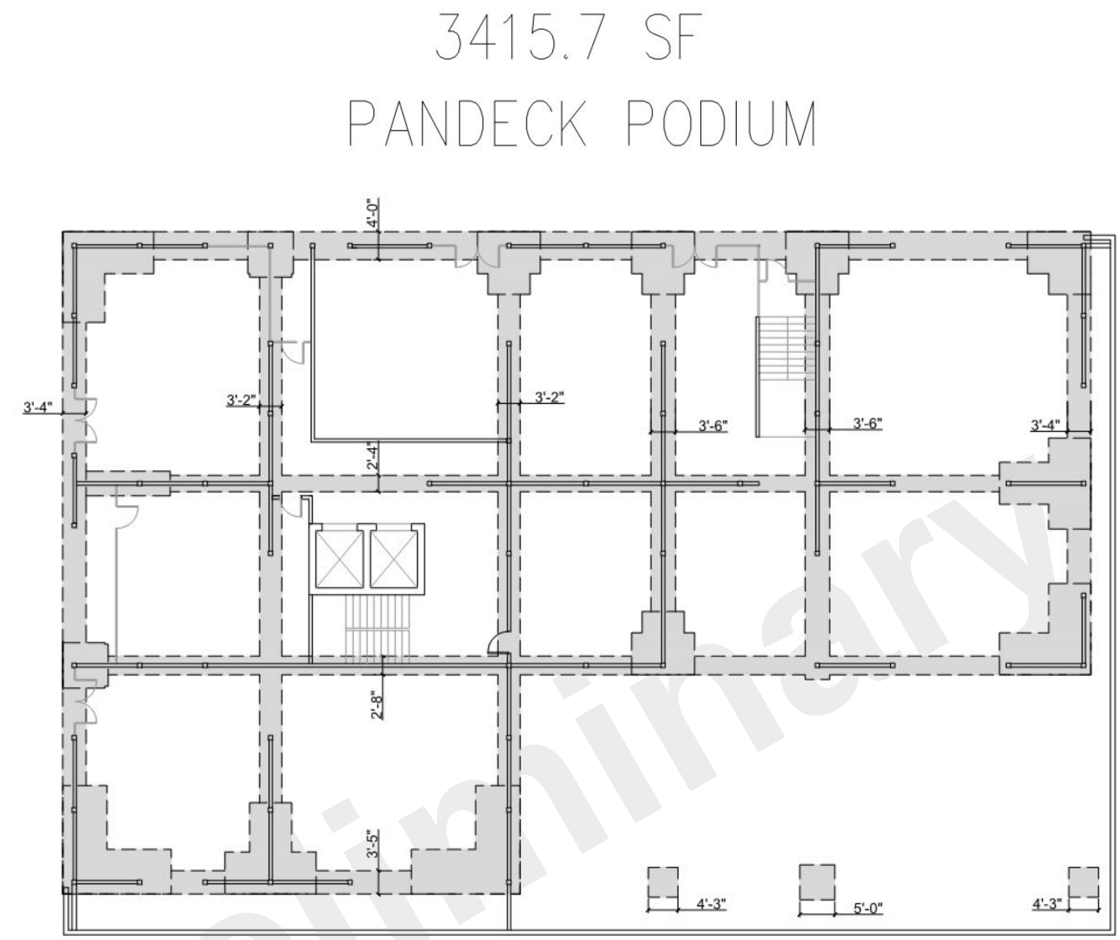
II. Foundation design, Model 2

2707.7 SF

FIBERGLASS WALLS


2'-4"
2'-0"
2'-10"
2'-10"
3'-6"
3'-6"
2'-0"
2'-0"
2'-0"
2'-0"
3'-3"
3'-3"

III. Foundation design, Model 3



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 salb	3000 psi	1.0%
Conc. Beams	3000 psi	1.7%
Conc. Posts	3000 psi	1.8%
Conc. Wall	3000 psi	1.7%

(1) Reinforcemnt ratios applies to all building types

Appendix B

BCA calculator results

Appendix C

Reprint of David's article in Fine Home Builder

Acknowledgements

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<u>Reviewers/Contributors</u>
Raphael Sperry
Christine Tiffin

Author Bios

David Arkin, AIA

Massey Burke

Miya Kitahara

Frances Yang